PDHonline Course G296 (10 PDH)

Aero Navigation - Part 10 Through 35 of 35

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2012

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1. Course Summary:

This is a continuation of the Introduction & first 9 Aero Nav systems.

This two part Aero Navigation course provides an Engineering perspective on 35 different Aero Navigation systems, including three Navigation Systems that are not actually used in aircraft. Most pilots are familiar with only 4 Aero Nav systems, & few military or professional pilots use over 6.

This course includes three "truly revolutionary" new Aero Navigation systems that are still under development & implementation, & will very soon revolutionize many types of flying; especially instrument approaches. Only a handful of pilots had heard of these as of late 2009.

Few avocations or hobbies draw upon Engineering as strongly as Aero Navigation, which is like much of Engineering in that no two flights (or projects) are exactly the same, & most are a challenge.

Much of the theory & application of Aero Nav systems are truly fascinating; especially to Engineers. The complexity & ingenuity of Aero Nav systems appeal to most Engineers. The same applies to the applicable tools & instruments that were developed.

Some of the information covered in this Aero Navigation course could literally save a person's life, even if he is not a pilot. It gives extensive ancillary information pertinent to Aero Navigation, & its relationship to flying.

Unsigned words of wisdom found on the internet: "Remember that the science of Navigation can be taught, but the art of Navigation must be developed from experience".

Although it is not essential that a pilot understand all theory in order to navigate a plane, it behooves him to understand more than the minimum required to navigate. Most Engineers would certainly be curious enough to desire to understand background & theory.

The introduction included much ancillary information & 9 Aero Nav systems (one not actually Aero):
4.1 Overland navigation system.
4.2 Dead Reckoning. Still essential for all Aero Nav systems.
4.3 Map Reading. Still essential for all Aero Nav systems.
4.4 Visible tower airway system; the first airway. Served as the basis of the Victor Airway system.
4.5 Line of Position. Seldom used in the original form, but an important feature of most Aero Nav systems.
4.6 Celestial by 3 Star. With original manual sextant & technique, rarely used for Aero Nav.
4.7 Non Directional Beacon. Used from the 1920s to the present.
4.8 Low Frequency Range. Initially a revolutionary Aero Nav system with significant features retained to the foreseeable future.
4.9 Marker Beacon. An essential parameter of the low frequency range & destined to continue indefinitely.

The number & sequence of Aero Nav Systems considered in his course is somewhat nebulous. Some might argue that some of these Systems should be combined with another, because of their interdependence or similarity. Conversely others might say that the E-6B, Weems Plotter, Trail Angle, Airplot, Autopilot, & several others should be discussed as standalone Systems, as opposed to being included with others.

2. Table of Contents; Part 2.

3. General background information; these important items are included only in course G295.
Retaining numbering system of Part 1:

Appendices (in the Introductory course, with first 9 Aero Nav systems).

4.10 Aero Navigation System No.10: Measuring Drift with a Driftmeter

4.10.1 Background:

If there are no Navaids at his disposal, an Aero Navigator must rely on DR. Lacking any method of obtaining fixes, he is at the disposal of wind & weather forecasters, or possibly weather updates. Widely spaced weather stations are still often unreliable for large portions of a route.

The major benefit of direct drift measurements is that it provides the ability to remain on course without the benefit of fixes.

Wind reversal upon frontal passage could easily result in an unknown change that could result in a change from 5° left to 5° right drift; or even a 10° reversal. A 5° drift reversal would cause a 10 mile error on only a 60 mile DR flight.

A means of measuring drift is a very important asset when otherwise limited to DR. The driftmeter is priceless in such a case, since knowledge of drift can permit correcting for drift, & thus staying on course, regardless of the extent of changes in the crosswind component.

Even without knowledge of the GS, drift correction permits the Aero Navigator to reach the destination, whether the magnitude of the headwind component is large or small, as long as fuel capacity is adequate.

An indication of the industry recognition of the importance of drift measurements is the development of multiple methods of measuring same. The inclusion of the drift attachment to airborne radar, the electronic driftmeter, & the even more sophisticated Doppler Radar are extremely valuable in situations where DR is the only Aero Nav system available.

4.10.2 Theory:

A driftmeter is capable of measuring wind induced drift. To read drift, the Aero Navigator must rotate the transparent disc to align the longitudinal grid lines with an object on the ground. Once the object is describing a path parallel to the lines, the angular scale may be read at the index mark to obtain an accurate drift angle. See Fig. 52. The object shown followed the rotated, parallel line.

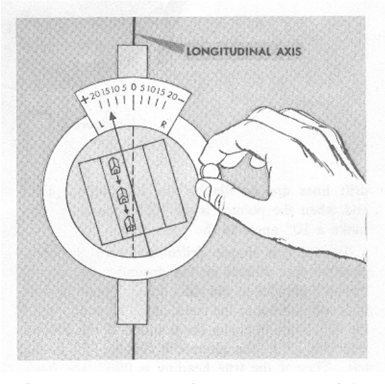

Fig 52: A Simple Driftmter

Both GS & drift are impacted by W/V. The drift can easily & accurately determined by use of a driftmeter. In some cases & situations the Aero navigator can measure or estimate GS. With TH, drift, TAS, & GS the E-6B can be used to determine the W/V. He can then compute the actual TC, & determine the course error; then adjust the new desired TH, & estimate his ETA. If a course alter is necessary, it is easy to apply the new more accurate W/V to determine the exact new heading.

If he cannot obtain a reliable GS, he must rely only on drift & TH to maintain the correct TC. Lacking knowledge of GS he should assume a measurably lower than expected GS, & make a premature, precautionary fuel stop.

4.10.3 Accuracy & Efficiency:

A complex driftmeter used with radar altimeter & DR can potentially approach the accuracy of the more sophisticated Aero Nav systems.

The drift angle can be measured within 1 to 2 degrees. The driftmeter is not limited to airway routes, so permits direct flights; thus the shortest distance & flight time.

Accuracy of distance is the most important concern. On a 60 mile flight the plane should pass within 1 to 2 miles of the destination, per the above. The Aero Navigator might still fly past with the destination abeam his route without seeing it. On a 600 mile flight, 1 to 2° becomes10 to 20 miles. Since VFR requires 3 miles visibility, a 60 mile flight should be safe, but not necessarily a 180 mile flight.

In fact, visibility would normally exceed the 3 mile limit. Conversely, in the N.E. U.S. & parts of California, visibility below 3 miles is very common. Visibility must obviously exceed probable off-course distance if there is no Aero Nav capability for homing or otherwise locating the destination. Considering the likelihood of errors in reported W/V, & the probable changes during the flight, a drift measurement would be immensely valuable.

4.10.4 Application:

4.10.4.1 There are a variety of methods for obtaining GS, W/V & Drift. If actually limited to DR, without the more sophisticated drift measuring methods mentioned above, the simple driftmeter, offering only drift, may be the only option.

The simple driftmeter can only provide drift; or at best, very with limited GS information. The simple home-made driftmeter shown in Fig 52, might be justified, & provide reliable drift information, even in lightplanes if actually limited to DR. To optimize drift measurements the Aero Navigator should also have a means of sighting that eliminates parallax errors; preferably by use of an optical system.

Considering the vast selection of excellent Aero Nav systems, it is unlikely that anyone would want to install a complex driftmeter; certainly not a large heavy military surplus unit. There does not appear to be a simple driftmeter, such as that of Fig 52, on the market.

4.10.4.2 While in Engineering school the author made a simple experimental driftmeter from a 3.5" diameter 1/2" thick transparent plastic box with lid that was free to rotate. He mounted it by the side window of his Cessna 120 with a suction cup, & aligned the reference lines with the longitudinal axis of the plane.

A simple amateur built driftmeter might justify experimentation. One like the above would be practical without aircraft modification. If the result justifies an improved driftmeter, the reader might develop a permanent driftmeter. It may, in some planes, be practical to utilize an existing inspection plate hole; or cut a special hole in the belly aligned with one in the floorboard. These holes would require an unobstructed area between the 2. A fixed clear acrylic disc on the belly would require a series of parallel readily visible longitudinal lines. Lateral lines would permit approximate GS measurements. A rotating clear disc with corresponding lines & angular calibrations on the floor board would be practical. It would be preferable, but not essential, to add optics for better operational results. Any modification to a certified plane must be performed, or at least signed off, on a FAA form 337, by a certified aircraft mechanic; with at least an airframe certificate.

A potential difficulty in a lightplane, if the pilot is also the Aero navigator, is that a constant heading is essential during observation.

4.11 Aero Navigation System No.11: Measuring Ground Speed with a Driftmeter

4.11.1 Background:

As stated in system10, drift information would be extremely valuable if DR is the only available Aero Nav system. Nearly as important in such a case, is the GS. Knowledge of drift can facilitate keeping the plane on course, but it does nothing to assure a GS sufficient to assure that the destination will be reached without refueling.

Wind reversal & enormous changes in wind speed &/or direction is very common, which can render unassisted DR nearly useless. A means of measuring drift & GS is a very important asset.

A sophisticated driftmeter used in conjunction with a radar altimeter may allow DR to be nearly as accurate as several other Aero Nav systems. DR is excellent only if accurate W/V is known.

The major benefit of direct drift & GS measurements is that it provides the ability to remain on course & accurately predict ETA without the benefit of fixes.

The multiple drift technique is dependent on accurate measurement of W/V.

4.11.2 Theory:

The theory is similar to the previous Aero Navigation System (No. 10).

Although the drift is very valuable information, GS is also important.

The time to pass between the fore & aft lateral lines can be recoded. The distance covered by traveling between the corresponding points on the ground can be computed, based on known included angle & absolute altitude. The GS can then be computed.

4.11.3 Accuracy & Efficiency:

A sophisticated driftmeter is a major contributor in this application.

The drift angle can be measured within 1 or 2 degrees. The driftmeter use is not limited to airway routes, so can be used on direct flights; thus the shortest distance & flight time.

Over land, absolute altitude will change with terrain elevation changes. On flat ground, with airport or tower elevation as a guide, the absolute altitude error will be minor. In hilly or mountainous areas it may not be worth the effort. Hilly or mountainous terrain reduces accuracy. Absolute altitude information is precise if a Radar altimeter is available. Since an altimeter setting, although imperfect (miles from a reporting station), provides a moderately accurate MSL value, the absolute altitude error will be minor over water. The biannual altimeter check assures an error no greater than 20 ft. One problem with overwater use is the fact that some floating object must be observed.

A 1 percent error in either time or absolute altitude will cause a 1 percent error in groundspeed. As altitude and time increase, a given error in time will result in a smaller error in groundspeed. Therefore, the greater the absolute altitude, the more accurate the results will be. A stopwatch is preferred for timing, which should reduce net timing error to one-tenth of a second. Considering only the timing contribution to GS computation, a 1% GS error is minor. If absolute altitude is measured or estimated within 1%, gross error may be 2%, but if altitude has a 10% error the GS will not be very useful. A 0.1 second error would result in an error of less than 1 kt, if at 228 kt GS & 10,000' absolute altitude with a 60° included angle. This is determined per the following (in part from the computation under paragraph: 4.11.4.2.1) below:

[60/6080] x [60/30] x 10,000 x 2 x Tan 30° = 0.00987 x 2 x 10,000 x 2 x 0.57735 = 23,094 ft / min. = 228 kts GS.
A 0.1 second timing error for the 30 second timing period would result in a 77 fpm = 0.76 kt positional or speed.

4.11.4 Application:

4.11.4.1 A driftmeter It is best used over land, but there are actually merits in using it over water. One advantage of using a driftmeter over water is the fact that absolute altitude will be constant, & at a precise, known value.

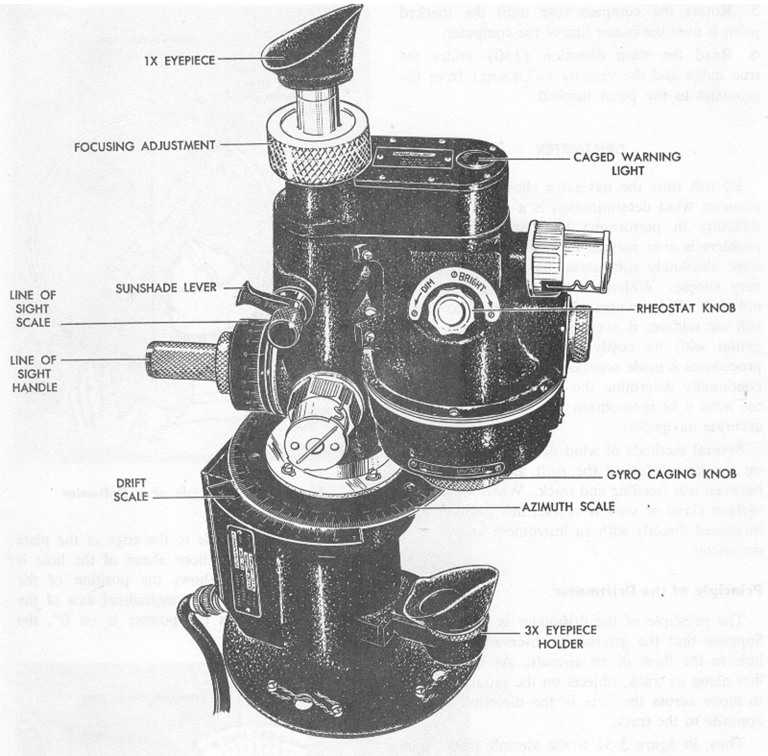

Fig 53: A Complex Driftmter

It is not necessary to know the position of the plane to obtain drift or GS drift value.

A complex driftmeter such as shown in Fig 53 can provide both drift & GS information. A Radar altimeter will measurably improve GS accuracy, but is not necessary for drift measurements.

Timing a point from, for example 30° forward to 30° behind the plane is easier than trying to identify the point of interest than at 60°. With knowledge of absolute altitude, GS computation will be quite accurate. The Aero Navigator must also have a means of sighting that eliminates parallax errors; preferably by use of an optical system, such as in the complex driftmeter of Fig 53.

A more complex driftmeter is obviously heavy, & requires minor structural changes, & thus an FAA form 337, signed off by a certified aircraft mechanic. Such a driftmeter usually includes an optical system with adjustable magnification, several interchangeable value density filters, a rheostat controlled light to control day & night illumination to improve the grid and the image visibility, & a gyroscope to stabilize the line of sight. Operation by the only pilot aboard is not really practical.

If flying solely by DR the Aero Navigator must do his best to fly the intended TC; not just his predicted TH. A driftmeter is excellent for this. The simple driftmeter relies on fixed lateral reference lines & a predetermined corresponding included angle. The complex driftmeter has a knob that allows the Aero Navigator to read the object at any desired included angle.

Another method of measuring GS by use of a driftmeter is the Trail Angle method, per schematic; Fig 54.

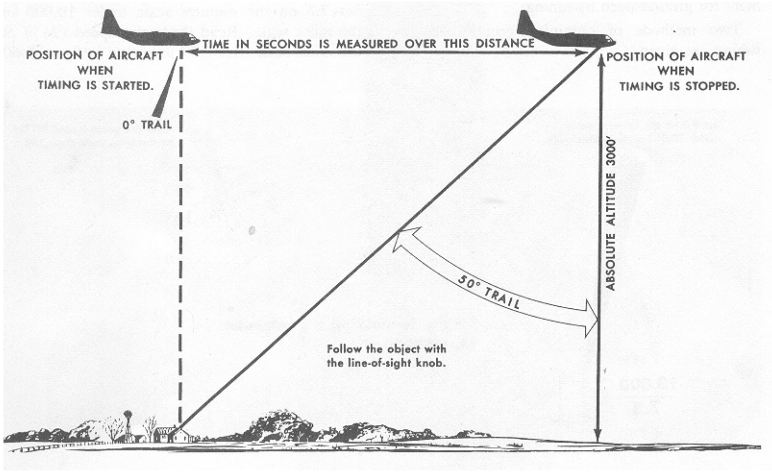

Fig 54: GS by Trail Angle; 0 & 50°

4.11.4.2 To compute GS:

Determine the absolute altitude.
With the line of sight either straight down (0° starting angle), or preferably 30° forward [a forward reference line], start timing when an identifiable but unknown object on the ground passes under the 0° [or 30° forward reference line]. The larger the included angle the more accurate the GS computation.
Determine the time when the object passes under the aft line with a known angle.
Compute distance traveled based on included angle & absolute altitude.
Compute GS based on time & distance traveled.

FACTOR TABLE FOR GROUND SPEED (In Knots)						
Finish	Starting Angle					
Angle	O'	10.	20.	30.	40.	SO'
5.	.052					
10.	.104					
IS.	.159	.054				
20.	.216	.111				
25.	.276	.172	.061			
30.	.342	.238	.126			
35.	.415	.310	.199	.073		
40.	.497	.392	.281"	.155		
45.	.592	.488	.377	.250	.095	
50.	.706	.601	.490	.364	.209	
55.	.846	.741	.630	.504	.349	.140
60.	1.026	.922	.810	.684	.529	.320
65.	1.270	1.165	1.054	.928	.773	.564
70.9.	1.706	1.602	1.490	1.364	1.209	1.000

Fig 55: Driftmeter GS Computation

Effort can be reduced with either type of driftmeter by using a spread sheet-table. A simple table that incorporated short cuts is illustrated in Fig 55 facilitates the GS computation. Drift, of course, is instantly observed.

4.11.4.2.1 Direct Computation Example:
True altitude = 10,000 feet

Starting line 30° forward; ending line 30° aft.
Time to move through 60° included angle: 30 seconds.

tan 30° = 0.57735.
10,000 x tan 30° = 5773.5 = distance along the ground from the vertical position of the plane each way to the 30° line of sight points.
5773.5 x 2 = 11,547'/ 30 sec = distance between the two 30° points.
23,094' / min. = distance flown per minute.
(23,094' / 6080) x 60 = 227.9 kts GS
The above could be written as the equation:

GS = [A x 0.57735 x 2 / T] x [60/T] x 60 / 6080
Where A = altitude in ft, 0.57735 = tan 30 for 60° included angle, 6080 = ft / nautical mile, & 60 minutes per hour.
GS = [A x 0.57735 x 2 x 60] x [60/T] / 6080 = 227.9 kts

The above could be simplified to an equation that could be quickly solved in flight; especially if an Engineering calculator retains the constant in memory, so could be quickly pulled up to solve the equation:

GS = 0.6837A/T = 227.9 kts

4.10.4.2.2 Fig 50 & the Tabular example:

Starting angle 30° (forward)
Ending angle 60° (aft of start)
Table shows 0.684
(10,000' / 30) x 0.684 = 228 kts (agrees with direct computation method)

4.12 Aero Navigation System No.12: Multiple Wind Drift

4.12.1 Background:

Knowing the drift & GS measurements of the previous two Aero Nav systems it is possible to artificially improve the W/V information by simple tactics that cost only a slight amount of lost time.

4.12.2 Theory:

The multiple drift techniques require measurement of drift on two or 3 headings with a reasonably large change between headings. It is practical to obtain a drift reading in as little as 1 minute, although a longer time will result in greater accuracy.

4.12.3 Accuracy & Efficiency:

W/V measurements may be made with greater accuracy & ease by the Multiple Wind Drift Technique than with a simple cruising drift measurement. This technique is similar to that of a 3 star fix.

The drift angle can be measured within 1 to 2 degrees. The driftmeter use is not limited to airway routes, so can be used on direct flights; thus the shortest distance & flight time. The few minutes wasted in performing the multiple drift maneuver may be rewarded with a significant improvement of TC.

A more efficient & accurate multiple drift analysis can be more performed at a time when a large alter is required; such as when following a chain of islands or circumnavigating a large lake or mountain.

The major benefit of the multiple drift technique is that W/V can be determined without the benefit of positive fixes. For best accuracy, GS values should be based on absolute altitude (Radar altimeter).

4.12.4 Application:

4.12.4.1 Knowing actual W/V is extremely important when navigating by DR. Lacking the ability to obtain positive fixes, some means of determining drift & GS is essential. W/V is especially valuable if a heading alter is expected during the flight. Knowledge of W/V would permit turning to the correct new heading, & at the correct point, since GS is also known within a moderate error. Without knowledge of W/V, multiple minor heading alters might be required to stabilize on a new heading correctly. If only the GS is incorrect, the alter point will be in error, so the plane will be offset, & the Aero Navigator will be unaware that he is paralleling the desired track.

With the complex driftmeter of Fig 53 a few turns will permit gathering info from several headings & reduce the error during determination of W/V. Each heading will produce a reasonably accurate W/V, but multiple headings will statistically improve W/V accuracy.

As is true of several Aero Nav courses, drift may be measured to facilitate determination of W/V by an Aero Navigator. In flying over irregular terrain a GS measurement may be seriously without a Radar altimeter.

4.12.4.2 A two heading wind analysis:

The two heading drift technique requires measurement of drift on two headings with a reasonably large difference between headings. It is practical to obtain a drift reading in as little as 1 minute, although a longer time will result in a greater accuracy. A good example would involve a turn of 90° in either direction, remaining on that heading for 90 seconds, followed by a turn of 90° to parallel the original heading. Neglecting time & cross track component of distance in turns, this would result in being two miles per minute x 1.5 minutes = 3 miles to the side of the desired track at a cruising speed of 1two0 mph. Total loss of progress along ground track = 1.5 minutes & 3 miles. Standard two minute turn rate gives two minutes per 360°, so two 90° turns would consume 1 minute of time.

The resulting two drift readings provide two values of drift & sufficient information to compute two GS values by using the DR computer. Both drift & GS accuracy can be increased with longer cross track headings. The two W/V values should agree within a few degrees & mph. No alters less than 45° should be used, & 90° is ideal.

An example of the two heading computation technique is:

A 045° TH is the desired TC; 210 mph TAS.
The driftmeter provides a drift of 5° left.

Assume that the second leg is flown at a TH of 170°, but at 200 mph TAS.
That the driftmeter provides a drift of 4° right.

Action required:

Set 045° TH opposite the E-6B wind face true index (left hand illustration of Fig 56).
Move the "speed slide" to set the TAS of 210 mph under the point "C"; the center of rotation of the rotating disc.

Draw a line on the lightly frosted transparent disc along the 10° angled left drift line to the left of the centerline per the left hand illustration of Fig 56.

Set TH = 170°, per the middle illustration of Fig 56.
Set the "speed slide" value of TAS = 200 under the point "C".
Draw a line on the disc along the 4° right drift line.

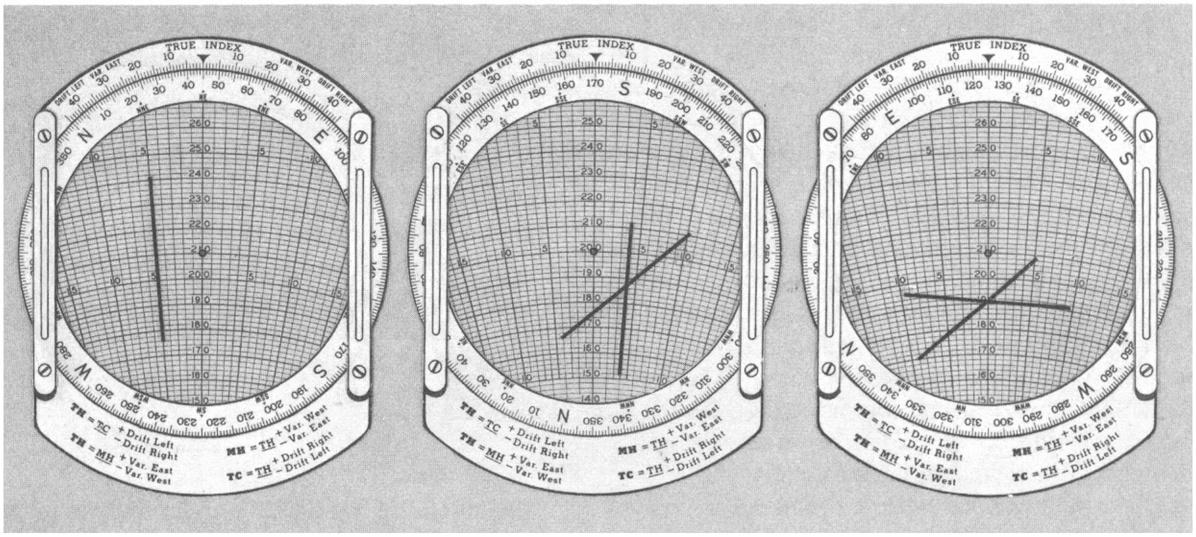

Fig 56: Drift Measurement by the two Heading Wind Drift Technique

For the right hand illustration of Fig. 56, rotate the calibrated disc to place the intersection of the 5L & 4R drift lines directly under the point "C".

Slide the speed arc portion of the E-6B to place the point "C" directly over any TAS value; in this example the 210 mph value is under the point "C", & the speed difference between point "C", & the intersection of the two drift lines indicates the wind speed of 19 mph.

In this example, 170° appears at the true index.

Thus the wind is W/V = 170/19.

Note that the intersection is actually the head of the wind vector.

With the W/V the GS could be determined in the usual fashion by use of the E-6B.

Note that wind speed, TAS, & GS could be given in either kts or mph, as long as all units are consistent.

4.12.4.3 A 3 Heading Wind Analysis:

A good example would involve a turn of 45° to the right, remaining on that heading for 90 seconds, followed by a turn of 90° to the left for another 90 seconds, followed by a return to the original heading. With the example selected, this would result in alignment with the original CH (See Note 1 Below) with a total loss of less than 1 minute times the GS. The resulting two-off-course & one-on-course drift measurement provides valuable wind information. The resulting 3 drift readings give him three values of drift; one for each heading, to solve for the wind vector on the DR computer. The smaller the heading difference in these alters the larger the W/V error.

Note 1: The Aero Navigator-pilot steers a CH to achieve a MH, & thus a TH & TC.

Figure 57 & 58 illustrate the tracks flown & DR computer action required to solve a multiple wind drift technique solution involving 3 headings, including the initial & final TH.
Note that per the norm, the chart must always be aligned with direction of flight; not true North. Thus Fig 57 appears to be inverted; North on bottom.

Assume that:

TAS remains constant at 220 mph, as it normally would.

A drift analysis using 3 headings is desired.

A 175° on-course TH is intended results in a 7° left drift.
Right leg heading = 220° results in a 7° left drift.
Left leg heading = 130° results in a 2° left drift.

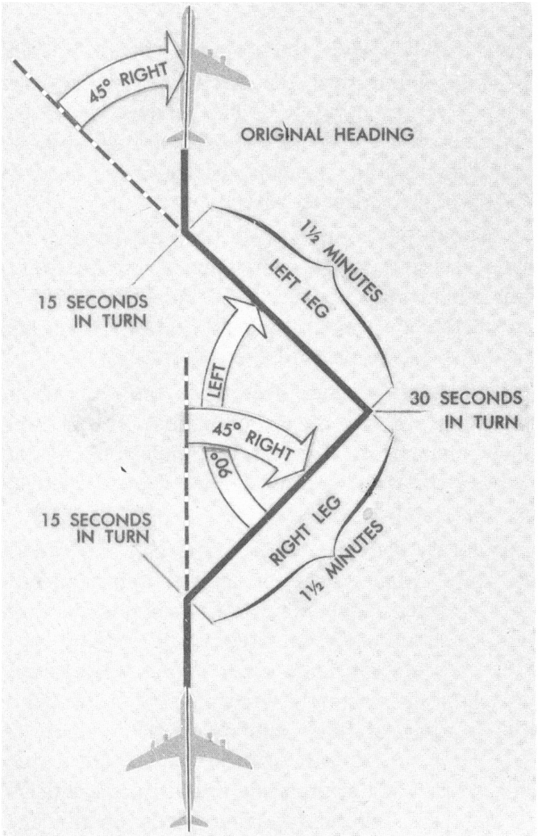

Fig 57: Tracks Flown to Accomplish a Multiple Wind Drift Technique with three Headings

Rotate the calibrated azimuth scale to set 175° TH opposite the E-6B wind face true index per illustration "A" of Fig 58.

Move the "speed slide" to set the TAS of 220 mph speed arc under the point "C".
Draw a line on the lightly frosted transparent disc along the 7**°** angled left drift line to the left of the centerline

Rotate the calibrated azimuth scale to set 220° TH opposite the E-6B wind face true index per illustration "B" of Fig 58.

Leave the "speed slide" set at TAS of 220 mph.
Draw a line along the 7**°** angled left drift line to the left of the centerline per illustration "B" of Fig 58.

Rotate the calibrated azimuth scale to set 130° TH opposite the E-6B wind face true index per illustration "B" of Fig 58.

Leave the "speed slide" set at TAS of 220 mph.
Draw a line along the 2**°** angled left drift line to the left of the centerline.

Observe the head of the wind vector at the intersection of the 3 drift lines. If the lines do not cross at a single point, as in illustration "D " of Fig 58, establish the center of the triangle. Ref paragraph 4.6.4.7 (Fig. 42) re solution to 3 LOP fixes.

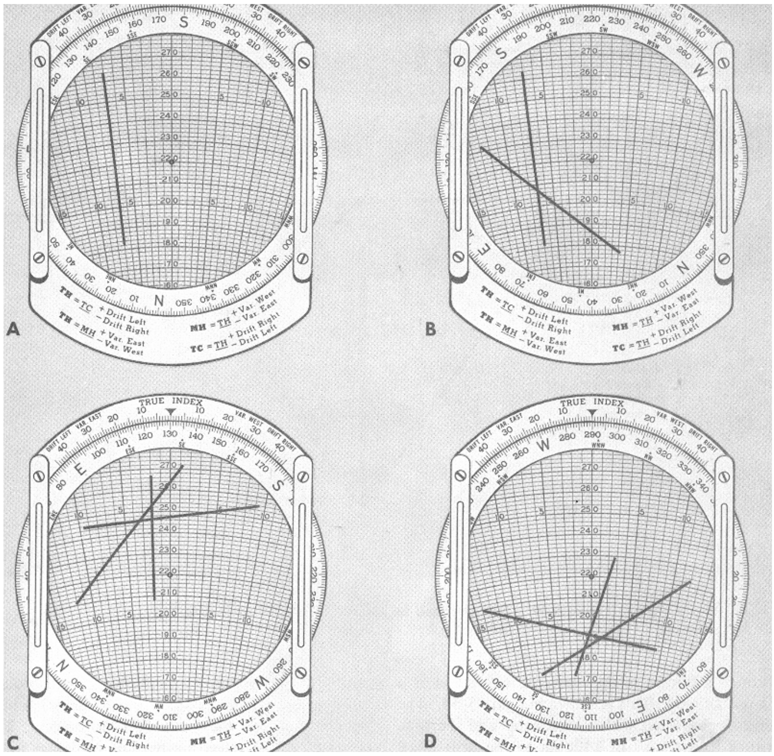

Fig 58: Drift Measurement by the three Heading Wind Drift Technique

Action required:

Rotate the azimuth scale to place the center of the triangle on the vertical centerline of the speed slider, below point "C". Read the average wind direction at the true index, & the speed as the distance of the center of the triangle below point "C".

W/V = 290 / 30.

Given an error free DR & flight conducted per the preflight the wind would be precise. If the W/V were constant for the entire flight the Aero Navigator could assume arrival at the destination at his ETA.

4.13 Aero Navigation System No.13: Running Fix by Multiple Sightings of One Distant Object

4.13.1 Background:

There are a limited number of methods of determining the location of a plane with no Aero Nav systems, & no identifiable objects near the plane. If a flight a few miles off-shore is necessary; or a flight across a barren desert or jungle, with a mountain several miles off-course, sightings can establish a fix. This Aero Nav system, lacking others, could prove invaluable. In that case this method is a simple & practical solution. The Lady Be Good Liberator might have had a better ending, had the Aero Navigator located even one light in the distance, or been able to see one mountain in the pitch darkness of the Libyan desert.

Trigonometry, & a means of measuring relative bearing, which is the angle of an object off the nose of the plane, can be used to compute a fix, as long as the heading is held constant. Each LOP must be advanced per the assumed GS to cross the latest LOP, in the same manner as two of the 3 star fix LOPs are advanced to establish the fix.

4.13.2 Theory

The position of a plane can be measured by use of a distant object if multiple bearings can be taken & the location of the object is known as long as heading remains constant.

It is possible to describe an aircraft position by measuring several bearings on the same object. It is most accurate if bearings are 45°, 90°, and 135° from the aircraft.

4.13.3 Accuracy & Efficiency

The accuracy of a running fix is actually not absolute because the advancing & retarding of the 45° lines is based on the best assumption of groundspeed, which may not be precisely known. Variation in heading directly influences bearing accuracy, as well as track. It is essential that no conditions change during the running fix. The larger the angle between LOPs the greater the accuracy.

The accuracy of a running fix depends on the RB measuring method (instrument) & care.

Accuracy depends on several factors. The instrument used to measure relative bearing is the most critical.
- If the TAS remains constant & the heading can be held within 1° that component of the error would potentially be 1 mile per 60 miles of fight.
- If the radials can be read to within 1°, that component of the error would potentially be 1 mile per 60 miles, but in much of the U.S. visibility would limit viewing distance.
- If the object is 30 miles abeam of the track, the error might well be less than 1/2 mile. A little inattention to heading during sightings, or carelessness in taking bearings will seriously reduce the accuracy.

Efficiency is excellent in that there is no need for detouring to follow airways.

4.13.4 Application

Fig 59 illustrates an example of a running fix. The identifiable mountain peak is shown at an unknown distance off course, & at a known location per a chart. The generic plane is cruising to the right at RBs of 45°, 090°, & 135° as it crossed the 45° RB to the right. The Aero Navigator recorded the corresponding times as 1402, 1405, & 1408. He added arrow heads to each radial; each pointing toward the mountain. Holding a constant heading he crossed the 90° RB & recorded the time again; this time as 1405 & added an arrow head to the radial; pointing toward the mountain. Since the most obvious bearing was the 90° RB, he advanced the first RB line to the time of the second radial. Then he retarded the final RB to the time of the second radial. Advance & retard distances were based on flying for three minutes at the assumed GS. The shifted LOPs were parallel to the radial that they represented, as shown in the illustration, but he added double arrow heads to distinguish them from actual radials. If all of these actions were error free, the three LOPs would cross at a point. It is probable that the actual fix may be at one of the three intersections, but unless he is doubtful of one LOP he should assume that the geometrical center of the triangle is the actual fix, as usual. The running fix gives the Aero Navigator a probable distance from the mountain so that he can adjust his heading if, for example, he finds from the fix that he is 10 miles off course. In this example he may actually be a little further along the course line than he predicted. The advanced fix seems improbable since he established a 90° radial that is displaced from the "fix".

The running fix provides the ability to compute groundspeed, which then permits computation of W/V; both with the use of the E-6B.

The obvious first choice for a method of determining relative bearing is an Astrocompass, although it would not be practical for most lightplanes. Any small theodolite, such as inexpensive surveying instruments would work well. A protractor could be affixed for sighting. A few sighting points, wires, or lines drawn or mounted to the airplane could serve as aiming aids. Aerobatic pilots often mount wires at pertinent angles from the aircraft axes for reference during aerobatic maneuvers. Similar markings would work for running fixes. An inspection plate screw might be used, or located such that one could anchor a wire for one of the three bearings; 45° forward, 90°, & 45°

aft. For adequate accuracy there should be a nearby reference sighting point; possibly a small magic marker on the side window. To allow placing the wing mounted wires further from the window for improved accuracy it may be preferable to use at least two window reference lines as the near sighting point. A protractor mounted under a high wing close enough to be read might be practical. An angular adjustable or fixed carpenter's tool may work.

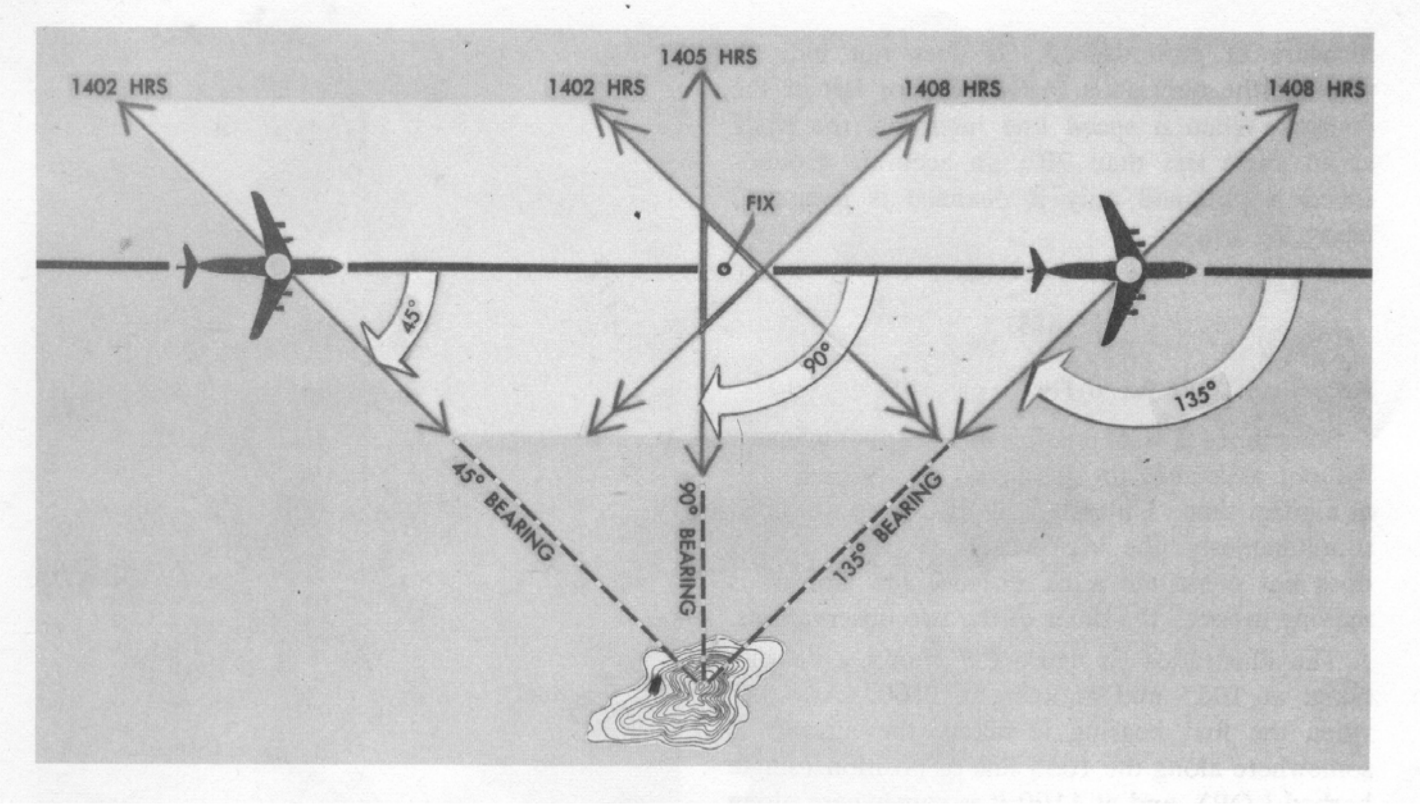

Fig 59: Running Fix

4.14 Aero Navigation System No.14: Ground Control

4.14.1 Background:

The earliest & most critical use of Ground Control by Radar may have been the Berlin Airlift in 1948 & 49. The Ground Control Approach (GCA) was certainly proven. Planes landed three minutes apart with Germany's exceptionally low ceilings; every minute at times. They carried all necessary items to satisfy the needs of the people of Berlin, including many thousands of tons of coal for heating homes. Although it seemed to be very hazardous, the safety record was twice as good as routine Air Force flying. Planes flew dangerously close to buildings of necessity. Communism, like Socialism, was as destructive, abusive of citizens, & counter- productive then, as it is today. The Berlin Airlift made 270,000 flights in roughly one year; including a typical daily cargo of 8,000 tons in 1949.

The GCA became a very successful instrument approach for many years, & is still used for convenience & to expedite IFR traffic at times.

With Radar or an onboard transponder the various FAA controllers can identify a plane & advise the Aero Navigator of his position if he becomes lost. Since nearly all planes are required to be transponder equipped, the pilot will be asked to "squawk" a specific code for positive identification. If within range of any Radar station within the U.S. the FAA, such as an enroute controller, may advise of the direction to fly to reach his destination. The controller might even continue monitoring & advising of headings to the destination. If continued to landing it is still considered to be a precision approach.

Re the transponder, any plane flying VFR is expected to squawk 1200 unless specifically directed by ATC, Approach, or Center to squawk a specific code. All IFR traffic is assigned a discreet code (set of numbers) to squawk to positively distinguish them from all other traffic. That code was changed by controllers as the plane progressed along a route until the 1990s when the code assignment system was computerized to permit a plane to keep the same code throughout a flight (especially beneficial for long IFR XC flight) to reduce the risk of lost communications.

A single frequency (vs. transponder code) is not true for voice communications. In fact, when the author was commuting across Houston in the family Cessna he was once given a frequency that he knew from experience that he could not receive below a few hundred feet, & advised Houston Approach of that concern. The controller chose not to change the frequency; not a wise decision. So on that occasion he failed to "break out" at the MDA (minimum descent altitude) for that approach. He was unable to advise approach that he was executing a missed approach until back within reception range. Not a major problem, but it might have been, had he lost power & landed short in a housing development, or had other IFR traffic been cleared for the approach into that airport. That was his most enjoyable of many commuting flights. A T.O. into low clouds, a short IFR flight followed by a missed approach, & an IFR flight back to the departure airport, & then another approach to near minimums. Both fields had dual VOR approaches, so they were easy approaches. Of course, he was a little late for work that day.

4.14.2 Theory

Radar allows an FAA controller to track horizontal, & in some cases, also vertical position. Though not intended for navigation purposes, it is a viable emergency external navigation system. ATC Controllers have certainly prevented off-field landings from fuel exhaustion, & in some cases, saved lives.

4.14.3 Accuracy & Efficiency

Ground Control accuracy depends on the FAA controller as well as the pilot. Instructions generally consist of headings & turn initiation.

Although Ground Control could be used to expedite a portion of a flight, it is more likely to result in a longer flight distance to merge with other traffic.

4.14.4 Application

Ground Control is intended primarily to expedite traffic to & from large airports in large metropolitan areas. Like instrument approaches, local traffic Radar control is used for Aero Nav only for small areas, & special purposes. In that respect it is Aero Nav.

A seldom used, but extremely important function of Ground Control is to literally, in even fewer cases, save lives in more serious emergencies. In this case the plane may be in remote areas rather than in congested airports.

Although Ground Control is not intended as an Aero Nav system, it certainly provides the Aero Nav function when the need arises. In cases where a pilot-Aero Navigator is lost, or caught in IFR conditions, controllers using Radar can vector the pilot as long as is necessary. If necessary a controller can even devote full time to that one plane; allowing others to assume most of his workload.

If the Aero navigator becomes lost "Ground Control" can be the great "face saver". Better to admit he is lost than to risk fuel exhaustion trying to find his position without help

Ground Control is occasionally used when a plane drifts into restricted airspace; to vector it back to authorized airspace. His error may be lateral or in altitude.

Ground Control is used when a VFR pilot is inadvertently engulfed in clouds. For over 50 years each Private pilot applicant must receive enough IFR training to safely make a 180° turn to return to VFR conditions. If that fails & he is unable to escape the IFR conditions, Ground Control can vector the pilot to an airport that has VFR conditions. if even that fails, they can provide a GCA to a landing; certainly not recommended. The author thoroughly enjoyed flying as sole manipulator of controls in the right seat in a Beech model 45 (powered by two 450 hp radial engines) for a few dozen GCA's under VFR conditions for flights conducted for GCA operator training.

The old GCA system faded away as better IFR approach systems were implemented, but it remained as a viable aid & emergency system.

4.15 Aero Navigation System No.15: Grid Navigation

4.15 .1 Background

Grid Navigation was to developed to facilitate Aero Navigation in the polar regions because of compass inaccuracies in these region. The magnetic compass is limited above 70° latitude; the closer to the poles the less useful they are. Magnetic compasses are not well suited for holding an accurate heading in high latitudes because it is manufactured to align itself with & respond to the horizontal component of the earth's magnetic field. The compass instead responds to the more powerful vertical component, which overpowers the horizontal component near the magnetic poles. Near the poles the horizontal component is too weak to provide a reliable indication of direction. This results in a sluggish and inaccurate compass.

Magnetic compass polar region response is degraded even further because that region experiences frequent magnetic storms which shift the magnetic lines of force. Another concern near the poles is the displacement of the magnetic pole from true North. Variation is thus very large & changes rapidly as the plane cruises along.

Another contributing factor to the difficulty of Aero Nav in the polar regions, when using the conventional geographic coordinate system, is the fact that meridians all converge at the poles. Each meridian represents a degree of longitude, while each is aligned with true North. On polar charts, the Aero Navigator experiences one degree of change in true course for each meridian, but he crosses meridians in progressively shorter flight time & distance as he approaches the poles. Eventually cruising straight-and-level on a Great Circle course the true course will change several degrees very quickly. This results in the requirement of placing the aircraft in a nearly constant turn to maintain a straight course.

Later discoveries proved that grid was useful at all latitudes.

A major advantage of grid navigation is the ability to plot & fly Great Circles, while most Aero Nav systems operate along Rhumb lines. As stated in paragraph 3..6.3.1 an example is the flight between New York & London, where the Rhumb line route is 140 miles further than the Great Circle route. Figure 4 illustrates this deviation visually by significantly curved lines where they should be straight lines.

The conventional spherical coordinate system of latitude and longitude sometimes proves difficult to use in the polar region because its units of degrees, minutes, and seconds are not comparable with the normal units of surface measurement.

As early as World War I, the French superimposed a military grid on maps of small areas in order to control artillery fire. After World War I, a number of nations followed the example of the French-devised military grid system for the use of their own military forces.

Fig 60 shows two straight lines of equal lengths that illustrate the problem of Converging Meridians.

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The line that contains points "C" & "D" crosses the 80° parallel, & also the 60° E & 60° W meridians. The magnetic heading changes 120°; between 30° & 150° true headings.

The line that contains points "A" & "B" crosses the 63° parallel, & also the 30° E & 30° W meridians. The magnetic heading changes 60°; between the 60° & 120° headings.

4.15 .2 Theory

When meridians converge at such an acute angle that it interferes with normal Aero Navigation & the North pole down force impacts magnetic compass reliability, a Grid method can measurably improve Aero Navigation.

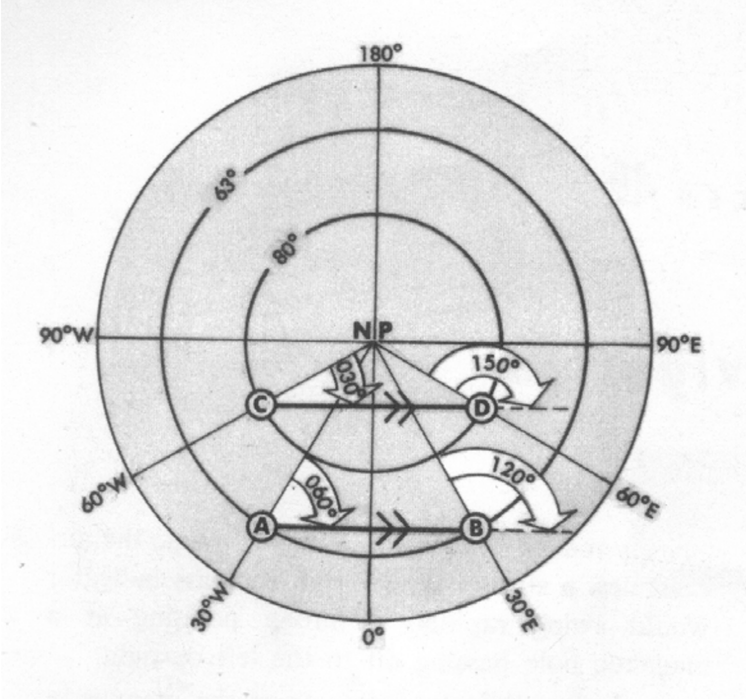

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Fig 60 converging meridians

4.15 .3 Accuracy & Efficiency

Grid nav provides a very accurate method of Aero Nav, as well as providing increased efficiency by facilitating Great Circle Aero Navigation.

4.15 .4 Application

4.15.4.1 Grid Navigation does not actually change the conventional fixing techniques. It is does, however, reorient the heading reference. Instead of the typical Lambert based Sectional or WAC Aero Nav charts, three polar projections are used in the polar regions for grid navigation. They are the transverse Mercator, the polar stereographic, & the polar gnomonic. The polar gnomonic is used only for planning while the transverse Mercator and polar stereographic projections are used in flight. The polar stereographic projection is most commonly used for flights in polar regions. The Lambert conformal projection is most frequently used for Grid flight in sub-polar regions. The division between polar and sub-polar projections varies among the type of aeronautical charts.

The graticule of the Grid overlay solves the problem that results from converging meridians. The Grid is square. All of Grid meridians point toward true North. Grid meridians do not converge.

A very important feature in Grid is that these projections approximate a Great Circle. As a Great Circle course crosses the true meridians its true direction changes although its grid direction remains constant.

More recently, the LORAN & GPS did offer Aero Nav by providing Great Circle routes. Although the heading must change when flying LORAN or GPS, the TC called for is correct, & changes are minor & infrequent except when nearing the polar regions.

4.15.4.2 Because Grid meridians are parallel to the Greenwich meridian, the angle between Grid North and true North is controlled by the longitude of the Aero Navigator, with a significant impact by the CF (Convergence

Factor). The CF is not intuitively obvious. So he must locate his position on the appropriate chart to establish the correct CF. Fig 61 shows that 71° West CA is identified as 90°W, which it represents on the grid chart. This illustrates a relationship that results in a convergence factor of 0.785; from the equation 71°/ 90° = 0.785.

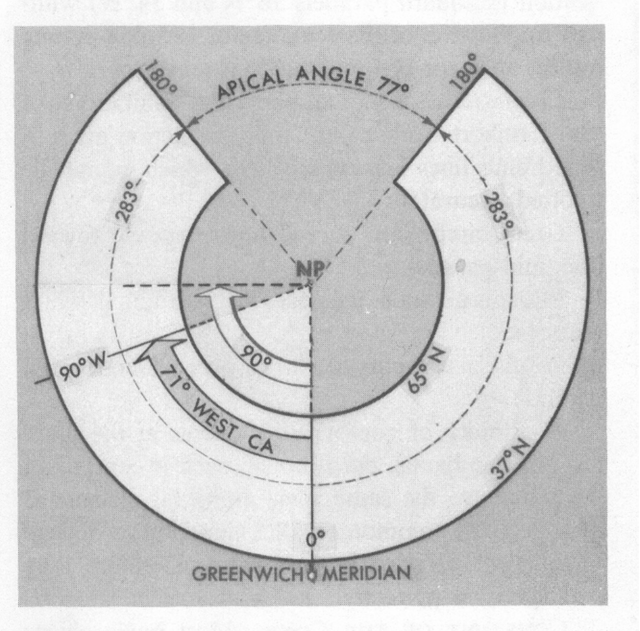


Fig 61: A Lambert Conformal Chart with 37°N and 65° N Parallels Shown

Exactly what is the Convergence Factor, & how does an Aero Navigator determine its value; & know how to use it?

The Convergence Factor (CF) of a chart may be approximated on sub-polar charts by drawing a straight line which covers 10 lines of longitude.
Then measure true course at each end of the line, observe the difference between them (d), & divide d by 10; d/10.
d/10 = CF of the chart.
On the Transverse Mercator projections the CF varies with latitude and longitude. See the Transverse Mercator Convergence Graph Fig 62 to obtain the correct convergence angle:

1. Mark the geographic location for which heading is desired.
2. Observe parabolic CF lines that indicate 0.5° interval of correction (values on lines in each quadrant; such as +1° 00', + 1°30', etc).
3. Interpolate correction factor to nearest 0.25°.
4. Apply CF to longitude of point; including the appropriate sign.
5. GH = TH ± CA

The CF in Fig 63 shows charts having convergence factors of 1.0 & shows the relationship of longitude to GN (Grid North) & true North. Looking down from the North pole at 30° W, Grid North is 30° West of true North; 60° W is 60° west of true North. Similarly, 130° E longitude is 130° East of true North.

Fig 64 shows a chart with a CF of less than 1.00, with a grid overlay superimposed on a Lambert Conformal.
39° / 50° = 0.785 convergence factor.

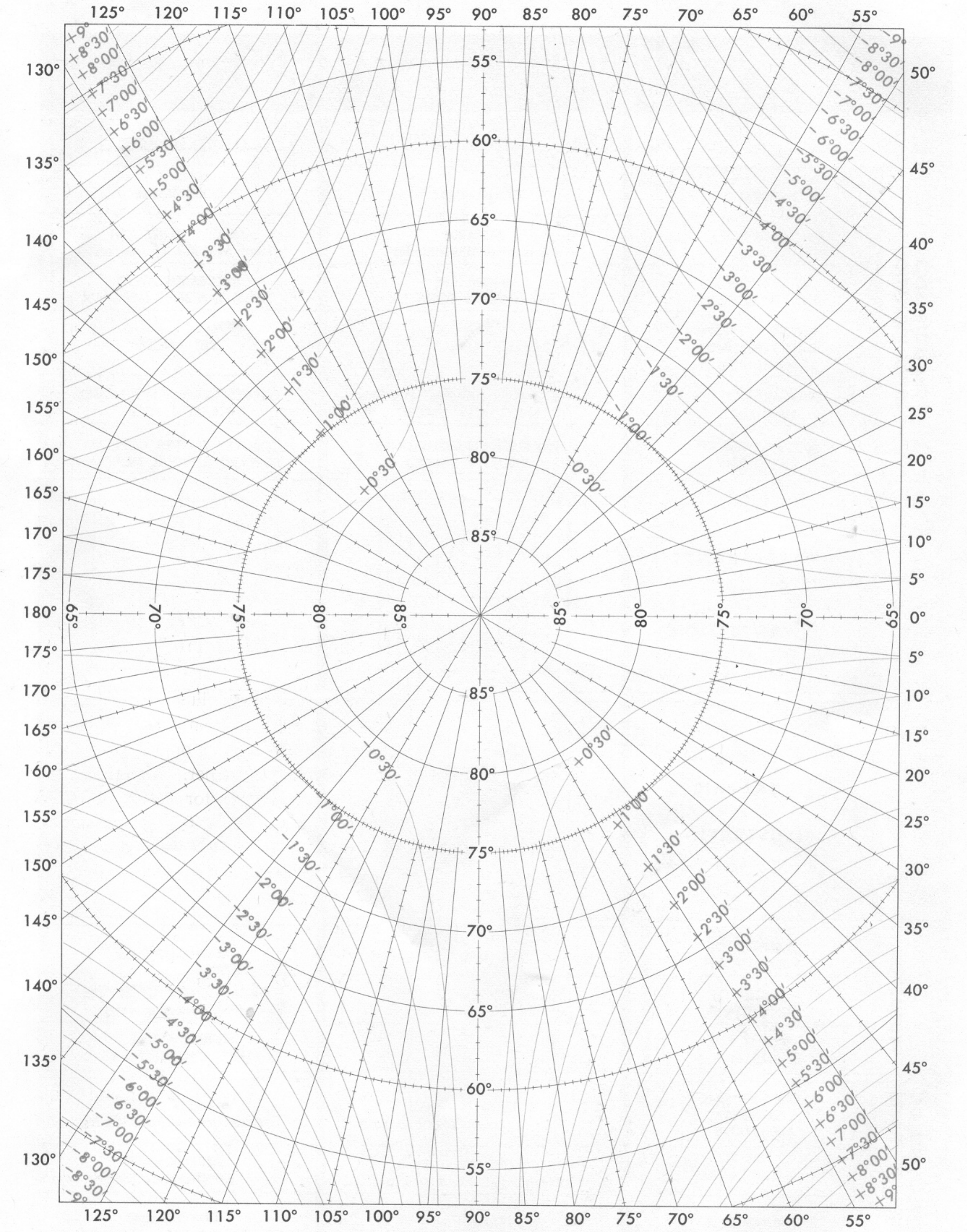


Fig 62: Transverse Mercator Convergence Graph

4.15.4.4 For the relationship between Grid North and true direction the Aero Navigator must apply equations to determine Grid direction:

Grid direction = true direction + West convergence angle (in Northern hemisphere)
Grid direction = true direction - East convergence angle

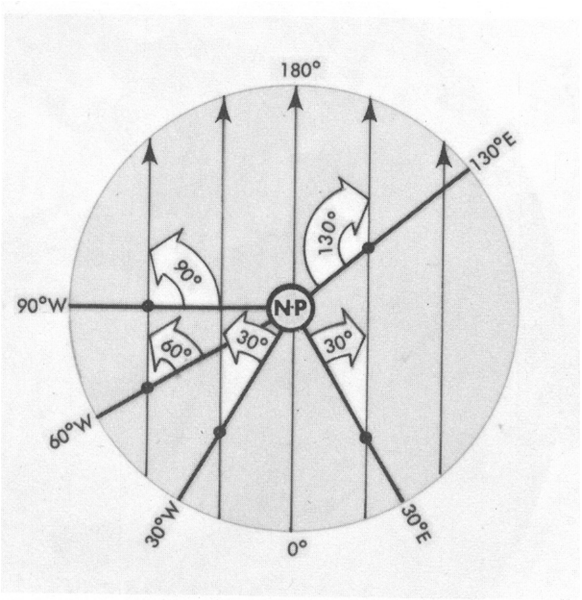


Fig 63: Grid-True North on a Polar Projection

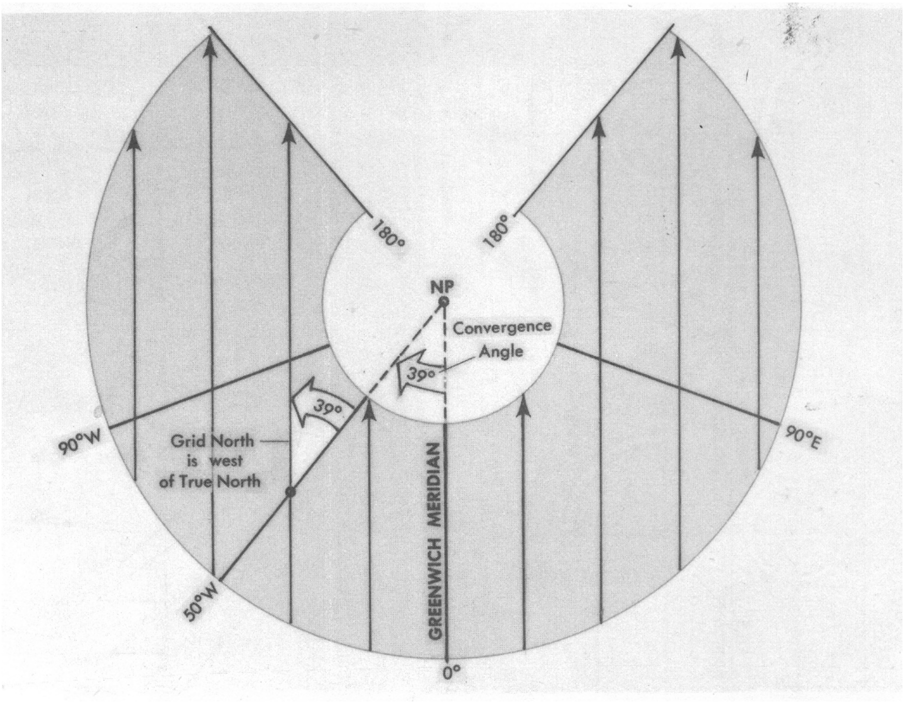


Fig 64: Grid Overlay Superimposed on a Lambert Conformal Chart.

Knowing polar angle & true direction the Aero Navigator can determine grid direction. Polar angle is Measuring in a CW (clockwise) direction from GN to true North. The equations to convert between directional references

depend on location & are:

Grid direction = true direction + polar angle where:

Polar angle = 360° - convergence angle in two opposing quadrants, NE & SW.
Polar angle = convergence angle in two opposing quadrants; NW & SE.

North on this chart is determined in the same manner as on charts with a convergence factor of 1.0. On charts with a convergence factor of less than 1.0, the value of the convergence angle at a given longitude is always smaller than the value of the longitude.

4.15.4.5 The different types of charts must be properly related. To change from 1 type to the other one must understand that the relationship between the true meridians and the grid overlay on sub-polar charts differs from that on polar charts. As such, the overlays do not match when a transition is made from one chart to the other. Thus the GC (grid course) of a route on a sub-polar chart will not be the same as the GC of that route on a polar chart.
To account for the difference, the charts must be changed as follows:

a. Select a change point that can be identified on each chart.
b. Measure the sub-polar GC and the polar GC.
c. Determine the difference between these GCs to establish the amount that the compass needle must be changed at the point of change.
d. Note which is larger.
If the sub-polar chart is being changed, & the sub-polar GC is larger, find the difference.
Read the compass heading.
If changing from the larger to the smaller GC, subtract the GC difference value from the CH for the appropriate proper Grid reading.
Instead of changing the aircraft heading, alter the compass needle to the new Grid heading.
If the plane crosses 180th meridian while using a sub-polar chart the grid heading will change because of the convergence of grid meridians along the 180° meridian. The Aero Navigator should change headings. If flying on a Westerly heading he should add the "Apical" angle to the GH (see Fig 61). If flying on an Easterly heading he should subtract the "Apical" angle from the GH. The apical angle can be measured from the chart at the 180th meridian between the opposing GN values, or it may be computed per the equation:

Apical angle = 360° - (360° X CF) .
For example: Assume CF = 0.785
Apical angle = 360° - (360° x 0.785)
= 360° - 283°
= 77°

4.15.4.6 Grivation is a new term that applies to Grid. It is the difference between the angular bearing values of the earth magnetic field & grid north is called grivation (GV). Grivation is analogous to variation in that it is applied to magnetic heading to obtain Grid heading, or the reverse. It is determined be the equation:

Grivation = $(-\ CO_w) + (\ +V_w$ or $-\ V_e)$

Grivation = $(+CO_e) + (\ +V_w$ or $-\ V_e)$

where CA_w = West Convergence Angle, where CA_e = East Convergence Angle, V_w = West variation, V_e = East variation, Grivation is + if West, & - if East. The above is for the Northern hemisphere; the sign of Grivation must be reversed in the Southern hemisphere.

4.15.4.7 Gyro Steering for Grid Navigation

The problems in using a magnetic compass were discussed. A vital solution to this is Gyros steering. As such, an understanding of the gyro is important. The DG is used for heading reference, but most DGs do not have a spin axis lock. Such a lock is important for Aero Nav near the poles to prevent precession.

The DG primarily intended for providing steering information during IFR flight. It is designed to limit gyro movement to prevent tumbling or shift of the spin axis from earth horizontal. As a unit, it is only free to rotate about the vertical axis; in the horizontal plane. A gyro is subject to several types of precession.

Movement of a gyro spin axis from its intended horizontal alignment is called precession. Types of precession include Real & Apparent precession.

Apparent precession includes Earth rate, Transport & Grid transport precession.

Real Precession is change of orientation of a gyro spin axis. from its initial alignment in space. It is caused by imperfections, primarily caused by friction, which is negligible in modern gyros. A gravity sensor keeps this axis in proper alignment during straight & level flight.

Apparent Precession results from the appearance that the spin axis has moved from its intended horizontal plane. This is caused by the fact that a gyro is stable in space.

Earth Rate Precession results from changes caused when the spin axis of the gyro remains aligned with its orientation in space while the rotation of the earth causes a change of relative aircraft attitude. A gyro in a plane flying at a fixed heading over the North pole appears to turn 15° (actually 15.04°) per hour in the horizontal plane, because that is the rotation rate of the earth. At the equator there is no earth rate precession.

Grid Transport Precession results because meridian convergence is not accurately shown on charts. Also, the plane is directed to fly a Rhumb line while the gyro follows a great circle. The rate at which the great circle track curves away from a Rhumb line track is grid transport precession. It is proportional to the difference between meridians as depicted on a chart & the actual meridians on the earth.

4.16 Aero Navigation System No.16: Radar Navigation

4.16.1 Background

Radar is similar to that used by the bat. The bat emits sound that is inaudible to humans, & it hears those sound reflected to navigate & dodge obstacles without eyes. Bat emissions travel at the speed of sound; fast, but not compared with the speed of light.

The theory of Radar was understood since the time of Hertz, who successfully demonstrated the transfer of electromagnetic energy through space, and showed that such energy is capable of reflection, in 1888. This resulted in the development of the radio; simply transmission and reception of an electromagnetic signal.

In 1922 the application of the receipt of reflected signal from a surface was conceived. The possibility of measuring the elapsed time between the transmission of a radio signal and receipt of the reflected signal from a surface was simultaneously evaluated in the United States and England in 1925. They measured the time required for short pulses of radio energy to travel to an object. They developed equipment capable of measuring time & converting that information to distance from ships or planes.

Sound travels at a speed of 1,100 feet per second. The total distance traveled is then:

D = 1,100 x T. If it takes 10 seconds for a noise, such as a gunshot, to reach a person, the distance would be:

D = 1,100 x 10 = 11,000' or 2 miles.

Radar signal & return can also be timed. This speed of light & radio signals is approximately 186,500 statute miles, or 985,000,000 ft / second; or 985 ft / microsecond. Given an interval of 100 microseconds from transmission to target & back to adjacent receiver is D = (985/2) x 100 = 49,250' or 9.3 miles

The English realized in the early 1930s that with the advent of modern warplanes they would not remain an island from the standpoint of security. They invested in research in an attempt to develop Radar in 1935. Several countries had been trying to develop the equivalent to Radar unsuccessfully for several years, but only the US had approached the success that Brittan achieved. The Brits were "so advanced" (though still primitive) by the start of the Battle of Brittan in 1939 that the Germans had no idea what their network of 400' tall towers were.

They made an unsuccessful attempt to determine by flying the retired Graf Zeppelin along the coast with an enormous collection of electrical radio frequency receivers (before development of electronics) & Goring concluded it was no threat (a very big mistake). Spitfires & Hawker Hurricanes met Germany's first 3,000 plane raid with less than its total of 600 Brit fighter aircraft. Radar gave Brits the 10 minutes extra time they needed to put Spitfires & Hurricanes at flight level in time to shoot down many German planes; thus saving enormous damage to English property. It thus permitted the Brits to flood the skies in a timely manner; causing Goring to think the Brits had several thousand more planes than their actual 600. Goring made his second big mistake when he called off the Battle of Brittan only a few days before the Brits would have declared it a lost battle. The author had the honor of belonging to the same local chapter of the EAA (Experimental Aircraft Assn) that a man from Canada did. He had flown every new Spitfire off the assembly line on a very brief test hop. He was too young for them to allow him to fly combat. The Brits used everyone. Even feeble old men. But a true life saver was the use of young women to operate the new Radar. Without those ladies they would not have won the Battle of Brittan. The Brits also invented the tiny very powerful Magnetron that permitted design of small ship & airborne Radar to virtually win the air & navy battles against Japan & Germany. The Americans, though, were the only ones capable of manufacturing Radar for all applications, in sufficient quantities. Some say that Radar won the war. In fact hundreds of "things" & millions of people were responsible, including that Canadian, who freed up a fighter pilot who may have permitted the Brits to shoot down just enough German planes to extend the success of the Brits enough to the battle of Britain. Without any of the above the Germans would certainly have won WWII.

There are now several types of airborne Radar. Some serve more than one purpose; Navigation, "active" (as opposed to the "Stormscope" that presents electrical activity), terrain clearance, & collision avoidance.

4.16.2 Theory

The theory of Radar involves the transmission of short spikes of electromagnetic radiation toward any reflective target, reception of the reflected signal, & measuring the time of two directional transit. With known speed of light-electromagnetic signals, a known time can easily be converted to distance. Given a means of transmitting & redirecting (scanning) a very narrow beam, directional in azimuth &, in some cases, elevation information can also be gleaned. Two wide beams that are very thin (narrow angle) at 90° relative orientations typically give separate information; azimuth & elevation. Conversely a Radar can perform a Raster scan with a round narrow angle beam.

Radar reflectivity is precisely the same as light reflecting off of a mirror, in that angle of reflectivity will be the same as the angle of incidence ($A_i = A_r$). As such, only the portion of the Radar beam that strikes a material when perpendicular will reflect back to the Radar antenna. Multiple reflections can appear to violate this rule, but the rule is actually true if multiple reflections combine with the same overall in-out values. This is illustrated with a "corner reflector".

A "corner reflector" is constructed from very flat Radar reflecting material arranged at 90° angles so that they form a three sided of the corner of a box. Any light or Radar energy striking any of the three sides will inherently reflect back directly toward the original source antenna (or light source). The portion of the incident energy that reflect depends on the reflectivity of the material & effective change in angle. The reflectivity of a corner reflector is such that it appears to be hundreds of times as large as it actually is.

4.16.3 Accuracy & Efficiency

4.16.3.1 The accuracy of radar varies from inches to miles , depending on the type of Radar involved. If a Radar screen is 6" diameter, the 3" radius would provide very limited range information accuracy. Given an selectable Radar range of 20 to 200 miles, the image on the screen could easily be misinterpreted by 1/16" on screen, netting 10 miles over the ground. RB accuracy, too, leaves a little to be desired for accuracy.

There are methods for improving accuracy, as noted below.

4.16.3.2 Aero Nav by Radar is not limited by weather, altitude, or ground track. It can be used to travel directly between any two points. In this respect it is one of the most versatile of all Aero Nav systems; thus it is efficient. An inefficiency might involve the lack of inherent ability to fly a Great circle route, & inability to navigate beyond line-of-sight; over very large bodies of water.

4.16.3.3 Errors: Aero Nav Radars do have some unavoidable errors.

Range error can result if the transmitter Radar pulse is sufficiently long that the GS of the plane impacts the range measurement.

Some Radars scan from a moderate included angle, some to a full 360°, depending on the type unit. Beam width is a finite angle. That angle contributes to an error. An example: An airborne Radar scans a 500' wide skyscraper from a distance of 10 miles. Given adequate reflected energy the return will start as the edge of the beam crosses the near side of the building. As it scans the signal will continue until the trailing edge of the beam passes the edge of the building. Total apparent building width is 500' plus beam width at 10 miles; presumably quite wide. The center of the sweep is still the center of the building, assuming that the plane did not move far enough to bias that relationship.

4.16.4 Application

4.16.4.1 Since terrain features can be identified on a Radar screen, a variation of map reading can be utilized to perform Aero Nav while flying above clouds.

Conventional (not Doppler) Radar systems of value to the world of aviation include self-contained airborne Navigation Radar, ground linked (transponder), ground-referenced, & ground based. Some utilize integral computers. Some are single purpose; for Aero Navigation, Weather, or collision avoidance (ground or planes). Some provide only azimuth & range information. Some also provide elevation information

A self-contained system is complete in itself and does not depend on the transmission of data from a ground installation. The airborne Radar transmits a continuous series of pulses; & detects & displays return reflections. Analysis is left for the Aero Navigator. Aircraft equipped with self-contained systems can operate independently anyplace in the world.

For the purpose of Aero Navigation System No. 16, only self contained Aero Navigation Radar is of interest.

When an appropriate computer is integrated into a Radar system, the capability & ease of operation can be improved. An Aero Navigator can identify assorted terrain features, & determine direction & distance from same.

4.16.4.2 A Radar is a very complex Engineered system. It includes:

Transmitter
Modulator (timer)
Means of chopping the transmitted signal into short pulses
Transmitting & receiving antenna that continuously oscillates through a predetermined scan angle
Transmitting & receiving antenna that alternately switches between the two functions
Receiver
Processing system that converts reflected signals into a CRT display such that bearing & range are continuously displayed.
A CRT is a cathode ray tube; similar to an oscilloscope or a TV screen.
Power supply.

Operation is sequential. First a pulse is transmitted from the antenna. Then the antenna is electrically disconnected from the transmitter & connected to the receiver. The return echo is received by the antenna. The signal is amplified by the receiver, and supplied to the CRT for display.

The CRT screen receives a continuous beam that activates a luminescent screen. Return reflections appear as bright spots that move radially outward from the center of the screen. The screen sweep is synchronized with the antenna sweep. The screen beam scans outward & returns to the center to sweep again; about the center. A typical Radar screen is illustrated in Fig 65. A home TV uses a raster scan; a series of horizontal lines that are

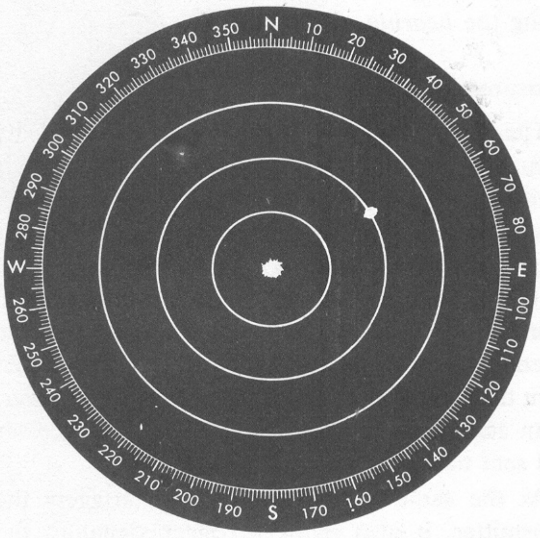


Fig 65: A Radar Scope with a Target at a RB of 60° & Range of 1/2 of the Range Setting.

painted across, & then steps down, & repeats until at the bottom of the screen. A Radar scope is circular, & the greater the range to the detected object, the higher the electrical current, which drives the "dot" the further from the center of the CRT screen. Each instantaneous dot represents a small point on the ground. The small spot on the CRT screen traces a faint line on the scope; a line called a sweep. With no echo received, the sweep intensity is uniform throughout its entire length. When an echo is received, the spot intensifies on a corresponding portion of the sweep.

Concentric circles represent ranges. Each position of the target is indicated by a specific relative bearing & radius from the center of the CRT screen. One method of improving accuracy is the multiple point analysis.

Another accuracy problem is slant range. A plane flying at 10,000' & 1 mile from a target will be roughly a slant range of the hypotenuse of a 30-60 triangle. Thus a 1 mile horizontal distance will display as roughly 2 miles. As distance increases, accuracy improves, but slant range does result in an error. That error can be corrected by trigonometry, or more practically, a simple table. An example: a triangle with 10,000 vertical leg & 1 mile (5,280') base will have a slant range of:

$S^2 = V^2 + B^2$, so $S^2 = (10,000)^2 + (5,280)^2$; & S = 11,308' = 2.14 miles. Displayed range is 2.14 x actual range.

Make that 10,000' altitude & horizontal range for a 45° triangle. The slant range is:

$S^2 = (10,000)^2 + (10,000)^2$, so S = 1,414'; or 1.414 x actual range.

Reverse the first triangle for a 10,000' horizontal range & 5,280 altitude for a slant range of:

$S^2 = V^2 + B^2$, so $S^2 = (5,280)^2 + (10,000)^2$; & S = 11,308' = 2.14 miles. Displayed range is 1.13 x actual range; a 13% error.

A system that automatically converts distance vs. time into speed will read an erroneous GS; especially for short ranges. GS is based on change of distance from the transmitter, so is only valid if flying directly toward or away from the DME transmitter.

4.16.4.3 For the purpose of this discussion the most important function of airborne Radar is map reading, although it is very important for several other applications.

In some respects map reading by Radar is logical & simple, although interpretation is necessary. Understanding material reflectivity is critical, since Radar reflections indicate the shape & identify the object. This information simply alerts the Aero Navigator on how to interpret various images on the screen.

4.16.4.3.1 Theoretical Operational Range

Although it is possible to receive Radar returns from objects at great distances, the curvature of the earth & atmospheric attenuation do limit range. Particles of dust & other foreign matter deflects the beam. An equation that describes the theoretical line-of-sight limit is:

$D = [(2a)^{1/2}]$

Where "D" is Radar range in statute miles, and "a" is the altitude in feet. This assumes sufficient power.

A practical limit for unpressurized lightplanes carrying oxygen would generally be 18,000', & without oxygen it is 10,000'. For these altitudes: $D = (2 \times 18{,}000)^{1/2} = 190$ miles & $D = (2 \times 10{,}000)^{1/2} = 142$ miles.

Some aviation Radar sets have a selectable range as short as 3, & as long as 400 miles. A 400 mile range would require an altitude of: $a = D^2/2 = 80{,}000'$. That would exceed the 2003 record breaking flight by Bruce Bohannon for a small custom built plane powered by a 350 hp Lycoming engine, turning a prop; 46,919' over Angelton, TX, & Steve Fossett's 2006, 50,722' altitude record for a sailplane; Larry Edgar's record was not much less & stood for several decades; Larry taught both the author & his wife soaring. The 80,000' far exceeds the absolute ceiling of airliners.

4.16.4.3.2 Several factors determine whether enough of the transmitted energy will be reflected from a given object to provide usable information:

Material of the object
Dimensions
Surface roughness
Distance from aircraft
Angle of impingement

Details of the impact of these factors on Radar reflectivity include:
Pr = (PtGt)(RCS)Ae /(4π r2) 2

Where
P_r = Received (by Radar antenna) reflected power (Watts)
P_t = Transmitted (by Radar antenna) power (Watts)
G_t = Ratio of output power to input power of the antenna (dimensionless); gain
RCS = Radar Cross section of target. Determined by comparison with an ideal (100%) reflecting sphere. RCS is also a function of reflectivity angle as well as object orientation. It thus varies as the plane moves to cause a foreshortening of some projected dimensions & others to increase. A converse to this is the use of extremely low reflectivity paint (near 100% absorbtivity) that absorbs Radar energy by converting it to heat. Radar absorbent material (paint) is used along with special shapes to reduce the Radar reflectivity of the Stealth aircraft. The goal in such applications is to reduce the RCS to 10^{-4} of the natural value. (square meters)

A_e = Effective area of the Radar receiving antenna (square meters)
r = Radar range (meters)

4.16.4.3.3 Material:

All substances absorb some electromagnetic energy, & reflect the remainder, just as in the case of light.
Typical reported reflectivity of steel is 90%; so it absorbs 10%.
Other values are: steel reinforced concrete reflectivity is roughly 80%.
Stone reflectivity is roughly 50%.
Wood reflectivity is roughly 30%. Wood does not generally reflect enough energy to be detected by Radar.
Earth (dirt, crops, etc) reflectivity is very low; possibly 10%

Water has an excellent reflectivity, but not as it applies to Aero Radar Navigation. Radar energy reflects away from the plane except when directly over smooth water, & that information is of no value for Aero Navigation. This is similar to light reflected by a mirror. Angle of incidence is equal to angle of reflectivity. If a person looks at a mirror from a 45° angle, he will see an object that is 45° away on the opposite side of the perpendicular to the mirror.

The water return is thus nearly zero, so in Fig 66 the water appears to be black; no Radar return. Assorted materials & shapes of the terrain around the water have a variety of reflectivity values, & thus brightness.

4.16.4.3.4 Dimensions:

Reflected energy is directly proportional to the surface area of the surface impacted by the outgoing Radar beam.

4.16.4.3.5 Surface Roughness

A perfectly smooth surface will reflect little energy back toward the aircraft unless absolutely perpendicular to the beam.

A textured high reflectivity material surface will reflect Radar energy back toward the Radar antenna based on the portion that is perpendicular to the impinging Radar beam.

4.16.4.3.6 Distance or Range

All forms of radiant energy, except for lasers, lose power in terms of unit density; watts per square foot at point measured. In the case of a spherical radiated area, πd^2. Thus doubling Radar range decreases power returned by a factor of 4. The return energy is also impacted by the same factor, so the overall loss is by a factor of 1/16. Both outgoing & return also decrease energy because of atmospheric attenuation.

4.16.4.3.7 Angle of Impingement

Although smooth water reflects virtually no Radar energy unless precisely normal to the Radar beam, rough water does reflect Radar energy from surfaces that are instantaneously normal to the beam. Thus, as is illustrated in Fig 65, rivers & lakes appear dark since nearly all energy is reflected away from the plane. Most land masses are not excessively bright since they have low reflectivity. Fig 66 indicates sporadic reflection directions since most targets have irregular surfaces, so a minute portion of the energy returns to the antenna.

Rough high reflectivity surfaces such as metal reflect only from the many small portions that are normal to the beam. Even smooth surfaces are, in terms of microscopic values, actually quite rough. Even the surface roughness of highly polished surfaces (see Note 1) are well above zero microinch rms.

Note 1: The standard unit of measure of surface roughness is rms (root-mean-square). A mathematical averaging technique based on the square root of the average value squared, of a series of measurements of deviations from the roughness centerline expressed in microinches. Even optically flat mirrors & diamond lapped tungsten carbide metal seated ball valve balls & seats are typically well over 1 microinch RMS.

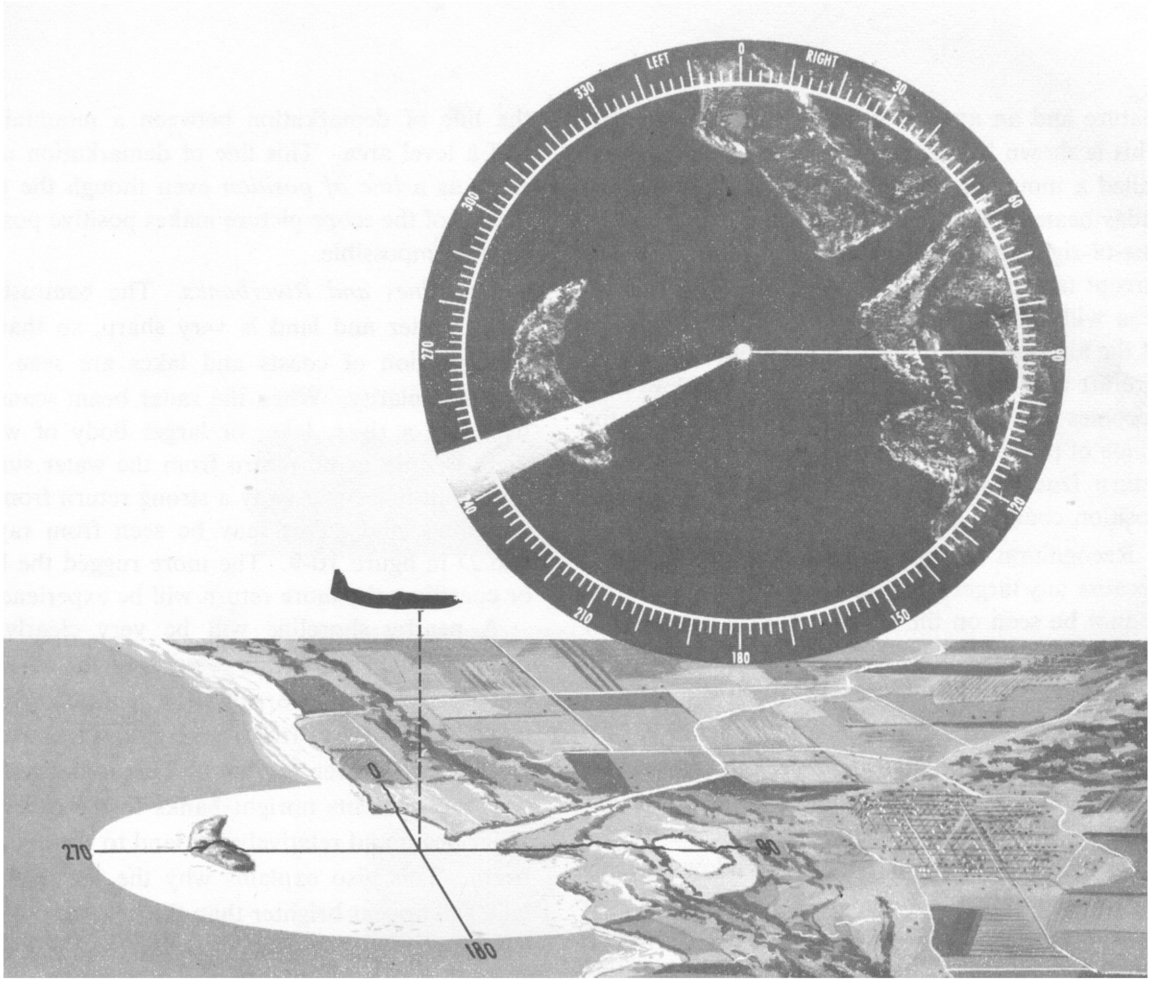


Fig 66: Radar Image vs. Terrain

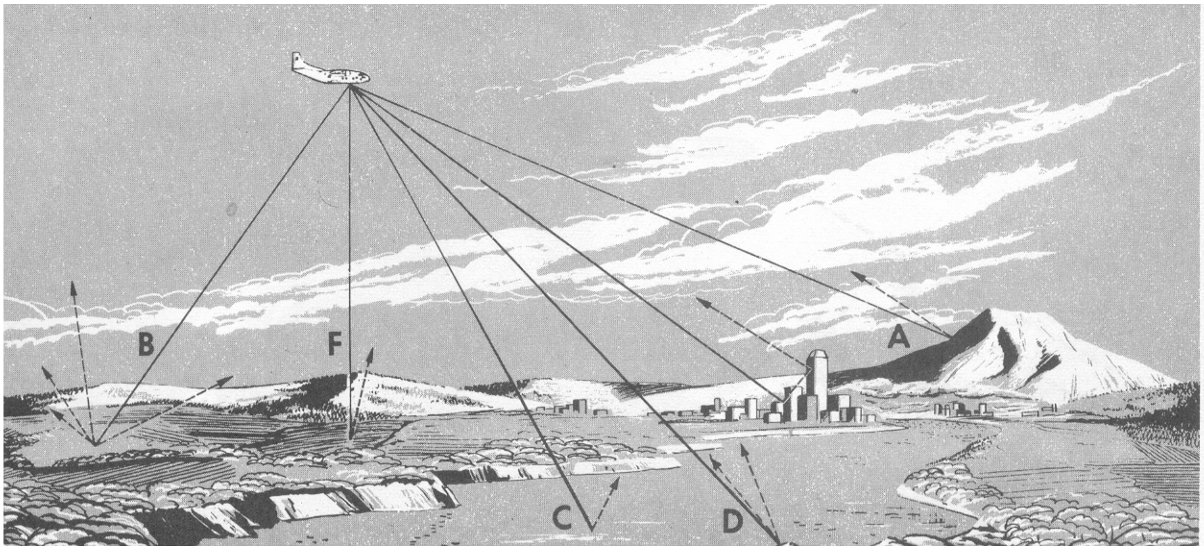


Fig 67: Radar Target Reflectivity

4.16.4.4 Map Reading by Radar

Only the portions of the surface that are normal to the Radar beam will contribute to the return signal. Portions of most materials do deviate significantly from the basic plane of the object, so most materials do reflect some Radar energy. Fig 67 illustrates typical directions of reflection of Radar energy.

Buildings seldom have any major surfaces that are normal to the Radar beam, but most do have irregular portions that will weakly reflect Radar.

Like thermal & electrical conductivity, the reflectivity of highly conductive materials tend to also have a high reflectivity. Most metals exhibit a high electrical conductivity, high thermal conductivity, & a high reflectivity.

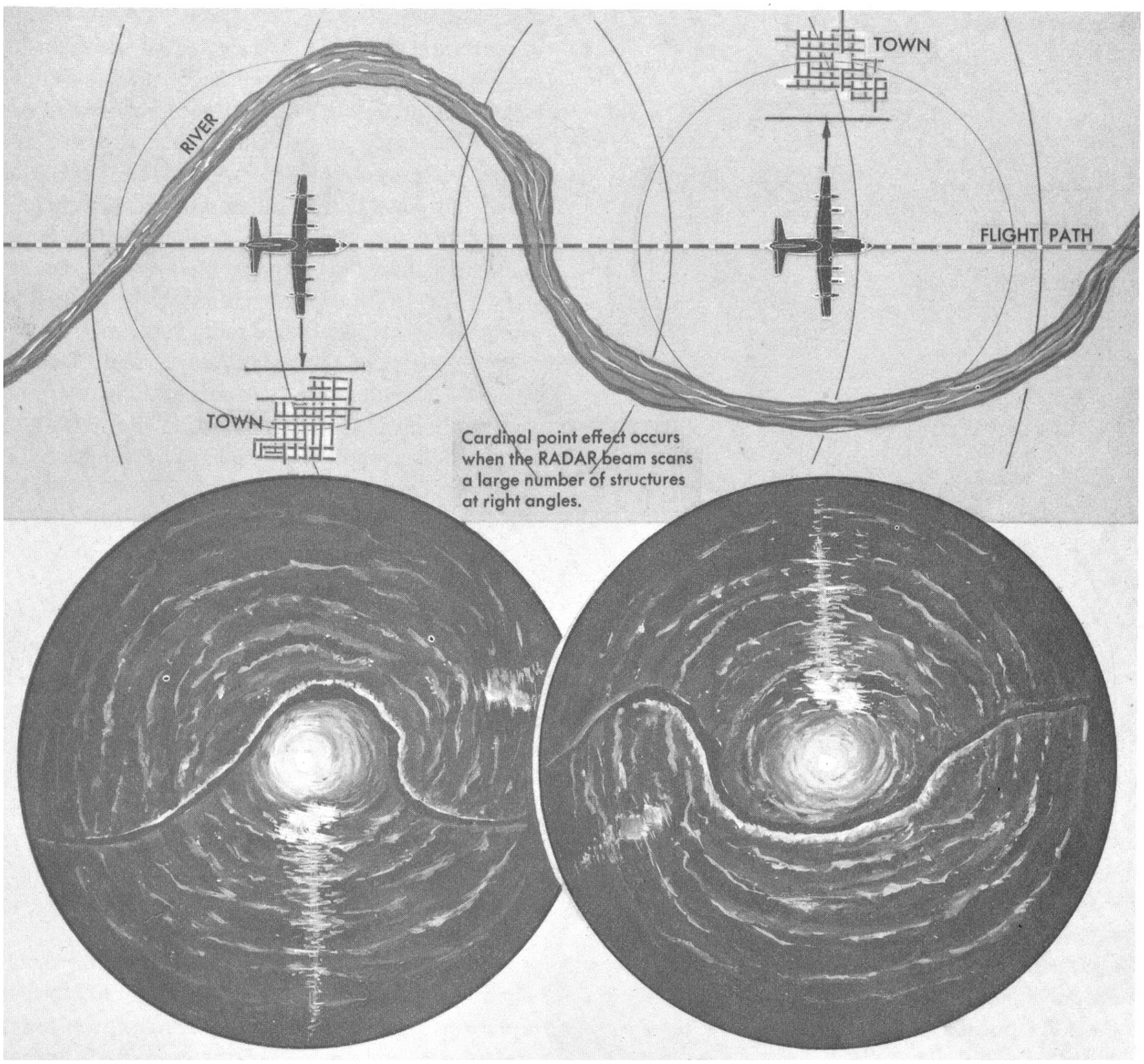


Fig 68: Radar Display of River & Town

The first impression in looking at the image on a Radar scope may be that it was shot at night; dark background & some lighting. Radar, of course, looks the same in the daytime, or through clouds. Sufficient rain, in or out of clouds, can sometimes actually give false imagery. There are techniques for eliminating the ambiguity in such a case.

Fig 66 illustrates a few characteristics peculiar to returns from specific ground features such as rivers & towns. Even though water is rarely shown on a Radar scope, the lack of a return does indicate the probability of a river in this case. A Radar scan of a river or lake often shows the shoreline very brightly. This is because the water reflects toward the shoreline & back to the Radar antenna to amplify the direct return from embankments. If those shores consist of rock cliffs they will be especially distinctive.

Fig 68 illustrates the relationship of a Radar screen to a map. Note that there is little to indicate a town on the Radar scope, but rather a long narrow random shape that seems much longer than the map indicates. This results from what are known as "glitter" and "cardinal point" effects. They cause much of the fluctuating returns that appear on the scope. The cardinal point effect occurs when the radar beam scans several relatively small reflectors that briefly present large reflections when aligned perpendicular to a series of buildings that are oriented with the cardinal points. A plane flying past such a city will experience very little illumination on the scope until the Radar beam is perpendicular to one side of the buildings; potentially quite a large number of large skyscrapers. The screen might burst into bright glowing. Towns & cities in much of the U.S. have most streets, & thus buildings

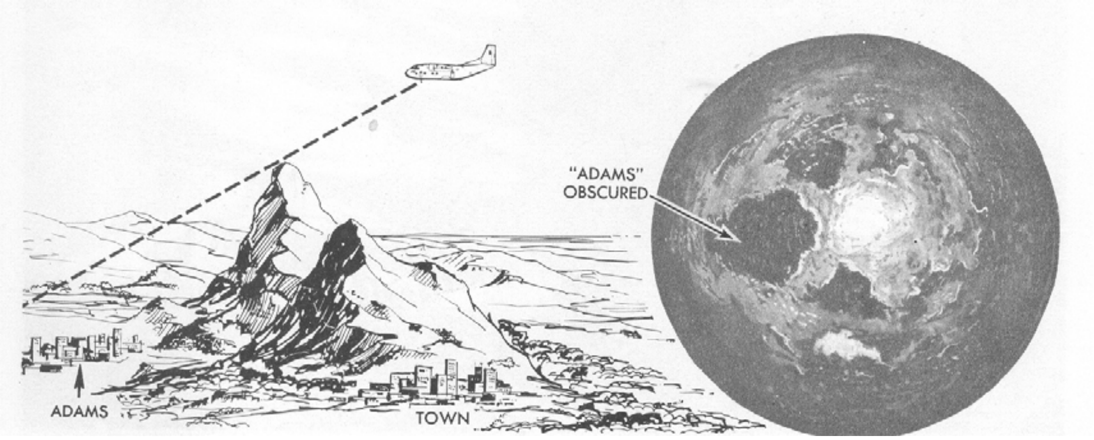


Fig 69: Radar Display of Mountains & a Town

oriented N-S & E-W. Thus the term "cardinal points". The N & S bursts are obvious in Fig 68. A view of the oscilloscope taken 60° before & after those points show very minor returns, as indicated by the same two cities in the opposite view. The flashing on & off of returns gives the impression of glitter.

Just as a Sectional is not informative if the Aero Navigator is lost, & looking in the wrong place, so is Radar map reading confusing until he associates an area on the chart with the Radar images of the terrain. Looking at the illustrations of Figures 66 & 68 may be confusing if only looking at the Radar scope, but with the associated illustration of terrain features they becomes clear. Some Radar images could be mistaken for entirely different terrain features without the map to aid in the interpretation process. Radar reflections of large stone cliff are not necessarily identifiable as such unless collaborated by a chart.

One characteristic of many objects is the variation in shape a the plane passes nearer or past them. Flying or driving past a beautiful rugged mountain in New Mexico illustrates the changes that take place. A few minutes in a lightplane often gives the appearance of a totally different mountain.

Fig 69 shows several things about Radar imagery. The images result from high signal strength from the two mountains, & a totally black screen where the town of Adams should be; & is actually located. It is dark because the Radar beam is blocked by the mountain. The dark spot between the two brightest areas represents the town of Adam that is obscured taller mountain.

The shadow area will vary in size, depending upon the altitude of the aircraft, elevations of the mountain & even the town of Adams. As the plane approaches & passes the mountain, the shadow area changes in brightness, shape, & size.

Without the chart, the mountain might be mistaken for a lake, because they are both associated with a dark area. The best way to discriminate in that case is the fact that the dark area in the shadow of a mountain will change greatly & rapidly. The lake will do so only if major obstructions obscure a portion of it, based on relative location. The error may be as great as the width of the radar beam.

4.16.4.5 Establishing a Fix by use of Radar; Other Than Map Reading

There are 3 basic ways to obtain a Radar fix: Azimuth & range, multiple target bearing, & multiple range.

4.16.4.5.1 The "azimuth-range" is fastest & easiest, although accuracy may be somewhat limited. All of the above radar scope illustrations have the potential for good fixes. The Aero Navigator must find an object that can be positively identifiable on the chart & the Radar scope. It could be nearby, or many miles away. If his Radar has digital range capability he can read range to with less than one mile error. If not, he must read from the concentric range rings. He can use the shortest appropriate range setting to improve accuracy. If his range control has infinite adjustment he can reduce the range error even further by placing the target on a ring. That chart could be a Sectional. Fig 70 is an excellent example, with an identifiable Radar target, & in this case a vague aircraft position identified by the range arc - LOP intersection marking the fix.

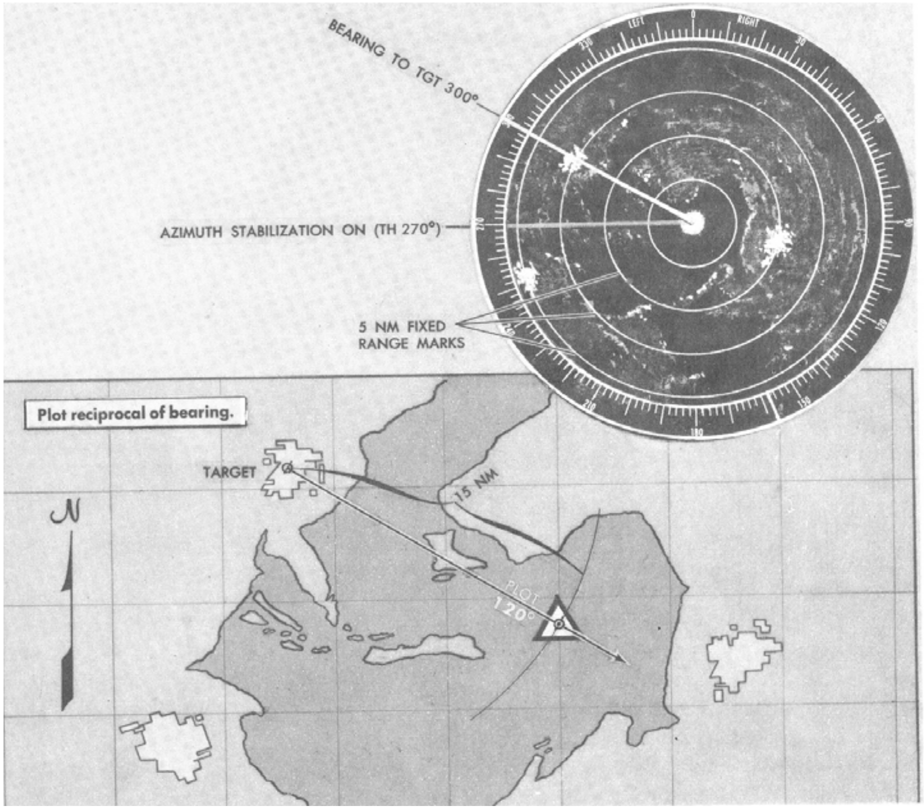


Fig 70: Single Azimuth-Range Radar Fix

4.16.4.5.2 A "multiple range" fix is illustrated in Fig 71. The Aero Navigator must find three objects that can be positively identifiable on the chart & the Radar scope. They could be nearby, or many miles away. Each range value must be swung with an arc that represents the range from a specific target; with the range as the center of its arc. Plotting must be on a chart; not the Radar scope. He must document the time of the range values, plot on his chart, & advance earlier range arcs to the time of the last arc. Crossing points are at the plane, & thus the location of the fix.

4.16.4.5.3 A "multiple bearing" fix is illustrated in Fig 72. The Aero Navigator must find three objects that can be positively identifiable on the chart & the Radar scope. They could be nearby or many miles away. He must document the time of the azimuth values, plot on his chart, & advance earlier LOPs to the time of the last LOP. The positive identification is not obvious in the illustration, but presumably those points are unique, such as an

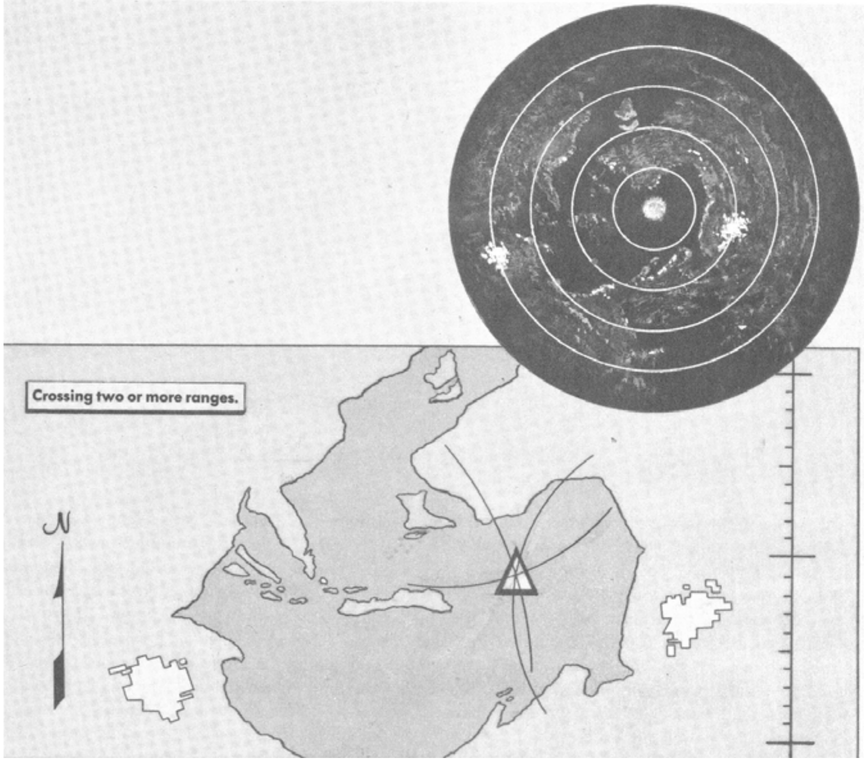


Fig 71: Three Range Radar Fix

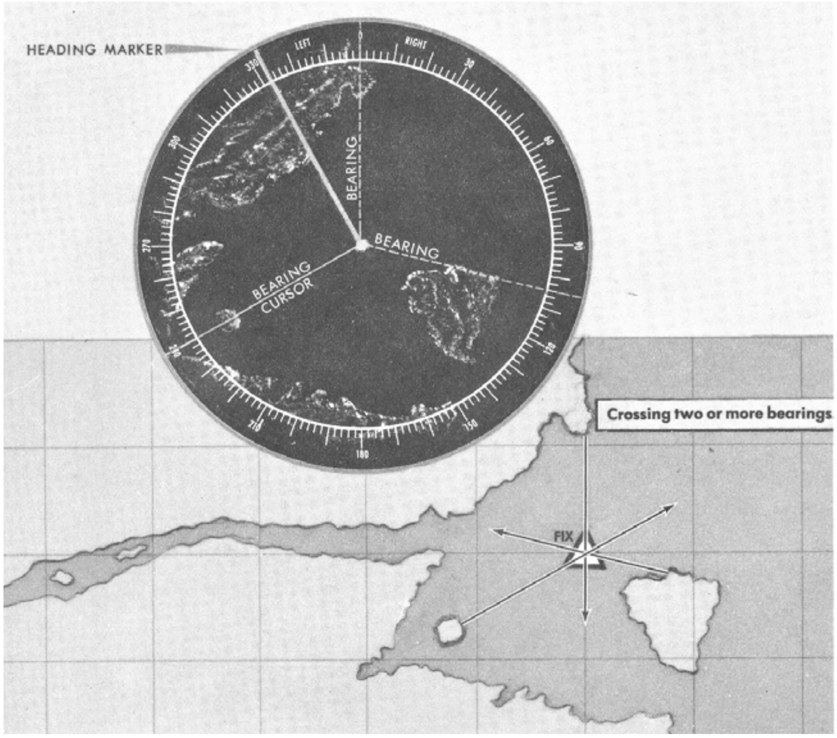


Fig 72: Three Bearing Radar Fix

outcropping of rock or a distinct feature of the shoreline. Each bearing value must be plotted as a straight line from the corresponding target.

4.17 Aero Navigation System No.17: Pressure Pattern

4.17.1 Background

Pressure pattern flying utilizes a combination of several activities which have one thing in common; all make maximum use of the pressure field at the cruising level of the aircraft. Forecast and inflight pressure data are more accurately forecast than W/V. As such, pressure differential techniques, where applicable, provide the navigator with a simple and accurate aid to navigation. Two essential components of Pressure Pattern are "Bellamy drift" and the PLOP (pressure line of position).

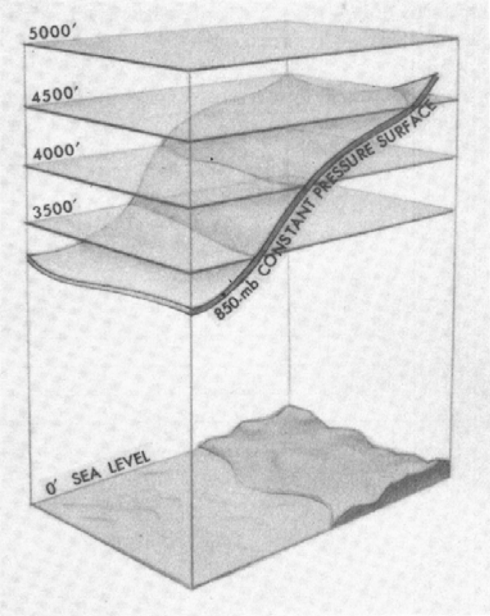
Pressure pattern is also called Pressure Differential Techniques.
Pressure pattern techniques require both "Bellamy drift" and the PLOP. Both are considered to be aids to navigation. Both are obtained by substituting inflight information into a simple equation. Both are independent of external equipment. None require any visual reference, special equipment, or ground equipment.

Bellamy drift provides recent historical drift data, from which aircraft track can be determined. Specifically, Bellamy drift is a mean drift angle, calculated for a past period of time. Thus the LOP is the track. It is most valuable when other Aero Nav systems are unavailable; particularly overwater.

PLOP, as the name infers, is a line of position; not a fix. PLOP is easy to obtain under poor flight conditions. A PLOP is as accurate & reliable as most other LOPs. It can be used with any other LOP to provide a fix. Like any LOP set, it is preferable that they intersect near either 90° to 120°, depending on number of LOPs; never approaching an acute angle. Like any LOP set, they can, & must, be advanced and retarded in the normal manner.

4.17.2 Theory

Pressure pattern techniques require both "Bellamy drift" and a PLOP



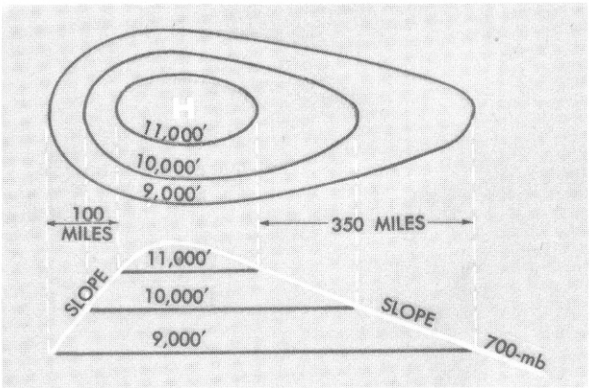


Fig. 73: Isobaric (Constant Pressure) Surface

Fig 74: Pressure Gradient

Pressure pattern navigation relies on a variant (which accounts for an Isobaric surface, & aviation use) of the meteorological equation for the geostrophic wind, modified for flying an isobaric (constant pressure) surface. The constant pressure surface is one on which the pressure is the same at all points, although its height above MSL may vary from point to point as shown in Fig 73. An altimeter will read the same at all points as it moves along an isobaric surface, even though it changes true MSL. A plane flying "up-hill" on the isobaric surface would actually be climbing in terms of absolute altitude, even though the altimeter will remain fixed at a single altitude.

4.17.3 Accuracy & Efficiency

Bellamy Drift may be determined more accurately than several other methods of obtaining drift. Accuracy of a fix does depend on specific conditions, including angle of intercept with the mating LOP. Although altitude varies, the TC may be direct & thus more efficient than Aero Nav systems that require deviations.

4.17.4 Application

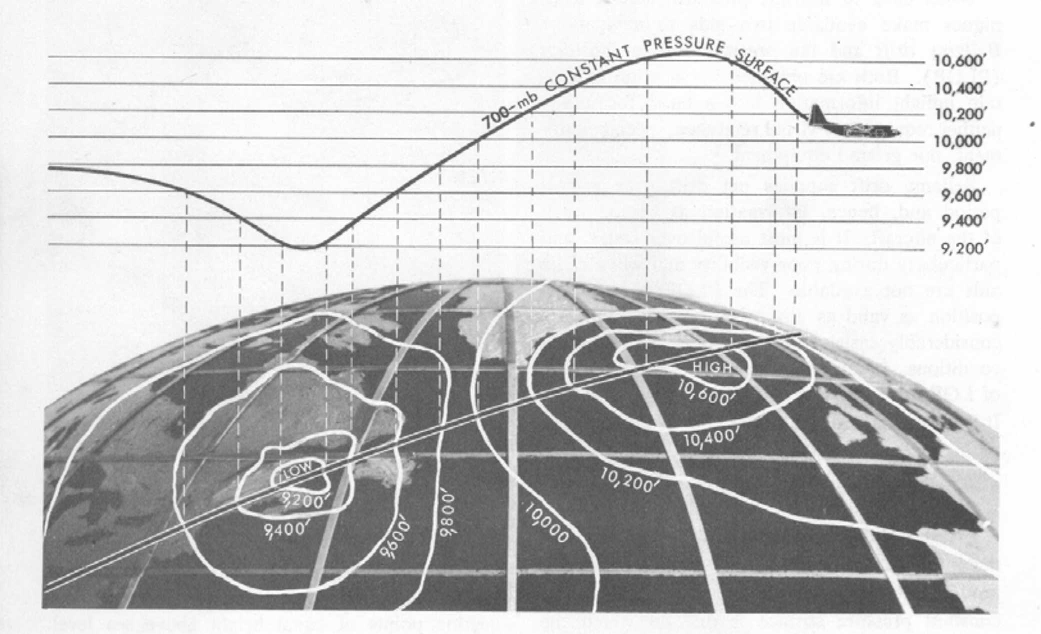


Fig. 75: Isobaric Lines & Surface

4.17.4.1 An aircraft could fly by reference to both the pressure altimeter & a Radar altimeter, while holding a constant absolute altitude. To do so, it would be forced to turn left or right when the pressure altimeter changed, & by trial & error, could trace out an isobaric line; called a contour line. A series of isobaric lines could generate a contour chart, for pressure gradients, as shown in Fig. 74.

4.17.4.2 A geostrophic wind describes the fact that the total atmosphere, like components of same (see note 1 below), & like water, tends to seek its own pressure. It tends to maintain uniform pressure, so air will move from high pressure areas to low pressure areas.

Note 1. Atmospheric components also seek their own partial pressure. Water vapor in a freezer condenses & creates a low water vapor "partial pressure". Thus additional water vapor outside tends to leak past the seals to equalize the "partial pressure" inside vs. outside of the freezer. If partial pressure outside is 0.1 psi, & 0.001 in the freezer, the freezer experiences a partial vacuum. The water vapor in the room then tends to force past the seals to seek a constant water vapor partial pressure.

In the atmosphere, Coriolis force combines with the force caused by the natural tendency of the air to equalize the difference in pressure, & causes movement. The resulting air flow is called Geostrophic Wind.

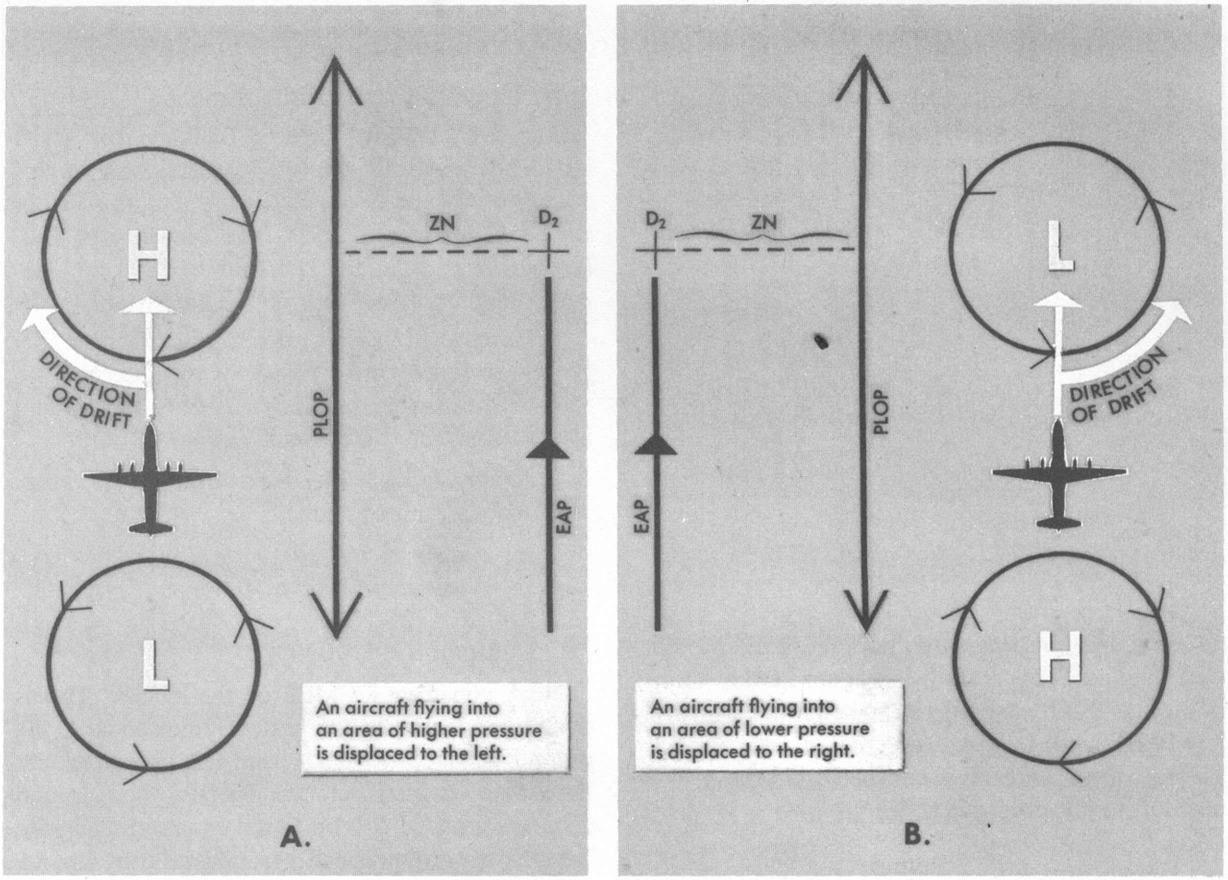


Fig 76: ZN; Bellamy Drift (in Northern Hemisphere)

Radially moving air, like water in a drain, rotates, as explained in the Introductory course. Any unbalanced condition thus causes Geostrophic Wind. As the sun's energy warms air in one area, while elsewhere the air is cooled, it causes an unequal distribution of air mass over the earth's surface. The atmosphere reacts in an attempt to restore an equal distribution of that air mass. The sun's rays continuously change, so equilibrium is never reached and atmospheric mass is always unequally distributed over the earth; always moving in an attempt to equalize the pressure over the entire earth. Thus atmospheric pressure continuously varies over the surface of the earth. The difference is sometimes large, & at other times or locations it is small. Variation in pressure per unit distance is called the pressure gradient, or slope of the pressure field, as indicated in Fig 75.

Geostrophic wind results from straight, parallel contours above the level of influence by surface friction of the earth; usually over 3,000'. If contours are instead curved, centrifugal force becomes a factor, & the resultant wind is called the "gradient wind".

Closely spaced contours indicate a higher gradient (steep slope), so result in a higher velocity geostrophic wind. Conversely, contours that are spaced further apart indicate relatively weak winds.

Geostrophic wind accurately approximates of the actual wind if contours are straight and parallel to prevent surface friction induced distortion. At less than 20° latitude Coriolis force is negligible, so the geostrophic wind is not useful, so pressure pattern navigation is not practical.

4.17.4.3 Pressure Computations and Plotting

Airspeed & heading must remain constant for the entire period of pressure pattern flight. If a change of either must occur, a new flight record logging should begin after stabilization.

Above 20° latitude, to determine position, the crosswind component of the geostrophic wind over a given period of time must be determined.

To determine the crosswind component of the geostrophic wind the Aero Navigator must enter data into an equation to solve for the effect that the atmosphere has had on the aircraft.

This resultant is called "ZN." To solve the ZN equation, the navigator must obtain and apply factors such as "D" soundings, effective TAS, effective air path, effective air distance, and "K" values.

ZN is a displacement in nautical miles perpendicular to the EAP (effective air path).
PLOP (Pressure Line Of Position) or Bellamy drift by pressure differential techniques is illustrated in Fig 76. This figure also indicates the relationships of high & low pressure areas; weather systems. EAP is air plot, where the plane should be. PLOP is from a Bellamy drift computation.
Barring inaccuracies in the Bellamy drift computation, the PLOP would represent the actual line which the plane would be following. Note the illustrations, however.

In Fig 76-A the initial portion of the illustrated track would have more of a tailwind than a left drift component. That would gradually change to a left drift, & then ease into a headwind. Bellamy drift is a mean of a varying effect. In this example, if the low pressure area is appreciably stronger than the high pressure area the result would also be different. That difference would be accounted for in the different gradient. Nominally the Bellamy drift would still be correct. In fact, in either case, the PLOP would actually be curved back & forth, with a final correct location.

Applicable equations are:

ZN = Displacement value derived from "soundings" at two air positions. It is the displacement perpendicular to the effective air path from the straight line air path between the soundings. Therefore a PLOP (pressure LOP) must be drawn parallel to the effective air path.

$ZN = K(D_2-D_1)/ S_a$

Where S_a = effective TAS
K = 21.49 / sin (latitude); use mid latitude for the flight or leg.
S = TAS

If the heading remained steady effective TAS = TAS, so S_a may be neglected.

$D = A_a - A_p$
Where A_a = Absolute altitude, A_p = Pressure altitude.

The first sounding, D1, is taken at the fix at the start of the pressure pattern measurement period. Sounding from marine terminology; the measurements taken are called "soundings".

The second sounding, D2, is taken at the time of the desired pressure pattern LOP.
difference between the true altitude of the aircraft and the pressure altitude.
D_2-D_1 indicates slope. A large value indicates a steep slope, but they must be related to time & distance between D_1 & D_2. Successive soundings continue the numbering sequence; the more soundings the better; D_1, D_2, D_3, D_4, D_5, - - D_x. If one differs significantly from the others it should be disregarded. Skipping a sounding simply extends the flight distance between the two adjacent soundings that are used.

Multiple readings for each D number assures more reliable data. Assuming that all are acceptable, they should be averaged & the mid time should be used.

Bellamy drift must be crossed with another type of LOP to provide a fix.

4.18 OMNI; VOR-OMNI Range.

4.18.1 Background

The VOR OMNI Range was introduced to Gen Av in the early 1950s, revolutionizing Aero Nav, but with a vacuum tube, crystal controlled transmitter in the same case as a tunable VHF OMNI signal receiver, it was primitive by modern standards. The nav portion of the navcom was tunable, with infinitely adjustable frequency, & covering the entire com & nav band. They predated simplex & digital tuning. It received either OMNI or the transmitter frequency, & contained an integral OMNI signal interpreter-indicator; the CDI (course deviation indicator). This prevented simultaneous receiving of com with nav signals. The transmitter had a very limited number of crystals, which often precluded landing at many otherwise suitable tower operated airports since many required unique transmitter frequencies. The lack of a receiver that served two specific frequencies simultaneously was inconvenient when approaching a control tower since it was necessary to interrupt OMNI homing during com. This was especially inconvenient for IFR. The pilot had to use "whistle stop tuning" to tune the receiver to the transmitter frequency before he could communicate. After com it was necessary to return to the OMNI frequency, audibly identify the station by Morse code, & finally adjust the integral CDI; then read the direction of the radial. Add to this the low reliability of vacuum tube transceivers, partially because of the heat they generated, & the early OMNIs left much to be desired. Nonetheless, it "led the way", & was state-of-the-art then, & represented a major advance in "nav" especially, but also in com. It was several times as tall as more modern Navcoms because of the large complement of vacuum tubes. It was the first Navcom & a great system until outdated by advances. The author once flew 75 miles to have his 5 year old (with 4 channel transmitter) Narco Superhomer repaired, & by the time he reached home, it had failed again. A few years later his Narco Mk 12 solid state, digitally tuned navcom with simplex & 360 channels rarely failed.

By 1960 OMNI based navcoms had made major advances. Both transmitter & receiver were digitally tuned with a communication transceiver that operated in the simplex mode (transmit & receive on the same frequency; simultaneously tuned). The OMNI receiver continued to share a case, but was tuned separately, & a mix of solid state & vacuum tubes provided improved performance, was lighter in weight, & produced much less heat. Vacuum tubes were soon phased out, further reducing heat, which further increased reliability. Morse code ID (identification) was essential with manually tuned navcoms because an error was too likely to occur. With modern digital tuning the greatest risk of tuning error is simply entering a number incorrectly, which would nearly always result in a lack of response, & a search for the reason. With the modern VOR transmitter stations there is another very good reason for listening to the audio identifier. The audio encoder is omitted when a transmitter malfunctions, or signal error exceeds specified limits, as an indication that the signal is not reliable. Some navcoms do present a red flag to indicate an unreliable signal. An erratic needle also indicates an unreliable signal.

The typical navcom by then consisted of a VHF com integral with an OMNI & separate panel mounted CDI such as in Fig 78. The power switch is also the com volume control. The nav volume control has no other function. Frequency control on each is a coaxial pair. The smaller near knob tunes only the tenth-hundredths frequency. The large knob selects the basic frequency number; left of the decimal point.

The GPS-com was introduced soon after the year 2000 to in effect upgrade both com & nav, although the OMNI is certainly still very important to Aero Nav.

Most panel mounted navcoms are legal for IFR, but some also include ILS capability. That would mean replacing the CDI of Fig 78 with the two needle version shown in Fig 98 (ILS CDI) in Aero Nav system No. 30; on the Instrument Approach. The vertical needle provides vertical position information for the precision ILS.

4.18.2 Theory

The OMNI is based on a phase shift principle. Though it nominally has 360 radials, in fact it has an infinite number, The VOR transmits two different signals. One signal serves as a reference. The second signal varies from "in-synch" to very far out of phase as it moves around the antenna. Much like a vernier caliper, which has 1 more line per full linear scale; or a pair of out of phase sine waves which may be shifted slightly. The OMNI receiver measures the lag of the AM signal phase relative to the FM sub carrier phase to establish the difference in angular position of the OMNI receiver from the station. Thus the MH is indicated at any radial line throughout the 360°. VORs are referenced to magnetic rather than true North. OMNI radials are given in magnetic values to eliminate the need to apply variation correction, to simplify flight on the Victor airway system.

See Fig 77 for a pair of sine waves covering from zero to 90° rather than the full 360°. One of the 360° sine waves has 1 cycle more than the other.

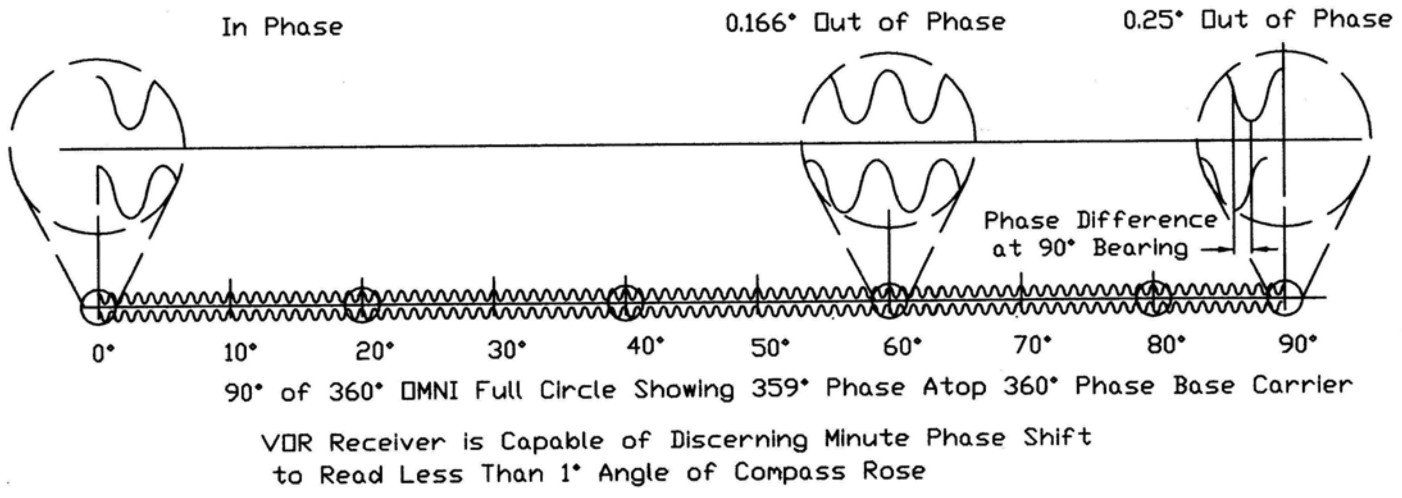


Fig 77: OMNI Phase Relationship

4.18.3 Accuracy & Efficiency

The VOR is exceptionally accurate at short ranges & better than most Aero Nav systems at longer distances. It provides radial error of less than 1°; often 0.4°. At 60 miles that results in an error of 0.4 to 1 mile. At 1/4 mile from the VOR that becomes 9 to 22 ft. error.

The VOR system is very efficient in terms of versatility. It is useful for cross country flight, instrument approaches, & travel to isolated areas, as long as at least one VOR is within range. A single VOR does provide only one LOP, so requires either another source for a LOP, or a technique described earlier to advance one LOP so it will cross a current LOP. The "Running Fix" illustrated in Fig 59.

Its only minor inefficiency is the fact that Victor airways do not lie in a straight line for long straight on-airway flights. It is much less efficient in cases where a large angle alter is required to follow a crossing airway, or reach an off-airway airport.

4.18.4 Application

4.18.4.1 Low frequency radio transmitters initially broadcast weather periodically, & upon request by pilots, specific weather information. Early VORs also provided this. Currently most VORs have voice com to respond to pilots who call on standard frequencies. Turning audio volume up on both com & nav is a safe way to initiate any enroute call to FSS. The one of interest should be set to a higher volume than the other; & the lower one high enough to be heard. When receiving on the nav frequency over the VOR, simultaneous com transmissions may interfere with understanding the nav audio, but turning volume down fully is very likely to result in interfering with another plane calling on the standard com frequency.

Most VOR transmitters have voice capability for com between pilot & FSS; usually by remote capability since few VORs are manned.

The VOR-OMNI Range radio transmitting facility is much more complex & expensive than NDBs. Both VOR transmitters & OMNI receivers are more sophisticated & expensive than the ADF - NDB system. In fact, as stated in Aero Nav system No. 7, any standard broadcast transmitter may be used as an NDB. OMNI is limited to line-of-sight, so requires more transmitter stations than the NDB. The higher frequency, & change to FM (frequency modulation) nearly eliminated electrical interference, including those generated by thunderstorms. The lower cost of the low frequency AM (amplitude modulated) NDB allowed many more ADF approaches than VOR. Even remote areas transmitters often have LF Transmitters that provide another priceless nav aid. In many cases smaller airports installed their own NDB transmitters. LF signals are subject to diffraction, or bending of the radio beam around mountains & coast lines, which accounts for some of the greater accuracy & reliability of the OMNI. Earlier VORs used mechanical systems to rotate the antenna, while advances to electronic rotation reduced maintenance costs, & improved reliability.

Victor airways (surface to 18,000'; called Jet Airways above 18,000') blanket the US, with VORs generally located between 50 & 100 miles apart, along the airways. Range is occasionally limited to prevent coverage overlap of VORs operating on the same frequency. It is rare in the US. to be beyond the range of a VOR. In third world countries like Mexico radio nav is very limited; especially OMNI.

Many VORs are located at airports to facilitate their use for instrument approaches & landings.

4.18.4.2 One advantage of the ADF vs. the VOR is the simplicity. Less knob twisting for routine homing. The pointer always points directly to the station, so whether equipped with a fixed or rotating dial, the ADF requires little knob twisting. The only OMNI that does not suffer from this problem is the Collins Microline, which has both digital & analog CDI. Most OMNIs have an analog CDI such as that in Fig 78. A few have only digital CDI display, which is much less practical for many operations. The dual display is ideal from an ergonomically, as opposed to the digital-only display. The ability of the Microline to provide analog & digital displays simultaneously saves time, & again reduces cockpit workload when appropriate; again less knob twisting. All digital display is quite poor for an ILS under IFR conditions; it handicaps operational interpretation.

Unlike the GPS (which requires advance calculations), VOR response on approaches are user friendly & direct. In a lightplane the VOR range is typically 30 to 125 miles, limited by line-of-sight. The author initially had a Narco Mk 12 & a Cessna ARC 300 in the radio stack of his new Cessna. He found that the ARC consistently communicated & navigated (VOR) at twice the range of the Mk 12; over a 4 year period. The ARC routinely navigated & communicated at ranges beyond 125 miles in mountainous country. After he installed a complete Collins package, including dual Collins Microline navcoms, glide slope receiver, & transponder, he found they had lightly shorter ranges than the ARC, but even better reliability.

Fig 78: OMNI CDI Indicator

The OMNI Head instrument includes a CDI (course deviation indicator needle) & OBI (OMNI bearing indicator), as is illustrated in Fig 78. It includes a dial that can be rotated throughout its 360° scale called an OBS (OMNI Bearing Selector, or course selector). The compass rose is rotated by the knob at the lower left, to select either

the "desired course" (MC) or the "actual OMNI bearing", "Desired course" is set manually, & then the plane is flown to center the CDI pointer. "Actual OMNI bearing" is indicated by turning the knob to center the pointer. It indicates the VOR radial that the plane is aligned with at a given instant in time.
The CDI pointer pivots at the top, so the bottom deflects to either side, if the plane is not precisely on the selected course. If to either side, the pilot must adjust his MH slightly in the direction of the pointer deflection to return to the selected course; "fly to the needle". If the plane is flying "to" the VOR, the small diamond shaped window should have flipped from the orange & white striped slash marks to a "TO".

If the pointer remains centered, it shows that the plane is tracking either inbound or outbound on that radial.
If the pointer suddenly moves across the CDI face, it indicates that the plane is crossing that radial; possibly the ideal of 90°.

If operating with two OMNIs, & tracking one VOR while crossing a second VOR, it provides a positive fix.

The "TO - From" indicates direction of the OBS reading vs. the location of the aircraft relative to the VOR. In Fig 78 the OBS reads 285° with the CDI centered, regardless of the plane heading, although it may remain stable only for an instant.

Since the pointer is vertical (centered) the plane is precisely on the 105° radial (reciprocal of 285°) while flying a MC of 285° "TO" the VOR. As it passes over the VOR, the flag will flip to "FROM", & the needle will remain centered. In fact, the pointer would normally move to the side; or possibly back & forth briefly, since it is unlikely that the plane would pass precisely over the VOR.

What if there is a crosswind component? If the plane is "heading" directly to the West (MH = 270°), but steady on the 105° radial, with the OBS (MC) steady on 285°, he must have a 15° right drift.

The OMNI is entirely different from the ADF, which points directly to the transmitter regardless on the heading or location. In making a 360° turn the ADF pointer will follow with a 360° rotation.

The OMNI CDI pointer is centered only when the OBS is set to the value of the VOR radial (or its reciprocal) that it is on the moment. In the case of Fig 78 the needle would be centered only at OBS readings of 285° or 105°. Heading has nothing to do with the CDI orientation. Flying a 360° turn the CDI pointer will remain stable unless close enough to cause minor change each way.

If the plane is heading North, the OBS is set as in Fig 78, & the flag reads "TO", the needle will point ahead of the off-course VOR; to the right of center, until crossing the radial. To the left, or behind after radial passage.

The only time the needle routinely responds in reverse is on the "Back Course" to the ILS approach, as will be discussed under instrument approaches; Aero Nav system No. 30. When tuned to the ILS frequency the "TO-FROM" indicator & the OBS are irrelevant; neither responds to rotation, or can be changed except by turning the plane off of the heading specified on the approach plate.

4.18.4.3 To use the OMNI, the procedure is lengthy, but logical:

Determine from the Sectional determine which VOR is the next one along the track.
Read the frequency, TH, Identifier,
Tune in the frequency.
Verify identification of the station by briefly listening to the Morse code identifier.
Set the OBS value by rotating the compass rose to the TH; 285° per value shown in Fig 78.
Turn plane to the TH that was set into OMNI.
Fly TH until CDI moves off-course.
Turn toward needle; small angle preferred (such as 5°) for gradual intercept to find whether needle increases or decreases deflection. Not over 45°, at most.
After needle is centered note difference between TH & OBS setting. This angle represents wind induced drift in the time flown.

Later on in the flight, if the Aero Navigator desires a fix, it is easy to locate a second VOR that is near 90° off his heading. The closer it is to 90°, the greater the accuracy of the fix, but even with the VOR 30° off the nose or tail

it will still provide a fix; just with a greater possibility of a larger error. If equipped with a second OMNI he can tune it
in to avoid losing his track information to have exact fix without requiring LOP shift similar to several previously discussed cases. A simple rule reduces confusion in flying to a cross bearing. Set the OBS to the desired radial. While approaching the radial, the CDI will point to the VOR. After passing the VOR, the needle will point away from the VOR. The radial number is the radial "from" the VOR. If flying North, & the VOR is to the West (to the left), set the "cross-track" OMNI to 090°. The CDI will point to the left; toward the VOR, until on the 090° radial, when it is centered. The needle will immediately begin swinging toward the right, away from the "cross-track" VOR.

If the VOR OBS directly indicates the MH being flown, the needle is centered, & the "TO" flag is shown, all will remain stable unless a crosswind component causes drift. The same is true after station passage except the "FROM" flag will appear.

As discussed previously, Fig 12 shows a dashed magenta line angling slightly to the right from the 108° 29' longitude at the bottom of the Sectional. It indicates near the bottom that variation is 11° E. It passes near the Silver City VOR, where the zero-360 on the compass rose is 11° right of the vertical (Tue North) to verify the 11°E variation. The plane magnetic compass, barring drift & deviation, will then read precisely what the VOR radial reads. Having VOR radials & airways based on magnetic vs. true North reduces cockpit work load, & the risk of adding instead of subtracting (or vice versa) the variation correction. Note that the direction across the terrain of the variation line is irrelevant. It is merely a line of equal variation. Some variation lines curve severely.

4.18.4.4 VOR Tracking

4.18.4.4.1 VOR tracking is illustrated in Fig 79 by position number:

1. OBS = 350° desired MH to BRAVO VOR, CDI centered, flag on "TO", aircraft MH = 350°. Exactly the way things should be.

1. 5 Left drift is obvious on illustration, but not yet to Aero Navigator.

2. OBS = 350°, CDI to the right, "TO", At this point, plane turned to = 020° in response to CDI ("turn TO the needle") to estimated)preferably computed) correction for drift.

3. OBS = 350°, CDI centered, "TO", Back on course, plane turned to = 360° for estimated drift correction at this point.

4. OBS = 350°, CDI to left, indicated overcorrection for drift, "TO", starting turn to approximately 358°.

5. OBS = 350°, CDI centered, indicated final minor correction for drift, "TO", turning to approximately 355°. Back on course, plane turned to 355° for estimated drift correction at.

5.5 OBS = 350°, CDI centered, crossing VOR, flag switched to "FROM", maintaining 355°.

6. OBS = 350°, CDI centered, "FROM", maintaining 355°. Back on course, remain on = 355°.

7. OBS = 350°, CDI centered, "FROM", maintaining 355°. Back on course, remain on = 355°.
8. OBS = 040°, CDI centered, "FROM", maintain 040° MH.

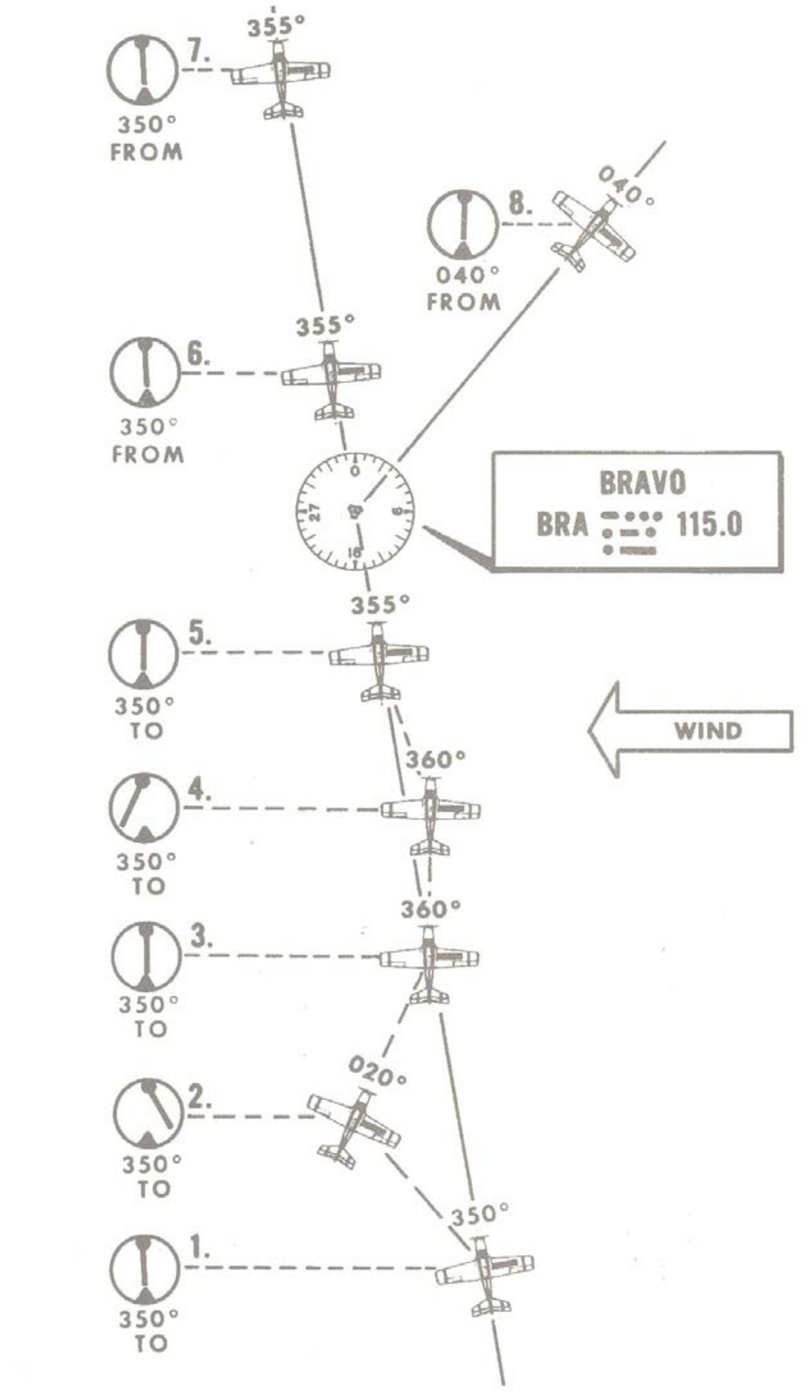


Fig 79: VOR Tracking

4.18.4.4 .2 Optional route; immediately before reaching BRAVO VOR, begin turn to 040°, based on W/V computed after establishing drift, GS, & applying TAS for last leg (from point 5 to Bravo VOR).

5.5 Reset OBS to 040° & turn to 040° MH upon crossing VOR, "fly to the needle", if necessary to align with the new radial,

4.18.4.5 VOR Availability

OMNI stations are located closely enough, & cover such a large part of the country that VOR signals are within range of a majority of the country, at reasonable cruising altitudes.

4.18.4.6 OMNI capability for IFR Operations.

OMNI is easily certified for IFR, while LORAN & GPS require extensive approval & testing effort to obtain approval for enroute navigation, which includes approval for IFR approaches. Most planes flying in the U.S. are equipped with an OMNI. OMNI has no data base, so requires no updates to maintain IFR capability. It must, however, be periodically checked against a VOT (special purpose test transmitter), known position on or over the ground, or against a second OMNI. These calibrations may be quickly performed by the pilot. The allowable error varies with the type of calibration. Any OMNI installation must be properly accomplished, which automatically includes IFR certification.

Most planes in the U.S. are equipped with at least one OMNI. Even if the plane flown is an antique, lacks an electrical system, or for some other reason has no OMNI, a handheld OMNI is readily available & quite practical. Most handhelds are actually a nav com. A handheld can be used to supplement or replace a full 1-1/2 system (navcom). A handheld ADF does not appear to be on the market, but a loop could be designed & made for any AM radio with appropriate bands. The loop & azimuth scale could be temporarily mounted to the plane. A handheld GPS is also popular & practical. Temporary installations must still be at least evaluated by a certified technician or mechanic, & may not be used for IFR flight.

4.19 DME (distance measuring equipment)

4.19.1 Background

DME was added to the VOR system, even though they used separate transmitters. DME relied on VOR, & the receivers shared components. DME is, as the name infers, distance measuring equipment.

The OMNI-DME system offers slightly more accurate "range" than TACAN.

TACAN "bearing" information is slightly better than OMNI.

The FAA predecessor, the CAA, began installing VOR transmitters just before 1950 so they could obsolete the LF A-N radio ranges to greatly improve the flexibility from nominally cardinal-points-only airways to virtually infinite selection of bearings. The eventual total cost of the VOR-OMNI range was $200 million, including navcoms installed by users.

OMNI was the primary Aero Nav system for the military & airlines for decades, although for polar regions & long overwater flights Inertial nav dominated on planes with nearly unlimited finances. OMNI soon dominated Genav Aero Nav, which accounted for the vast majority of users.

Voice capability & DME were added much later to the OMNI system. Voice was never added to TACAN.

When the Navy discovered that OMNI was not functional on a pitching-rolling aircraft carrier they invested approximately another $200 million on the questionable, unreliable TACAN system.

Since OMNI-DME could not co-exist with TACAN, a fight ensued. OMNI-DME & TACAN used the same UHF frequency band. The USAF & airlines agreed with the Navy, but the highly successful OMNI system survived for most applications.

OMNI was initially implemented when only the military operated jets, & most planes operated at cruising altitude well below 20,000'. VOR transmitter spacing was thus appropriate for lightplanes cruising below 10,000', & airliners near the same altitude. Duplicate frequencies were well beyond reception range. As jets became operational by airlines, & 30,000' ± a few thousand feet became the norm, reception range increased well beyond that of the nearest VOR. Duplicate frequencies are rare, but possible. In such cases the DME automatically selects the strongest signal. Even that results in a problem, in that as the plane cruised along, the relative distances, & thus signal strength changed.

4.19.2 Theory

The VOR continued to provide magnetic bearing information, & the DME transmitter provided range in NM. Range is provided, given sufficient altitude, from zero to beyond 190 NM.

The DME must convert the travel time of radio frequency signals traveling at the speed of light into distance values; much like the Radar does. The DME transceiver sends out a distance interrogation pulse, which the ground based transponder (a transceiver; or transmitter-receiver) responds with a pulse signal reply containing distance information. Response is time dependent, so pulses require over 10 microseconds for each NM of distance between the aircraft & the DME transmitter. Even at 100 NM the time delay is negligible.

It might appear to be impossible to provide distance information for numerous planes on a single frequency; rather than just one plane. The DME transponder must segregate signals from numerous planes. It is not practical to provide a discrete frequency for each plane, so a means of coding & decoding signals is essential. This is accommodated by sending pulses from each plane with random time delays. The DME station then responds with the identical spacing simply by sending each pulse out immediately. The DME receiver in the plane must then search for the same time delay code. The DME in the plane must also delay the next signal to prevent interference. The randomly spaced signals safely allow discrimination between different aircraft. The transmitters are all omnidirectional, so each DME equipped plane in the air must reject all signals that have a different time spacing.

4.19.3 Accuracy & Efficiency

Neglecting the slant range influence, the DME accuracy is excellent at ± 600 feet, ± 0.2% of the range. An example: At a 10 nautical mile range, the distance error is ± 720 feet; not much more than 0.1 NM; 2,160' & 0.35 NM at 30 miles. A short range loss of accuracy results unless slant range can be translated conveniently. Even at moderate altitudes the slant range error must be understood.

An advantage of the DME is the efficiency gained, when it is practical to fly off-airways to reduce distance & time between departure airport & destination. That does, however, require extra cockpit work. A more thorough preflight is recommended. If a little effort is expended during the preflight a series of hash marks across the intended track can be labeled with bearing & range as frequently as desired to facilitate in flight course monitoring.

Some loss of accuracy results at short ranges, unless a slant range vs. absolute altitude spread sheet is available.

4.19.4 Application

Many DMEs show distance, speed, & time to VOR-DME station on separate displays, which is less useful, while some show both on the same display.

Distance Measuring Equipment (DME) was added to ground based VORs to provide bearing & distance information. This is interpreted in a single panel mounted avionics package. It provides a fix rather than simply a LOP. One problem is reminiscent of that of radar nav; slant range. At long distances, the range is reasonably accurate, but a spread sheet is recommended at ranges less than 3 times the altitude. Another serious shortcoming of the VOR-DME is that unless the plane is flying directly to or from the transmitters, neither the speed nor the time to transmitters are valid.

The fix does permit flying to a point that is within range of only one VOR-DME. Without DME the single VOR only provides a LOP.

OMNI-DME is efficient in that it reduces Aero Navigator work load & provides continuously updated position information that allows instant response to controllers who ask for position. Such requests are commonplace when outside of Radar range, & may be critical to flight safety.

A series of simple plots during preflight can be marked on the Sectional as bearing & distance from any DME-VOR transmitter pair; as closely spaced as desired. In flight, even without the preflight effort, the fix is still useful; on or off-airways. The convenience of being able to advise ATC in an instant the exact position is especially desirable in heavy traffic areas or when IFR.

One concern is that DMEs have a poor maintenance history, although they are more reliable than their chief competitor; TACAN.

A more thorough preflight is recommended for flight off-airways with DME. If a little effort is expended during the preflight a series of hash marks across the intended track can be labeled with bearing & range as frequently as desired to facilitate in-flight course monitoring.

As with OMNI, the I.D. code is not transmitted if either OMNI or DME portion is out of calibration, or inoperative.

4.20 DCE (Distance Computing Equipment): Once a revolutionary, complex computer based system.

4.20.1 Background

When the Collins DCE-400 was introduced in the early 1980s at a moderate price, it literally revolutionized Aero Navigation. It was soon displaced by the LORAN. This little known DCE was absolutely a major breakthrough, It was more computer than avionics. Before then, the OMNI was only capable of providing a LOP, except when flying over a VOR transmitter, or crossing another LOP. Manual plotting was generally necessary. Such manual plotting was imprecise, if not impractical with a Sectional many times the size of the Aero Navigator's strapped-on-leg writing surface, lying on his lap.

The DME did provide much the same information, but with a distance related slant range error, low reliability, & exceptionally high maintenance cost, as well as a high initial price.

The development of progressively smaller computers made the DCE possible.

Aviation gained a truly great avionics device because Collins & ARC were so advanced that they always developed the most reliable & advanced avionics system; in this case, Collins. ARC & Collins were the undisputed leaders at that time because they had manufactured avionics for the airlines for decades. The author, having flown with most American made brands, believes that none compare with ARC in nav & com operational range; & that otherwise none were as advanced as Collins in terms of ease of operation, & amount of information provided. Most competitors have yet to provide some of the very useful functions that Collins offered in the 1980s. The FAA used a Houston based commuter airline to routinely calibrate their own equipment by interacting with the all-Collins Microline avionics in their fleet of twin Otters. Both claimed that the Microlines were the best for their purpose.

4.20.2 Theory

A complex programmable electronic package capable of converting MH information from two VORs into a continuously updated string of fixes, with GS, & ETAs, by use of an advanced computer. A simple trig problem except that a computer could perform those computations continuously as opposed to a manual operation by E-6B or hand calculator.

This could have been quickly performed on a large Aero Navigator's table; had they been available in lightplanes.

4. 20.3 Accuracy & Efficiency

DCE radial accuracies for radial intercept angles greater than 30° are ±1°. Distance errors are 1 NM for distances up to 20 NM; ± 2 NM for 20 - 50 NM, & ± 3 NM for >50 NM range. Time-to station accuracy is ± 30 seconds. With a typical OMNI accuracy, the average OMNI fix has an error of less than 1 mile. A fix using a Sectional would be at least a minute or two behind the plane, & is difficult to obtain without a large table for a reasonable degree of precision. The DCE is more precise & continuously provides precise fixes in an instant.

The ability to fly any route increases the efficiency over flying often devious airways.

4. 20.4 Application

4. 20.4.1 This computer was indeed ahead of its time, for this application. It performed continuous computations & displayed valuable information; most importantly a fix continuously displayed. An Aero Navigator no longer had the inconvenience of relying on futilely sketched (at least the final portion) two LOPs on a poorly supported Sectional, & hope he had a valid fix. The DCE permitted him to fly directly between two points.

4. 20.4.2 The DCE provides the Aero Navigator with all necessary flight information while flying to or from either of two VOR's which have a large intercept angle, & are within range. The DCE continually updates Bearing, Distance, Ground Speed, & Time-to-the-VOR, as the plane flies toward (or away from) it. The DCE system will usually include two previously installed nav receivers; presumably navcoms. The DCE uses the two VOR angular signals to compute & continuously recompute the Distance between the plane & each of the VORs, the Ground Speed, & Time-to-VOR as the plane cruises along. The DCE solves for distance by use of trigonometry instead of the pulse method used by the DME. The DCE Displays distance from either VOR up to 199 miles, & GS up to 400 knots. Like the other Collins avionics, it is equipped with automatic dimming LED display for maximum visibility without interfering with other avionics, under all ambient lighting conditions.

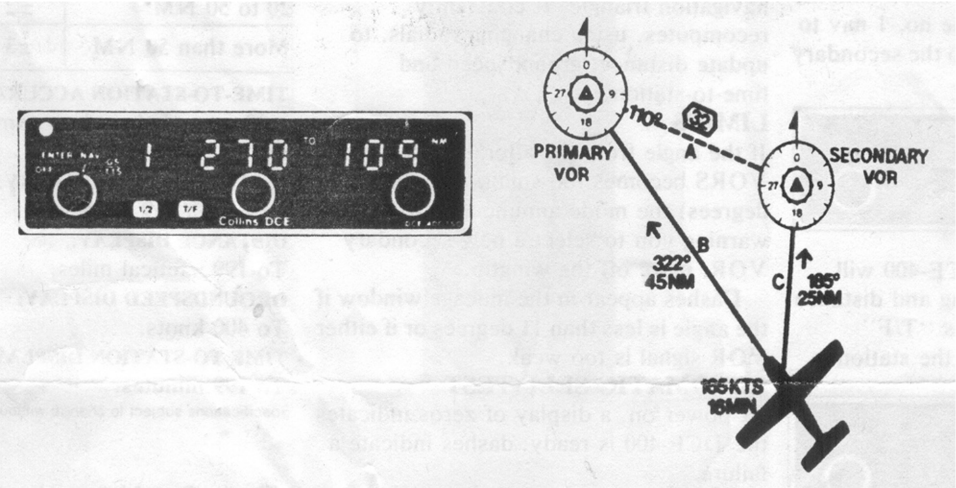


Fig 80: DCE

In cases of insufficient signal strength the questionable VOR is flagged, as a warning.
Data entry speed controls the computer information loading rate.

4. 20.4.3 The DCE provided the Aero Navigator with easier Aero Navigation, & lower workload, than any other Aero Nav system at the time of its introduction. The DCE is still available even though largely obsoleted by the LORAN & GPS.

4. 20.4.4 A limitation:

The DCE does require advance programming, which is time consuming & inconvenient. A more serious concern is evident If the flight must unexpectedly deviate beyond reasonable bounds while enroute; the programming may be inadequate for the new location or course.

4. 20.4.5 Fortunately for Aero Navigators, & unfortunately for the DCE manufacturer, the LORAN was introduced to Genav in 15 years, with even more flexibility & accuracy.

Fig 80 Illustrates the 6.25"standard avionics width x 1.75" high.DCE face with controls & LED displays. It also shows a simple bearing - distance for a typical DCE flight.

4.21 TACAN

4.21.1 Background

The FAA, military & airlines wanted a better & more accurate way to obtain a fix, but disagreed on which was better; DME or a mysterious new system called TACAN. Some were certain, when various merits & objections to TACAN were fully exposed. The expectation was to reduce error by a factor of 10. Great goal, but it proved to be unrealistically optimistic.

When the Navy discovered that OMNI was not functional on an aircraft carrier they invested nearly another $200 million on the questionable TACAN system that proved also to be unreliable initially.

The U.S. navy wanted an Aero Nav system that offered much greater accuracy than OMNI & DME, & operational success on a warship. TACAN used the same basic technology as DME. Development testing proved that it did not live up to expectations. It proved to be a little less accurate in range than the DME, & only slightly more accurate than OMNI bearings, so usage eventually decreased.

The FAA predecessor, the CAA, began installing VOR transmitters just before 1950 so they could obsolete the LF A-N radio ranges to greatly improve the flexibility from nominally cardinal-points-only airways to virtually infinite selection of bearings. The eventual total cost of the VOR-OMNI range was $200 million, including Genav, which accounted for the vast majority of users. TACAN cost nearly that much before the disagreements disrupted progress.

4. 21.2 Theory

A TACAN system provides, when co-located with a VOR, a continuously updated fix by continually updating radial & range.

4.21.3 Accuracy & Efficiency

TACAN accuracy is the composite of OMNI & TACAN. At a 30 NM range the OMNI contribution to positional error is less than 0.5 miles while the TACAN is contribution is 0.35 NM. From 0 to 0.85 NM & 0 - 5,000'.

TACAN with OMNI is efficient in that it reduces Aero Navigator work load & provides information that allows instant response to controllers who ask for position. Such requests are commonplace when outside of Radar range; & may be critical to flight safety.

The OMNI-DME system offers slightly more accurate range than TACAN.

TACAN bearing information is slightly better than OMNI.

4. 21.4 Application

A TACAN measurement begins when the aircraft transceiver sends out distance interrogation pulses. The ground station receiver responds with a distance reply pulse signal. Response is time dependent, so pulses require over 10 microseconds for each NM of distance of then aircraft from the TACAN transmitter. Since that would be only 1 second if range were a preposterous 1 million miles, the time delay is essentially zero.

The position of the aircraft is determined by obtaining the bearing & range simultaneously and then displaying the true bearing and range between station & the aircraft. The Aero Navigator simply monitors bearing & range from the VORTAC transmitter.

A serious concern for the designers of TACAN equipment was the possibility that many planes sending out multiple interrogations would create discrimination problems for the airborne. Since a large number of aircraft could simultaneously interrogate the same station, the solution selected was to design into the airborne unit the capability of determining which responses were in reply to its interrogating pulses. This search & discrimination process requires approximately 20 seconds; somewhat long, but tolerable. Contributing to the success of this process was the random timing of pulses.

The VORTAC system consists of a VOR transmitter & TACAN transceiver with co-located antennas. Aircraft equipped with OMNI and DME can also receive bearings from the VOR station and distances from the TACAN station. The TACAN transmits a Morse Code identifier.

Duplicate frequencies are rare, but possible. In such cases the VORTAC system automatically selects the strongest signal. Even that results in a problem as the plane cruises; the relative distances, & thus signal strength changes.

Voice capability & DME were added much later to the OMNI system, but voice was never added to TACAN.

Since OMNI-DME could not co-exist with TACAN, because they used the same UHF frequency band, a battle ensued. The USAF & airlines agreed with the navy, but the highly successful OMNI system survived for most applications.

TACAN bearings continue those of OMNI; magnetic variation.

4.22 LORAN; an Engineers dream. Highly technical, & initially very tedious; now a simple & high precision system.

4.22.1 Background

The original basic LORAN-A was a medium frequency (2 MHz) electronic navigation system that was developed during World War II, based on signal time differentials that result in hyperbolic curved LOPs. See Fig 81 for a theoretical schematic, & Fig 82 for a portion of an actual early LORAN chart illustrating a fix. It was highly secret, & used an adjustable time offset for the purpose of preventing enemies from using an intact, captured LORAN-A receiver. Each day required a new offset. The unit was very primitive, but priceless for Navy, & Army Air Corps missions over Germany, & even more valuable in the Pacific. LORAN did require a devoted Aero Navigator with a large nav table for the chart. Once tuned for operation a fix could be obtained in less than three minutes. Accuracy was reported by the US Coast Guard to be 1% of the distance between plane & station; reasonably close to the reported error on the flight to Japan. One claim that was presumably substantiated by use of a three star fix or map reading was that the LORAN error in navigating the 1,400 miles from Tinian to Japan was 28 miles. After a few (≥ 2) fixes the drift, GS, & ETA were known.

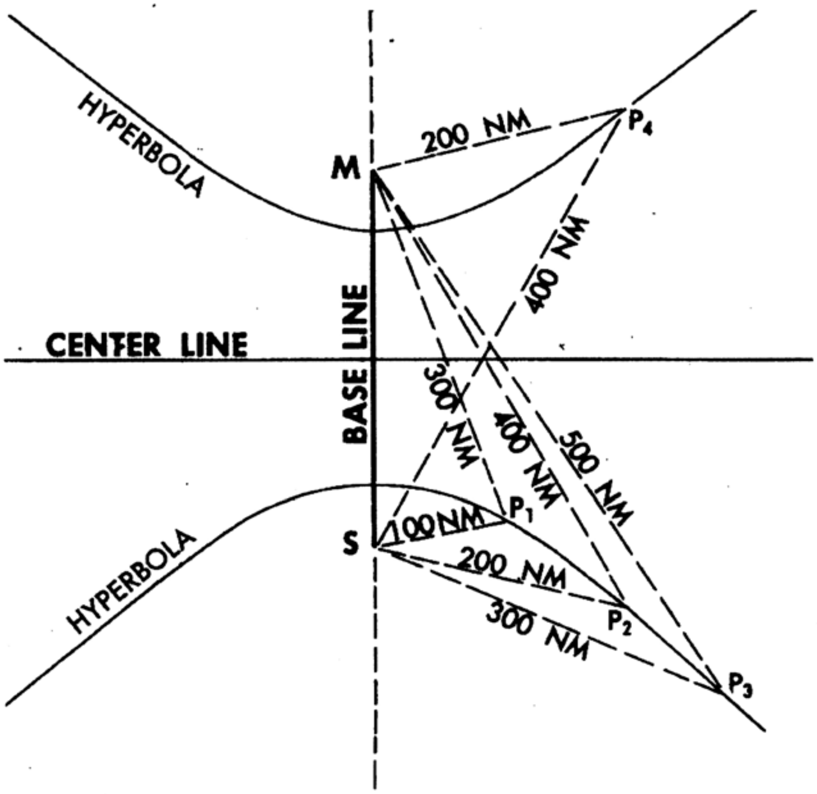
The LORAN-A CRT (cathode ray tube; oscilloscope) screen was only about four inches in diameter; the case nearly 1' wide x 15" high x 28" deep, & weighed 40 lbs, vs. its 80 lb predecessor.

The simplicity of the LORAN transmitters, & the fact that weather rarely reduced effectiveness, made it an exceptional navigational system for the time.

The Japanese were a marginally primitive enemy, so fortunately were too inept to jam any of the LORAN systems. Somewhat like the vastly more advanced enemy, Germany, that failed to identify & destroy the "odd looking" primitive British Radar; even though they tried once. Had they been a little wiser, & destroyed those towers, they would almost certainly have won the critical battle of Britain, & as a result, WWII.

The LORAN & LORAN A were used until 1957 when LORAN-C was placed in service by the USAF. They were all large & bulky, & required half an hour to perform preliminary adjustments in preparation for operation, with dozens of knobs & screwdriver adjustments. The first LORAN-C version was still bulky, as shown in Fig 83. It looked much like the original versions; very complex, with 36 items to view, study, or adjust.

The only display was the small oscilloscope. Looking at the oscilloscope was not at all informative. The pulse information had to be used to select the correct LOP. It was almost immediately replaced by a small unit much like the one that was sold to Genav 20 years later; both still qualified as LORAN-C. The WWII versions, & the



AT P_1, 300 NM − 100 NM = 200 NM
P_2, 400 NM − 200 NM = 200 NM
P_3, 500 NM − 300 NM = 200 NM
P_4, 400 NM − 200 NM = 200 NM

Fig 81: LORAN Hyperbola Schematic; for one of two hyperbolas required for a fix

large postwar LORAN-C were used by the USAF, Navy, & Coast Guard until the mid 1950s. LORAN-C operated in the LF (low frequency) band (100 KHz). The second generation LORAN-C was adapted by DOT (Dep't of Transportation) in 1974 for marine applications. The first approved aviation LORAN-C units were marketed in 1983. The resulting civilian version was used by Genav for decades, & fit the standard avionic rack, so was 6.25" wide, such as the Foster LRN-500; although the heights varied. The Foster LRN-500 is 2" high, & typical of most avionics, 10.25" deep. The Collins transponder is closer to 6" deep. Most navcoms require more depth; closer to 10".

During World War II, Germany developed a navigation system called Sonne that was time differential & hyperbola based & somewhat similar to LORAN. After the war the British improved their similar Consol system, while the U.S. called such a system Consolan. Even during WWII, LORAN was superior. More recently the Russians developed CHAYKA; a LORAN type nav system.

4. 22.2 Theory

The LORAN system takes advantage of the fact that radio frequency pulses travel at the speed of light, which permits the airborne LORAN system to measure time & convert that to distance. The three distances of interest

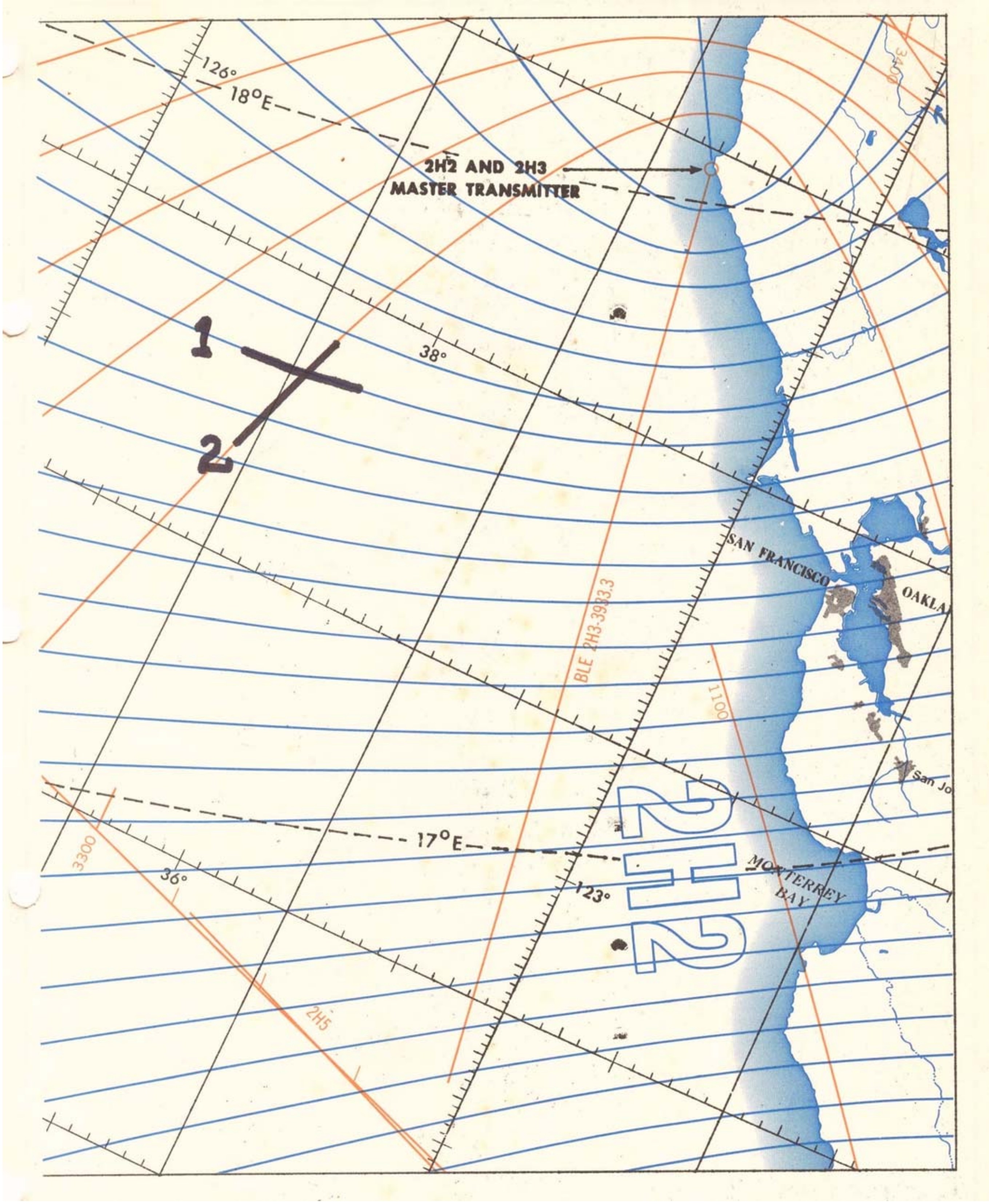


Fig. 82: Loran Chart Fix

are between aircraft & master, between aircraft & slave, & between slave & master. Fig 81 shows a series of points that have the same delta time (time differences), & thus the same difference in distances, such as 300 -

100 = 200. In each case the time for the signal to travel between master & plane is the time it takes for the signal to travel 300 NM. Simultaneously the time for the signal to travel between slave & aircraft is the time it takes for the signal to travel 100 NM. The difference is 200 NM. That point is represented by point P_1. A series of points with the same Δt (& comparable difference in distances) from two stationary points from the pair of hyperbolas shown in Fig 81. The fixed points are called "foci", per the standard parabola. In the case of LORAN those two fixed points are LORAN transmitters. Per Fig 81, there are actually two hyperbolas represented by a single delta time. Thus the aircraft must be at some point along one of these two hyperbolas. Since these hyperbolas represent hundreds or thousands of miles, the Aero Navigator must use his DR position to determine his most probable position along one hyperbola. He then crosses the hyperbola with another LOP to establish a fix. The two selected hyperbolas (LOPs) actually cross at two points. The two points would typically be many thousands of miles apart, so selecting the correct intersection is obvious.

All of this relies on the fact that when one unmodulated omnidirectional signal pulse is sent from the master it is also received by the LORAN receiver as well as by slave stations in that "chain". The slave stations delay, & then rebroadcast an identical signal, which will arrive at the LORAN receiver at a time that is related to aircraft position per the above. That time delay is critical to the safety of all involved in the case of wartime operations. All allies who use LORAN must know the delay, but the enemy must not.

Fig 84 illustrates the methods of propagation of LF signals involved in LORAN reception. Time measurement accuracy depends on the ground wave propagation as well as skywaves.

4. 22.3 Accuracy & Efficiency

The WWII Loran was reported as stated above; 1% of distance from LORAN transmitter chain. Before the LORAN-C was available the older LORAN actually was capable of routinely reducing error to 1 mile. Even then error was much less than 500' in an area where spacing between hyperbolas was small; near the base line that lies between the transmitters.

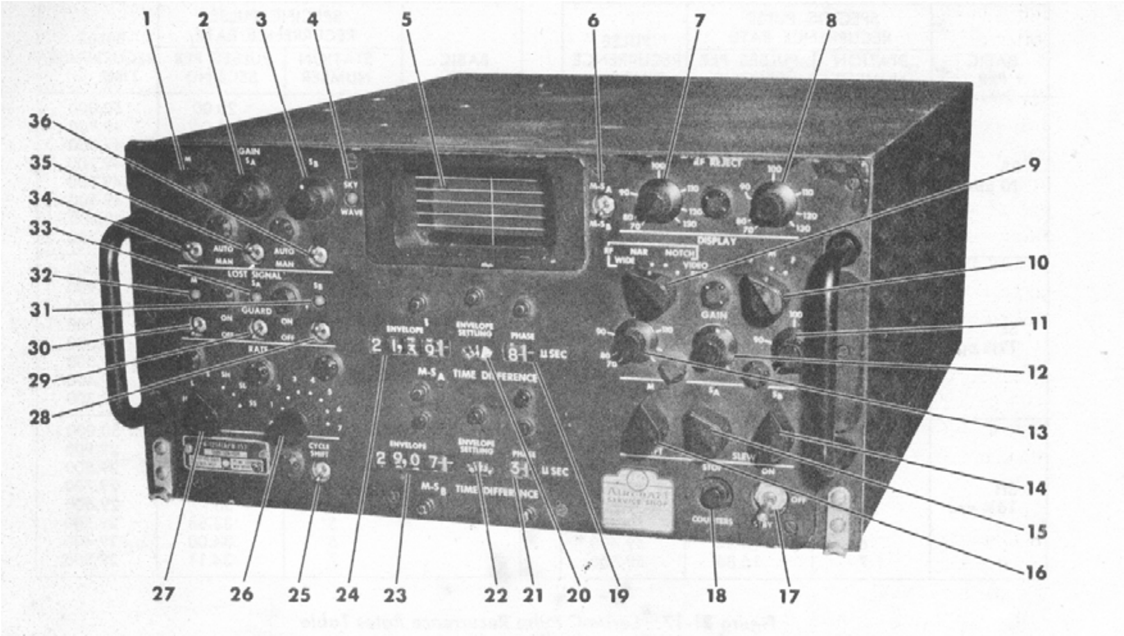


Fig 83 : The First Version of the LORAN-C

1. GAIN/M CONTROL
2. GAIN/S_A CONTROL
3. GAIN/S_B CONTROL
4. SKY/WAVE LAMP
5. VISUAL DISPLAY OSCILLOSCOPE
6. M-S_A/M-S_B SWITCH
7. RF REJECT CONTROL (LEFT)
8. RF REJECT CONTROL (RIGHT)
9. DISPLAY/RF/VIDEO SELECTOR
10. DISPLAY SWEEP S-M-F SWITCH
11. VISUAL DISPLAY REJECT CONTROL (RIGHT) .
12. DISPLAY/GAIN CONTROL
13. VISUAL DISPLAY REJECT

CONTROL (LEFT)
14. SLEW/S_B SWITCH
15. SLEW/S_A SWITCH
16. DRIFT/M SWITCH
17. ON/OFF/STDBY SWITCH
18. STOP/COUNTERS BUTTON
19. M-S_A TIME DIFFERENCE/ PHASE COUNTER
20. M-S_A TIME DIFFERENCE/ ENVELOPE/SETTLING DIAL.
21. M-S_B TIME DIFFERENCE/PHASE COUNTER
22. M-S_B TIME DIFFERENCE/ ENVELOPE/SETTLING DIAL
23. M-S_B TIME DIFFERENCE/ ENVELOPE COUNTER
24. M-S_A TIME DIFFERENCE/ ENVELOPE COUNTER
25. CYCLE/SHIFT SWITCH
26. SPECIFIC RATE SWITCH
27. BASIC RATE SWITCH
28. GUARD/S_B SWITCH
29. GUARD/S_A SWITCH
30. GUARD/M SWITCH
31. LOST SIGNAL/S_B LAMP
32. LOST SIGNAL/M LAMP
33. LOST SIGNAL/S_A LAMP
34. AUTO/MAN/M SWITCH
35. AUTO/MAN/S_A SWITCH
36. AUTO/MAN/S_B SWITCH

The modern panel mounted LORAN is capable of an accuracy of 60 ft. Note that the GPS is attributed with a 6 ft accuracy, but numerous credible comparisons have proven nearly the opposite operationally. Some small marine operators have reported that they can repeatedly return to a point using LORAN with no more than 20% of the error of the widely praised GPS. Some published comparisons indicate that a commercial fishing boat could return to within 25' using LORAN vs. 300' with GPS.

LORAN is exceptionally efficient in that Great circle Aero Navigation can be accomplished with outstanding accuracy, reliability, & to virtually any point in the U.S. & well beyond. Flights between two isolated, undocumented points within literally 100 ft of a Great circle route is notable & commonplace. Based on Fig 2 & related comments, a coast to coast flight near the Northern border of the U.S. would be 140 NM shorter using LORAN vs. a direct flight with no means of discriminating Rhumb line & Great Circle.

Some modern planes do have 3,000 mile ranges. In fact, a modified P-51 Mustang was converted to a "wet wing" (wings sealed to carry as much fuel as possible internally. The owner of that plane claimed a 6,000 mile range. He filed IFR for a coast to coast flight with the departure point also as alternate, just to puzzle the FAA. That meant that he had sufficient fuel to fly coast to coast, & return to the starting point. The modifier also claimed fuel burn as low as 35 mpg. General (retired) George Masterson (an acquaintance of the author; attended the same church) said such a low fuel burn was impossible, although the Mustangs that he had flown in combat during WWII were extremely heavy as flown. Military versions of the P-51 have empty weights of 7500, loaded of 9,000 & max gross of 12,000 depending on which model & source is shown. Remove guns & armor & empty weight should drop to roughly 5,000 lb. Reduce cruise speed from 365 (vs. top speed near 450) to 250 mph & fuel consumption might drop from 100 to 40 gph. If so, & range is boosted to 6,000 miles, fuel requirement must be near 1,000 gal.

The LORAN is one of the few Aero Navigation systems capable of optimizing descent speed, time, & fuel burn. This is a simple, easy operation for programming (preflight or in flight) to enroute & descent (V-nav) reduces time, engine abuse, & fuel consumption. A rapid descent results in excessively fast engine cooling & unnecessarily high fuel consumption. With V-nav the descent can begin at precisely the optimum time-distance form destination.

4. 22.4 Application

4.22.4.1 Omnidirectional signals are sent from the LORAN master transmitter, so that to the airborne LORAN receiver & slave stations can all receive the same signal per paragraph 4.22.2 (Theory).

4.22.4.2 If both signals were transmitted at the same instant, they would arrive together at any point along the center line, per Fig 81. A plane nearer the master station would receive the master signal first, but if closer to the slave station, the slave signal would be received first. There would be no way to discriminate between the signals. The ambiguity would render the system useless. The ambiguity was eliminated by delaying transmission of the slave signal long enough that it would remove any ambiguity.

A LORAN receiver can receive signals from more than one chain, so a means of identifying each chain is essential. That was accomplished by assigning a different pulse recurrence rate (PRR) & identifier to each chain.

4.22.4.3 Signal variances can occur, as indicated schematically in Fig 84. The different distance between the master and slave transmitters from the aircraft can affect LORAN signals. A ground wave from one transmitter and a sky wave from the other is possible. One way this can occur is when the ground wave from the master is beyond the range of the aircraft receiver, so the first pulse in the master pulse could be a sky wave. The time of day at one transmitter might result in one transmitter receiving a pulse at night while the other receives in the daytime. It is possible for the first reflection of sky waves to occur in the late afternoon before sunset, or for three hours after sunrise. Range, time of day, and intervening land may impact LORAN pulses.

4.22.4.4 It was possible to "Home" by following a hyperbola that crosses the destination. Since hyperbolas are so very large, they approach a straight line, so the distance increase would usually be negligible. Homing could be accomplished by maintaining the desired CRT spike location on the screen.

LORAN-C is a sophisticated extension of the basic principles used in the earlier LORAN.

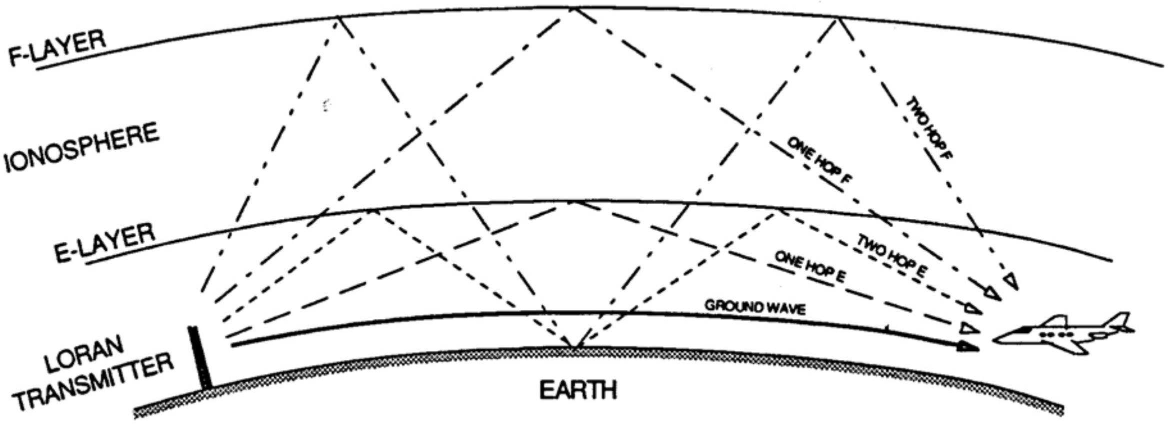


Fig 84: LORAN LF Radio Waves

4.22.4.5 Before LORAN-C the airborne LORAN receiver would process the time that each signal was received, determine the delta time (time differences), & present a spike representing time on a CRT screen. Time represented the particular hyperbola that the plane was on; whether crossing or cruising along it. The hyperbola in Fig 81 is mirrored across both horizontal & vertical centerlines, so that point P_1 could be on 4 different locations. Point P_4 is the equivalent of point P_2 , & each could be mirrored across the vertical centerline. The 4 point ambiguity is easily resolved by looking at his chart & plotting his best known position; his DR position. He could usually eliminate three possible fix locations by noting the enormity of the hyperbolas. Three fix locations will usually be hundreds of miles from his DR position. See Fig 82 for a typical LORAN chart plot. Beyond point P_4 the hyperbola is nearly a straight line; only slightly curved. The equation for a hyperbola is $x^2/a^2 - y^2/b^2 = 1$; based on a 90° reorientation of the axes & hyperbolas from those shown in Fig 81. The X & Y axes reversed from the basic equation vs. the illustration. The foci are the points where the curves cross the vertical centerline in this illustration.

In some locations, a slave transmitter may be used as a slave for more than one master transmitter. It is then known as a "double slave transmitter". Some master transmitters also may be used as slaves for other master transmitters. These are known as master-slave transmitters.

4.22.4.6 With LORAN-C the above is not applicable.

The LORAN-C handles it all without any effort by the Aero Navigator. In fact, these receivers track three or more transmitters. The receiver computes a fix & displays it, usually as distance & bearing from the next waypoint, or a navaid such as a VOR, even though the LORAN-C has no electrical link to a VOR. It may, if desired, display it as latitude and longitude.

Even the first version of the LORAN-C was complex & difficult to operate, as is evident in the illustration & annotations of Fig 83. It is similar to the LORAN-A.

4.22.4.7 A LORAN hyperbola is stationary on the surface of the earth, like an OMNI radial, as opposed to a sun line or star LOP.

A LORAN hyperbola normally intersects another LORAN hyperbola, but could intercept any other LOP, in the case of the older LORANs that required plotting on a chart. LORAN-C internally analyzes all hyperbola & instantly provides a fix.

4.22.4.8 Loran-C uses pulse groups instead of the earlier single pulse for measurement of time differences. This increased average transmitting power, but significantly reduces error. The typical master transmitter transmits 9 pulses in a group with 8 for slaves. The additional pulse in the master group provides identification of the station.

LORAN provides LOPs across the earth with signals that are usable over water for up to 1,000 miles during daylight hours, & 3,000 miles at night.

A LORAN chain may have from two to four slaves. The proper number of slaves will be displayed for each GRI.

The use of both low and medium frequency radio permits these very long ranges. The fact that the lower frequency waves could follow the curvature of the earth, & also reflect off of the Ionosphere as Skywaves, thus permits very long ranges. This is illustrated in Fig. 84.

A claim made against LORAN C initially was high susceptibility of signal loss when near thunderstorms. In several thousand hours of Aero Nav by use of the Foster LORAN that only happened one time very briefly when within 5 miles of a severe TRW; much too close in most parts of the U.S., but not in location noted.

4.22.4.9 The Foster LRN 501 LORAN-C

The Foster LRN 501 is typical of the modern panel mounted Aero Nav LORAN-C. It provides continuously updated position, GS, & other pertinent information. GS has an adjustable update to preclude jittery of simply excessive updates & the resulting flipping by any value.

The initial 1970 Era LORAN-C chains (Transmitting Stations) are illustrated in Fig 85.. M = master station; X, Y, & Z are slave stations. During system start-up, one of the Southwestern chains was not operational, & on repeated flights by the author between Houston & Denver, Albuquerque & Phoenix the signal was lost near the TX-New Mexico border; regained on return flights.

These flights were made with one of several excellent new designs of LORAN-C, a Foster LRN-501 was introduced by the Airdata division of BF Goodrich; before the units had been approved for IFR flight. That was also before approval for area navigation, so IFR flights were restricted to Victor airways, although the LORAN could be used for back-up & familiarization. The LRN-501 panel face is illustrated in Fig 86.

The LORAN frequency of 100 kHz was chosen because of the stable propagation characteristics and the long range of the Low Frequency (LF) band. LF signals meet the requirements for time measurement accuracy and the ability to predict ground wave propagation conditions although they are subject to skywave interference at long ranges.

Not every character position on every page will be highlighted by the cursor.

When Data Entry Knob rotated clockwise from A - Z, to 0 - 9; & the reverse for CCW. There is a "blank space" before A- after 9.

The Foster LRN-501 front panel face with display & controls is a typical LORAN C with a 6.25" wide x 2" high x 10" depth (length). It has a 5/8 x 2.5" LCD alpha-numeric display plus 9 controls.

Although these units differed in controls, appearance & features, a brief description of this LRN-501 indicates the general capability of all LORAN Cs. Excerpts from the manual for the first model made by Foster are included. Some are easier to program, or use in flight than others.

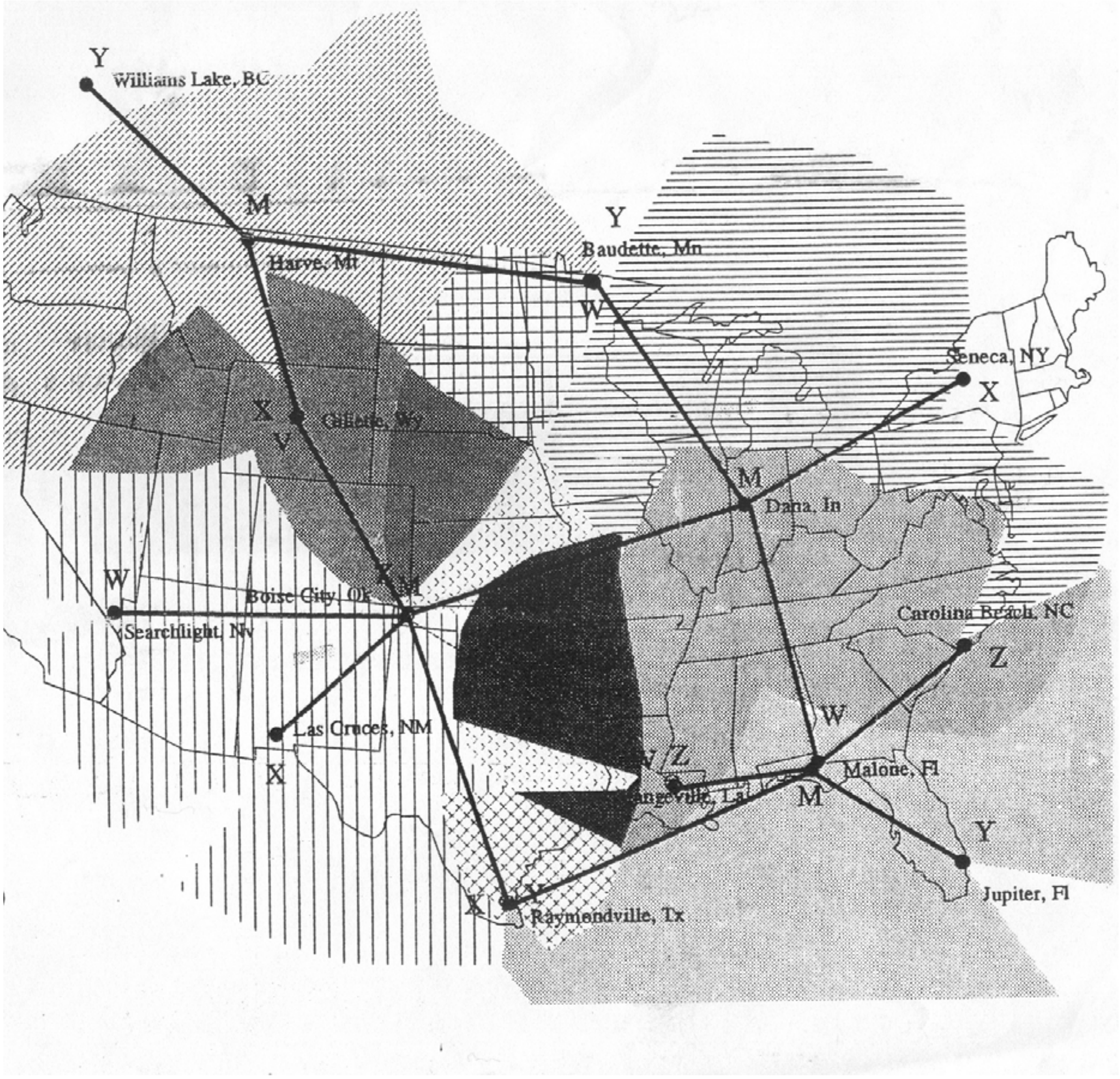


Fig 85: Initial LORAN-C Transmitting Stations

The controls include:
Left & Right Cursor arrow momentary contact push buttons.
Large diameter coaxial Mode Selector (Switch) knob that selects OFF, GRI, POS, FPL, WPT, & AUX. Each position corresponds to a different aspect of operation of the unit.
Small coaxial (Data Knob).
Momentary contact push buttons labeled as Page, MSG, EBTR, Dim, & Viewing Angle Adjust.

Fig 86: Foster LORAN-C Controls

The Message (MSG) button is used to insert or alter data that has been programmed, or to respond to messages from the unit.

To view the Pages of information, simply select the proper mode position and repeatedly press the Page Button to see the various pages displayed.

The Message (MSG) button is used to insert or alter data that has been programmed, or to respond to messages from the unit.

The Enter (ENTR) button is used to enter data into the unit. With data on the screen, use the Cursor push buttons and Data knobs, & press ENTR to store the information..

The right and left Cursor Buttons are used to select the display position where an alphanumeric character is to be entered. The location of the cursor is signaled by a blinking solid block alternating with a character or number. The left cursor buttons move the cursor in the direction of the arrow.

Manual dimming of the LCD display is controlled by the DIM potentiometer. Note that Collins & some other avionics devices have auto-dimming.

The Viewing Angle adjust potentiometer controls of the horizontal view angle.

Entering Data:
The procedure for entering data applies to most situations. Enter or review data in any mode by using right-left cursor buttons, data knob and ENTR button.

Operating Modes & Page:
GRI (group repetition interval) mode and page.
The term Group Repetition Interval (GRI) is derived from the lengths of time between transmissions that define the various LORAN chains throughout the world. The single GRI page allows the user to monitor the status of LORAN signals being received.
The Foster automatically selects the next GRI when time to do so in flight. It does allow the user to over-ride this. A problem with LORAN-C vs. GPS is that if the Aero Navigator turns the unit on when half way to his destination it will be lost, & may not recover. If that were to happen he should check the chart & enter the GRI that he thinks is appropriate. There may be instances, such as during terminal control area operations, when you need to retain your navigation information and do not have time for a new chain to be acquired. In this case, instead of pushing ENTR to accept the new GRI, delay the GRI change until later. When time permits make the change.

It is preferable to use only the Auto Mode with the Foster LORAN-C.
The Master and slaves that are currently active are shown as upper case letters in the display.. As the plane cruises along the upper & lower case letters will automatically change as appropriate.

A Quality of Geometry number from 0 to 9 indicates the Quality of Geometry of slaves & master stations. A "0" or one will cause the message "Bad Geometry" to appear.

The POS (position) mode has two pages. The first page is the Nearby Naviaid (navaid; VOR, DME, NDB) page. The display is given as a radial from the navaid and the distance in NM. The display also provides the frequency of the navaid in MHz. The second is the Actual Position page, where the current latitude and longitude that the unit is reading will be displayed.

The Track Error (TE) page shows ground Track (TRK) or actual course in degrees, followed by Track Error (TE) on a digital variation of a CDI including distance off course & from waypoint.

The Desired Track (DTK) is given as a "**Great circle**"; a very important feature. LORAN was the first navaid to provide this time-distance saving opportunity.

The Flight Plan (FPL) Mode provides for programming & storing flight plans. The Foster LORAN-C is capable of storing 26 flight plans, 9 waypoints per flight plan, & 200 total waypoints. User entered waypoints permit any special locations such as alter points, fishing spots, or uncharted landing strips to be permanently entered.

The flight plan provides Estimated Time Enroute (ETE) in hours and minutes and distance to destination; & the same information while enroute, along with present position.

The Foster LORAN-C has an adjustable GS update to preclude jittery GS displays from excessive frequency of updates which would result in an unreadable GS value.

Potentially the most valuable feature of the Foster 501 is the Auxiliary (AUX) Mode which provides near instant information on heading & distance to the "nearest airports", along with many details such as runway length**.** If unsatisfactory, such as one requiring back tracking, successive airports can be displayed. Vertical Navigation (VNV) is another AUX Mode offering that provides information on time-location to start descent based on preset & flight data.

4.22.4.10 Factors affecting LORAN signals include GDOP (geometric dilution of position), skywaves, weather, precipitation static, & various other items effecting signal propagation.

- In the ideal world, LORAN signals would be generated by completely controlled ideal transmitters, received by perfect receivers, and propagated through an ideal transmission medium.
- In the ideal world, the time-difference numbers indicated by a receiver could be directly converted to a certain, unique position. The accuracy of this position would be determined only by the accuracy of the coordinate conversion algorithm.
- In the real world, random noise and systematic (bias) errors in the transmitted signals, the receivers, and in the propagation medium reduce uniformity & repeatability. These errors will interact with the geometry factors for a particular observation point to produce both uncertainties and offsets in position. Position uncertainty results from the random errors impacting the geometry. Offsets result from the geometry acting on the systematic errors. The geometric factor is the relationship between time-difference errors and the position errors. Thus the Geometric Dilution of Position (GDOP).

Skywaves impact the path over the range which LORAN signals can travel, & affect their range. Skywaves have an influence on their characteristics and the reliability of their time difference readings. Radio energy which travels along the surface of the earth is called the Ground Wave, and that which is reflected from the ionosphere is called the skywave. The Skywave is named after the atmospheric layer that reflects it and the number of hops it takes. See Figure 84 for examples of ground waves and skywaves.

A serious concern for the many LORAN users who have a critical need for it is that uninformed, irresponsible political mismanagement & interference threatened to decommission all LORAN stations. This threat discouraged LORAN data base providers from creating updates for over a decade. These actions resulted in lack of confidence in the system, although the LORAN remained a useful, & indeed a vital Aero Nav system even without data base updates, until more recent irresponsible political action decimated this outstanding Aero Nav system. Some users declare the LORAN critical & irreplaceable for important activities. Some have documented better LORAN accuracy than GPS. It is not totally a one sided argument.

4.22.4.11 Foster LORAN C V-Nav includes a very useful & efficient feature; the capability t o optimize descent efficiency & performance. The LORAN is programmed during preflight or in flight to establish so that it will alert the pilot on the time to start the descent. based on desired descent rate, actual altitude & destination airport elevation. This prevents excessive time circling the airport before landing, if too high, or cruising at low altitudes, if too low. This reduces flight time, engine abuse, & fuel consumption.

4.22.4.12 LORAN IFR Certification

LORAN IFR Certification is inconvenient, as are special requirements for IFR. LORANSs offer integral CDI & similar displays, but the FAA decided that a separate CDI was essential for IFR operations. Although the Foster LORAN has its own integral version of a CDI (Course Deviation Indicator) the FAA requires a devoted CDI similar to the OMNI CDI for IFR certification. The special CDI instrument with selectable sensitivity - accuracy was deemed necessary, considering the importance of IFR capability. This resulted in the lengthy process of adding & certifying a CDI for IFR flight, including:

- Proper signoff by a certified aircraft mechanic or avionics technician
- Completion of the official FAA form 337
- Flying & documenting a series of cross country verification flights.
- Completion of additional FAA paperwork & dealings.

The special CDI instrument with selectable sensitivity - accuracy is shown on the author's instrument panel (in Fig I-3) & equipment list.

4.23 Super Celestial & the Automatic Astrotracker

4.23.1 Background:

There does not seem to be a proper name for what the author chose to call "Super Celestial"; because it really seems an appropriate name.

The Automatic Astrotracker & Super Celestial were combined under one course since the Super Celestial is a further advancement of the previously very advanced Automatic Astrotracker.

Both are based on the century old celestial navigation system.

4.23.1.1 Automatic Astrotracker

The Astrotracker requires at least a small astrodome, which would not be tolerable on any point along the top surface of an SR-71 supersonic plane. Its computer was primitive compared with those in the Super Celestial Aero Nav system, but represented a major advance in celestial Aero Nav. Nonetheless the Automatic Astrotracker is still much more advanced than any other celestial nav system except for Super Celestial.

The Automatic Astrotracker was gyro stabilized, but to a moderate level of precision. It is shown in Fig 87. The control panel was, as shown in Fig 88, enormous, & old enough to predate the LED & LCD displays. It appears from the panel that the computer plays a moderate role.

The automatic Astrotracker integrates optical, electronic & mechanical systems, including computer, to locate & analyze celestial data, & provide a continuous true heading reference from any point on the earth. Capable of locating, locking onto, & tracking any celestial body of sufficient magnitude (brightness), & providing continuously updated heading with reference to True North. It incorporates a gyro stabilized tracking telescope in a mini astrodome. The Astrotracker modulates the light waves, after which a photovoltaic sensor converts the modulated signal to computer compatible electronic information. The Astrotracker database includes latitude, longitude, GHA, SHA, and declination of all usable tabulated stars & planets. The altitude and azimuth are included as inputs & outputs of the system. The Astrotracker provides aircraft heading information with an accuracy of ± 6 arc- minutes.

4.23.1.2 Super Celestial

Super Celestial is a massive improvement over the previously very modern "Automatic Astrotracker".

A well kept secret (classified) for many years is the sophisticated, complex fully automated computer based Super Celestial system that is so very accurate & sensitive that it was capable of locking onto as many as 11 stars simultaneously; even during daylight hours. The system performed an instantaneous statistical analysis of the 11 LOPs to optimize the statistical weighting of each for the most accurate possible fix.

4.23.1.3 Basic Concept of Autotracking

The autotracker is essentially four identical small square photo sensors in intimate contact. The light from a star is focused onto the intersection of the four sensors. Each photosensor electrical output balances a pointing system to equalize the star signal, thus pointing directly at the star. A star, being infinitely small optically, is detected by the optical system; not resolved.

4.23.2 Theory

Both systems, when introduced, had the ability to detect multiple stars & quickly shoot multiple LOPs with a heretofore exceptional accuracy, & perform a statistical analysis, along with a high performance computer. The statistical analysis is a critical portion of the capability. Super Celestial advanced all aspects of these claims.

4. 23.3 Accuracy & Efficiency

Both systems offer small positional error; Super Celestial the phenomenally small error of only 300 ft. The statistical analysis is even more critical for Super Celestial. Inherently, such accuracy & flexibility of location & time of observation maximizes efficiency. Pilots of the SR-71 & B2 said that the Super Celestial puts GPS to shame.

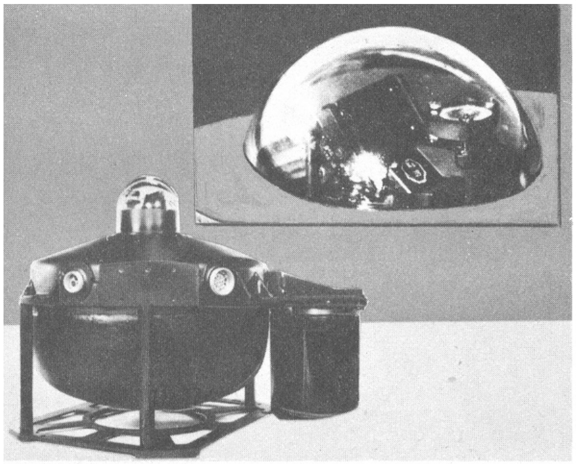
Super Celestial angular accuracy is nominally 1.2 arc second (6 micro radians; or $1.2 / 3600 = 3.333 \times 10^{-4}$; phenomenal for a stationary system, much less airborne.

Arguably the most efficient aero Nav system in that it is independent of all Navaids & other external equipment. It relies only on its self contained features & stars that may be seen daytime, & with the SR-70, IMC, since clout tops rarely reach 60 or 70,000', & when they do, they are widely spaced. Fixes are available in less than 2 minute increments. Magnitude 7 can be used, which is below the human visual range. Publications typically state that the star chart offer 57 stars, but the retired manager of the SR-71 program claims 61

The primary reason for development of Super Celestial was "probably" to support the USAF Lockheed built SR-71 Blackbird long-range strategic reconnaissance aircraft. Unclassified sources state that the SR-71 is capable of flying at speeds over Mach 3.2, & at altitudes up to 85,000 feet. Actual performance may actually exceed this released information.

At the extreme altitude of the SR-71, of course, the sky is so dark that stars are visible to the naked eye. It flies above virtually all of the atmosphere; approximately 99%. Absorbed light, of course, gives the sky its color & intensity.

Each LOP reduces the error, thanks to the ability of the algorithms & extremely versatile computer to precisely average LOPs & weigh errors; to reject questionable or inconsistent data. Because these assorted LOP optimization techniques are so effective, they can achieve the exceptional accuracy of 300 feet.



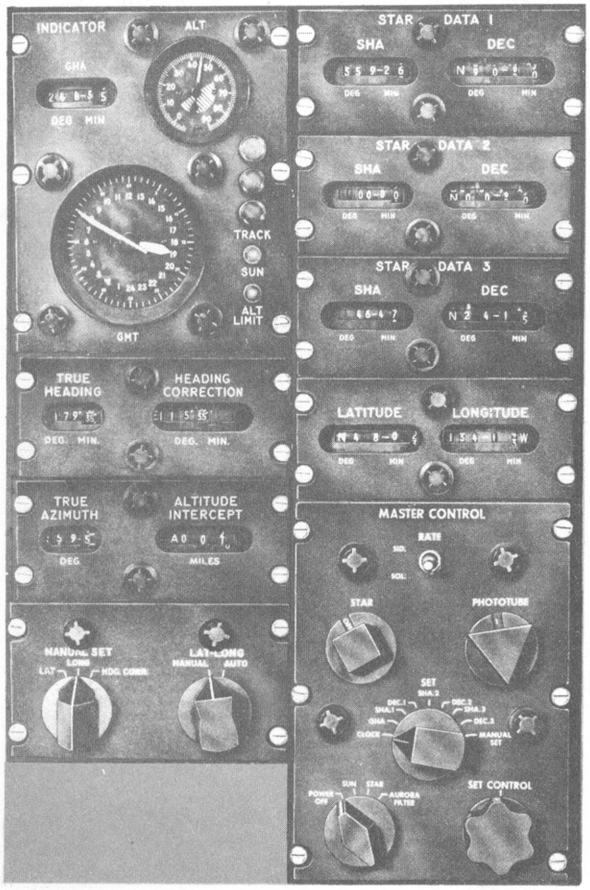


Fig 87: Astrotracker Sensing Unit Fig 88: Astrotracker Control Unit

4. 23.4 Application

The supersonic high-speed SR-71 reconnaissance aircraft, & two important applications by the U.S. Navy justify, & in fact, can afford the enormous cost of this elaborate, sophisticated state-of-the-art system. One of these applications is discussed in a later course. The other is for backing up & calibrating the GPS used on larger Navy warships. If accomplished manually, the large number of LOPs such as in Fig 35 would be very time consuming. It would also require careful identification & proper adjustment of each to the same time for a meaningful fix. Add to that the visual analysis of so many LOPs & it could be quite confusing. Whether there were two sightings of 9 different stars, or 9 different shots of each of two stars, the manual weighing of multiple LOPs would neither be consistent nor simple. The dichotomy of this is illustrated in fig. 35; a hypothetical 2 or 3 LOP fix; repeated several times. The scatter of these LOPs is much like a bell curve, so a visual review indicates the "approximate" center of each group; 90° & 120°.

Cassegrain optics & silicon array detectors CCD provide exceptional uniformity, reliability & precision. The Cassegrain is a folded optics design that reduces bulk & length while providing a compact high resolution telescope; generally for astronomers. The large diameter concave primary mirror is a parabolic reflector while the secondary is smaller, convex, hyperbolic reflector. They are normally coaxial, with the exiting light beam passing through a hole in the primary mirror.

4.24 Ride-the-Wind (RTW); Constant Heading Mean GS Optimization Method

4.24.1 Background

Aero Navigators & pilots have been trying to turn headwinds into tailwinds since the first cross country flight. As soon as they realized that winds changed with altitude they began trying to determine speed & direction.

The usual practice was to fly at the altitude with the most favorable winds, weather permitting.

As knowledge & capability of weather observation & forecasting improved it became possible to improve XC GS.

The RTW concept was developed & published many years ago by the author, & has often improved XC flying efficiency for him & others.

4. 24.2 Theory

Some well known facts are:

- The winds spiral CW in high pressure systems.
- The winds spiral CCW in low pressure systems.
- The closer spaced the isobars, the higher the wind speed.
- The wind speed decreases with distance from the center of the pressure system.
- Studying winds aloft & profile permits selection of optimum location & altitude to optimize tailwind component.

Some well known relevant generalities are:

- Wind direction "tends" to shift CW as altitude increases.
- Wind speed "tends" to increase as altitude increases.
- Official winds aloft are the best available source for wind information.

4. 24.3 Accuracy & Efficiency

Accuracy & efficiency depend on reliability of forecast winds, & the care taken to analyze available data.

4. 24.4 Application

The primary goal of RTW is to reduce flight time between any two points.

If an Aero navigator were to analyze winds within 100 miles of the desired track from surface to service ceiling manually by use of the E-6B, the winds may have changed before he finishes. It is practical to visually compare areas that are obviously not worthy of consideration. Figure 89 indicates that a direct flight would have involved mostly head winds. Even more detrimental would be a deviation that mirrors the route selected about the direct route line.

The drawing shown suggests three alternate route headings. Another option is to fly multiple headings to approximate a large radius curving route that optimizes GS vs. additional distance flown.

One important item not shown in Fig 89 is the winds aloft. It is important to study them for the route. It is the norm to browse, or preferably study winds aloft to pick the most favorable altitude. Again, a visual analysis will eliminate some routes or areas. It is always preferable to hold a single altitude for an entire flight, but there are times when a change is justified. The author has done so on many occasions, but often at least partly because of large terrain elevation changes.

The analysis illustrated considers only one altitude. In fact, winds loft would be the first consideration. At least, two altitudes should be briefly analyzed before a final altitude decision is made. A consideration in altitude selection is the legal flight altitudes, as discussed earlier. East bound flights should be made at odd plus 500', so above 3,000' AGL flights should be at 3,500, 5,500, etc. So the number of altitudes available is somewhat limited even if flying over low elevation terrain. The federal airspace begins at 1,200' on airways, but the VFR flight rules regarding altitudes begins at 3,000'. VFR airspace on airway extends to 17,500' (technically up to, but not including 18,000').

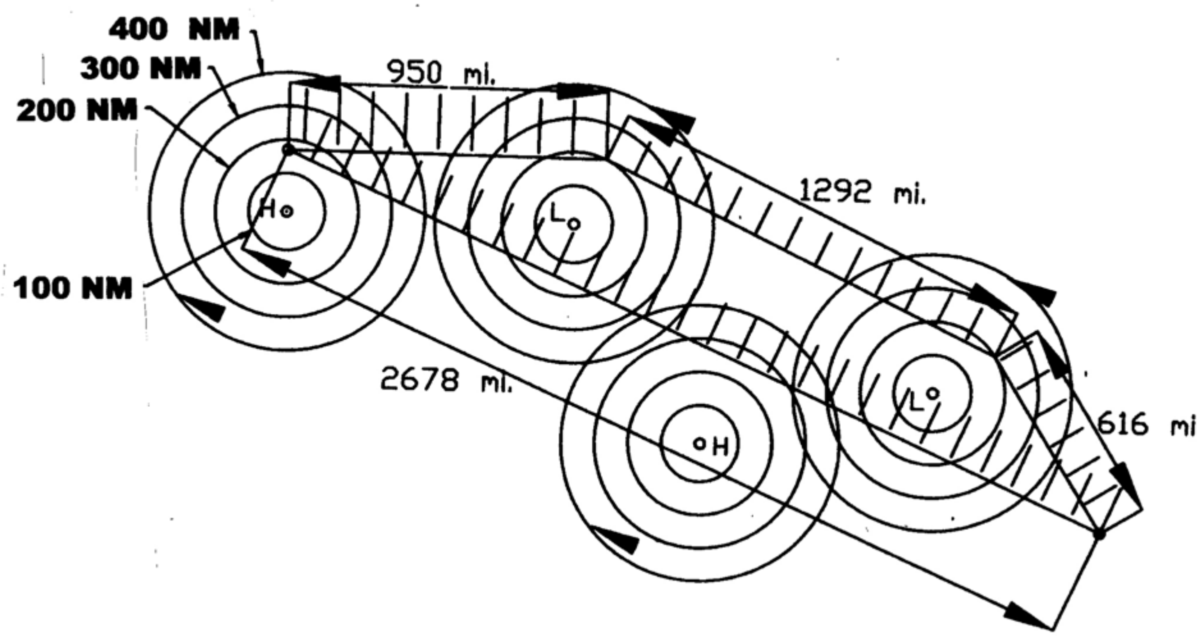


Fig 89: Ride-the-Wind; GS Optimization via Pressure System Method

The manual E-6B is the favored & logical tool for determining GS as impacted by W/V during the preflight as well as in flight. With so many possibilities, the fastest & easiest serious analysis would be an E-6B emulator found on the internet. Simply type in " E-6B emulator" & several options will appear. Some will be easier to use than others; by allowing the change of only one or two parameters, rather than requiring all parameters to be entered with each change. The small hand held electronic E-6B is also an excellent option.

Obviously the best way for such a complex analysis would be a special purpose computer program. A computer crash resulted in the loss of a program that the author wrote to simplify & expedite the solution of the Constant Heading Mean GS Optimization (RTW) method.

For the purpose of this example assume that the best winds for the route are at the constant altitude selected. Also assume that the pressure gradient & W/V are equal for all 4 weather systems, except for the reversed direction for High vs. Low pressure systems. An example is:

Parameters:

2678 NM direct route.
Selected route total distance = 2858 NM; 180 NM longer.
Four pressure systems as labeled; H or L,
Each circle represents a 10 kt step from 10 kt at outer ring, 20 at next, etc.
TAS = 100 or 150 kts to compare the impact of TAS with the benefit of "Ride-the-Wind"
W/V for either route could be carefully analyzed to determine the mean value; or simply estimated, per the below.
For simplicity, in this case only, assume that the crosswind components cancel out, so are negligible for most of the altered route.

100 TAS Case:

GS based on zero wind for direct route, 100 TAS for 2678 NM will require a total flight time of 28:47.
GS; 25 average headwind component, direct, 100 TAS; 75 GS; 2678 NM will require a total flight time of 35:42
NM flown per leg, average track component of wind, average GS per leg, total time flown using RTW method, & time saved:

616 NM at 10 kt tailwind + 1292 NM at 20 kt tailwind + 950 NM at 25 kt tailwind for:

616 NM at 110 kt GS + 1292 NM at 120 kt GS + 950 NM at 125 kt GS for:
5:36 + 10:46 + 7:36 = 23:58 total flight time.
119 actual average GS for 2858 NM actually flown.
112 effective average GS based on 2678 NM of direct route.

Time saved with RTW method: 35:42 - 23:58 = 11:44; or 33%

150 TAS Case:

GS based on zero wind for direct route, 150 TAS for 2678 NM will require a total flight time of 17:51.
GS; 25 average headwind component, direct, 150 TAS; 125 GS; 2678 NM will require a total flight time of 21:42.
NM flown per leg, average track component of wind, average GS per leg, total time flown using RTW method, & time saved:

616 NM at 10 kt tailwind + 1292 NM at 20 kt tailwind + 950 NM at 25 kt tailwind for:
616 NM at 160 kt GS + 1292 NM at 170 kt GS + 950 NM at 175 kt GS for:
3:51 + 7:36 + 5:26 = 16:53 total flight time.
169 actual average GS for 2858 NM actually flown.
159 effective average GS based on 2678 NM of direct route.

Time saved with RTW method: 21:42 - 16:53 = 4:49; or 22%

Whether flying a high or low speed plane, the RTW method can save a considerable amount of time vs. the direct route, even though the actual distance covered was in this example 180 miles longer than the direct route.

In this example, even a 200 mph plane would benefit from RTW. The analysis & necessity of alters increases the Aero Navigator work load. Savings obviously depends on the relative values involved. If the alters were to add an additional 30% to flight distance the direct route may be preferred.

4.25 Doppler Radar as an Aero Nav System

4.25.1 Background

A change in the frequency of a wave observed at a receiver, when either the source or observer is moving relative to the other, results from the addition or subtraction of the movement speed to-from the sonic speed. The effect was discovered in 1842 by C. Doppler, and verified in 1845 using sound waves with experiments conducted with a moving train.

4.25.1.1 Fig 90 shows that a 500 Hz frequency horn sounds like a 510 Hz to an observer standing in front of a car that is moving at a fixed speed that is a small portion of sonic speed. It also illustrates that the initial delta F would be doubled for the reflected sound (delta F = frequency difference between the true & apparent frequencies; or between the two apparent frequencies). Thus the frequencies of 500, 510 & 520. The relative speeds cause the horn output to compress the sound wave slightly to 510 Hz frequency. The delta F is 10 Hz.

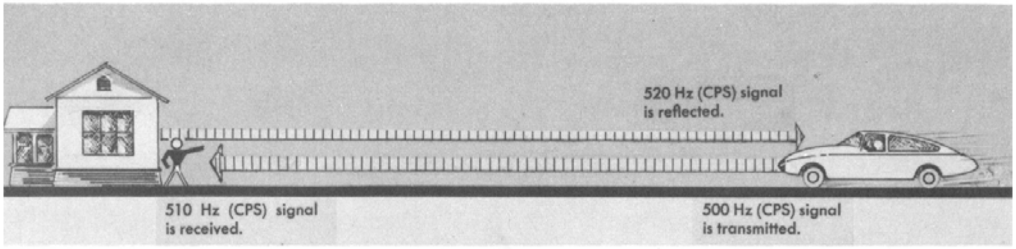


Fig 90: Doppler Effect Demonstration with Apparent Frequency Change as Car-Horn Moves

The reflected sound would be at 510 Hz, but as the car approaches the reflector the same delta F (frequency change) would result; to add the delta F again, double the original delta F, for a return frequency of 520 Hz.

When the sound source is moving, a return reflection from a stationary object results in what is called "Double Doppler shift". When the emitting source is stationary & receives its echo from a moving reflecting surface it is also called Double Doppler shift.

The Doppler effect applies to all types of natural wave motion, including electromagnetic, light, and sound.

Bats are not the only species that use the Doppler effect very effectively to locate & intercept prey & avoid obstacles. They somehow sense the speed of such movement, & identify various locations by listening for the echoes of their emitted whistles that reflect off of obstacles. The ability to interpret pitch changes as speed differences & distances is a mystery. To man, the application of the Doppler effect is highly "technical".

Meteorologists study Doppler radar returns to monitor the movement of storms. Doppler detects the direction and speed of raindrops, hail, & even wind. It is thus possible to predict weather patterns, sometimes hours in advance. The police use sophisticated electronics to interpret Doppler radar returns & compute information that the bat instinctively determines.

4.25.1.2 Fig 91 also facilitates the understanding of the Doppler effect. The approaching train adds to the speed of sound to give the appearance of a higher pitch or frequency. When the closing speed drops to zero the true pitch is heard. As the train moves away, its forward motion slightly expands the wave length of the sound, and the observer abeam of the track hears a lower-than-true pitch. This is an example of "Single Doppler shift". A simpler explanation is that as the train speeds ahead from left to right each successive sound wave is emitted slightly farther ahead on its path. The waves, though still spreading in all directions at a constant speed, no longer share a common center. They crowd together in front causing a higher frequency. Behind the train the distance between the waves is stretched, the frequency is decreased, and the pitch is therefore lowered.

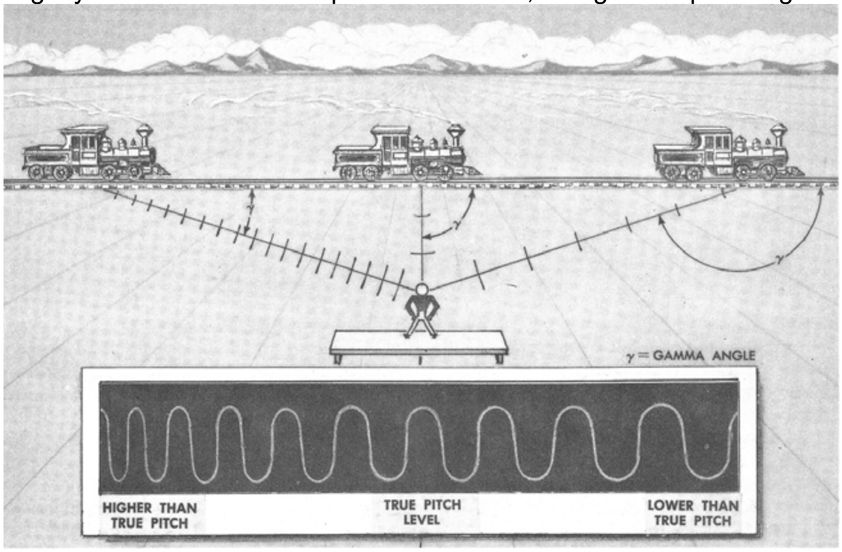


Fig 91: Doppler Effect Demonstration with Moving Train Horn

4.25.1.3 A third illustration shows groups of concentric circles representing uniform radiation from the sound source. The left half of Fig 92 shows concentric circles that represent uniform frequency & sound waves radiating from a stationary horn. The right hand circles illustrate the effective frequency change as sound radiates outward from a moving horn, the center of which is represented by the series of small dark circles following the arrow. Frequency heard from point "A" is higher than at the true frequency at "A' ",& even higher than that at point "A" ". Soon after man first flew beyond the departure "airport" he realized the need for identifying landmarks &

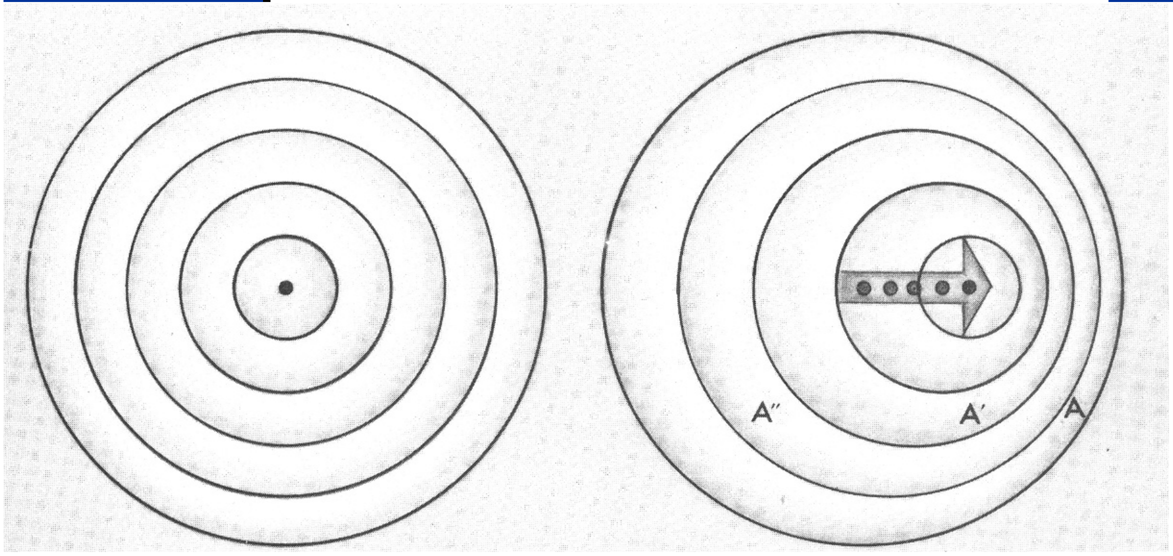


Fig 92: Doppler Effect Demonstration with Fixed & Moving Noise Sources

correcting for the wind. After he added a compass, he found that if he flew an hour due West, & reversed heading, it did not necessarily take exactly an hour to return. He also discovered drift. He then began searching for a way to determine aircraft groundspeed and drift angle. As flying evolved, he occasionally flew above the clouds. He searched for a way to predict drift & GS. DR became an important issue in flying, but there was no precise way to correct for wind effects; especially without reference to the ground. Various models of the driftmeter provided only a partial answer to the problem. An excellent breakthrough came with Doppler radar.

4.25.2 Theory

4.25.2.1 When a sound source moves toward the observer the speed of travel adds to the sonic speed to increase frequency proportionally, & vice versa.

The change in frequency resulting from the Doppler effect is a function of the sonic speed & the velocity of the target. From this relationship it is possible to determine the velocity of the target since the frequency change can be measured & the speed of sound (& thus radar propagation) are known. Specifically the relationship is:

$F_2 = F_1(1)(+ \text{ or } -)\ V_V/V_S)$
where F_1 = True frequency
F_2 = Apparent frequency
V_V = Speed of Car
V_S = Speed of Sound
Sign; + for Approaching & - for Separating

In the case of the car of Fig 90, transpose the equation to: $V_V = (F_2 / F_1 - 1)\ V_S$
Solving this equation to determine speed of the car:
$V_V = (510/500 - 1)\ V_S = 15.36$ mph

Applying the basic equation to a 60 mph approaching train with a 600 Hz whistle frequency:
$F_2 = F_1(1 + V_V/V_S) = 600(1 + 60/768) = 647$ Hz
or for a train moving away: $F_2 = F_1(1 - V_V/V_S) = 600(1 - 60/768) = 553$ Hz

4.25.2.2 Doppler Radar operates at the speed of light rather than the speed of sound.
Multiple Doppler beams projected forward, aft, or to either side can be compared with beams with opposing orientation to provide lateral or longitudinal speeds; GS or drift. These speeds can then provide velocity information. A Doppler beam pointed off of the vertical will sense plane speed by interpreting the altered frequency; different than that emitted.

4.25.3 Accuracy & Efficiency

The Doppler is a very precise system for supporting DR, but it does not provide fixes per se. Thus its accuracy is only in providing precise wind information.

Doppler is efficient because it provides the Aero Navigator with continuous, instantaneous, accurate readings of groundspeed and drift angle, regardless of how erratic the headings may be, at any altitude or TAS, under any type of weather, above or below clouds, over land or water, day or night, anyplace in the world.

4.25.4 Application

4.25.4.1 Change of wavelength caused by motion of the source can be measured & interpreted to determine GS & drift, if antennas are appropriately oriented.

Doppler is a logical variant of conventional Radar.

Aircraft equipped with Doppler & other self-contained systems can operate anywhere in the world without the assistance of ground-based aids. Thus they permit Aero Navigation without regard for any modern external Aero Nav systems or navaids.

Drift angle alone can significantly improve the viability of DR. Drift angle is an integral part of a Doppler navigation Radar.

4.25.4.2 Fig 93 illustrates the 4 beam Doppler beam system. Each beam is oriented 20° forward (or aft) of the vertical centerline (axis) of the plane, & also 20° off the longitudinal axis; off nose or tail. The Doppler Radar system would very likely weigh more than the payload of the very small homebuilt plane shown, & require 400 HZ electrical power, which the small plane would not conveniently offer.

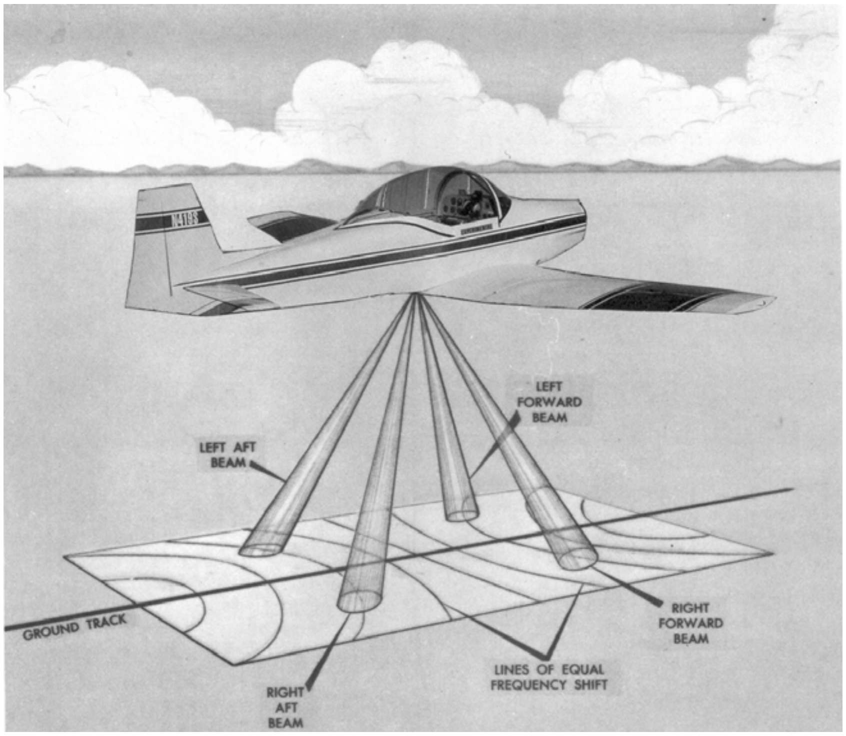


Fig 93: Airplane with a 4 Beam Doppler

Three beam Doppler system beams are oriented the same as the 4 beam with one forward beam omitted.

4.25.4.3 The 4 beam Doppler system measures 4 different frequencies to determine delta F values per the below to establish GS & drift. Groundspeed is measured by comparing frequencies from the forward Doppler beams with frequencies from the aft beams. The delta F value is converted to groundspeed.

Drift is determined by use of a different analysis involving delta F. The delta F_1 is determined between the right forward and left aft beams. The delta F_2 is determined between the left forward and right aft beams.
If delta F_1 = delta F_2 , the drift is zero.
If delta F_1 > delta F_2 , drift is to the right.
If delta F_1 < delta F_2 , drift is to the left.

Drift is then applied to TH to obtain TC.

The 3 beam Doppler analysis is similar, with a single forward beam.

4.25.4.4 The Doppler system transmits an inaudible electronic pulsed beam of radar toward the ground. The beam is transmitted at a known angle "y" from the direction of aircraft travel. Not all radar energy reflects back to the aircraft. In airborne applications the Doppler system moves, & the ground is fixed, similar to that in Fig 90. The frequency of the radar energy returned to the aircraft is obviously increased by Double Doppler shift. The delta F of returned radar energy is proportional to GS.
Doppler was used extensively before GPS & other superior Aero Nav systems became very popular. It remains in use in the military, & on helicopters; the latter primarily to improve holding of position when hovering.

4.26 Inertial Navigation

4.26.1 Background

The Jet age speeds demand resulted in improved Aero Nav systems resulted in a state-of-the-art system called Inertial Navigation. It is a very sophisticated, high precision Aero Navigation system, although without any capability of a positive fix; much like DR & Doppler.

Inertial Navigation & Doppler rely on other Aero Nav systems to provide positive fixes. Both are essentially DR systems, but use entirely different approaches to support DR.

Inertial navigation is based on the concept that all changes in direction or speed could be measured to determine position changes if instrumentation is sufficiently precise.

Inertial navigation utilized acceleration measurement, as derived from Newton's laws of motion.

The basic theory was known for decades before sufficient precision was attainable.

4. 26.2 Theory

The inertial navigation system is based on the theory that if position, direction & acceleration are very precisely known, it is possible to apply DR to plot successive positions. With sufficiently sensitive sensors, & measurements DR can establish position very precisely. With the addition of automation, position updates can be instantaneous & continuous.

4. 26.3 Accuracy & Efficiency

Inertial navigation is an exceptionally precise method of flying DR, & if high quality fixes are occasionally available, the overall track (TC) record will be very accurate, regardless of how erratic the headings may be.

Its similarity to Doppler is that both provide the Aero Navigator with continuous, instantaneous, accurate readings of groundspeed and drift angle, at any altitude or TAS, under any type of weather, above or below clouds, over land or water, day or night, anyplace in the world. Thus, inertial navigation is also highly efficient.

4. 26.4 Application

An advantage of the Inertial navigation system is that it is completely self-contained.

4. 26.4.1 The most critical portions of an Inertial navigation system are the accelerometer & gyro-stabilized platform.

4. 26.4.1.1 An accelerometer performs a critical a critical function in an Inertial navigation system.

A simplified explanation of the operation of an accelerometer is the measurement of displacement distance of a ball of known mass, hanging on a string of known length, with recording & analysis capability. Displacement is a response to an acceleration force. These values are measured with extreme precision. Turns & changes in airspeed result in measurable acceleration.

With knowledge of the mass of the pendulum and the amount of the deflection, the acceleration of the aircraft can be computed. Multiplying acceleration by time provides velocity. Multiplying velocity by time nets distance traveled during acceleration.

After acceleration ceases, speed is constant & the pendulum returns to the state of equilibrium.

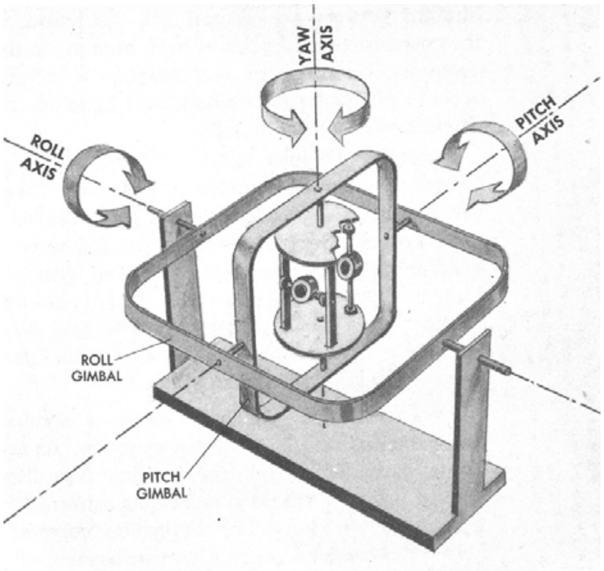


Fig 94: Inertial Platform Gimbal

A disadvantage of the accelerometer is its inability to separate acceleration induced displacement from gravity related errors. This concern is eliminated by use of a high precision gyro-stabilized platform which is capable of precisely maintaining the vertical axis. This is acceptable because modern accelerometers are so very sensitive that an apparent acceleration indication is only caused by gravity if the accelerometer is minutely tilted away from vertical.

4. 26.4.1.2 The gyro is the heart of a stable platform, which is absolutely essential for a precision inertial navigation system. Fig 94 is a greatly simplified illustration of the gimbal system that supports & aligns the gyro stabilized platform. This gimbal system is stabilized by three high-precision gyros. Each gyro stabilizes one axis; pitch, roll or yaw. Some gyro stabilized platforms are limited to very small angles from the nominal pitch & roll axes orientations. Some are unlimited in orientation, so would accurately track a fighter plane even with rapid large angle attitude changes about all three axes during air to air combat.

4. 26.4.1.3 Doppler is sometimes used to level the stable platform initially in flight. In many inertial systems, it may be used to periodically check the platform for accuracy throughout the flight. Initial leveling takes 20 minutes & is performed by comparing Doppler with accelerometer. If these velocities differ it indicates a tilt of the platform. From that point on the inertial unit will be sufficiently accurate for a limited time without any further monitoring.

4. 26.4.2 Update by Fix

Because Inertial Navigation systems merely perform DR, even infinitesimal errors accumulate & may eventually become excessive. Error sources include accelerometer imperfections, gyro drift, and computer errors. Some means of updating the inertial navigational system must be implemented. Without some means of updating the inertial platform it will drift off eventually. Data from any Aero Nav system capable of providing a positive fix can be manually, or preferably automatically input into the inertial navigational system to update or correct it. Some Aero Nav systems that are occasionally linked to the Inertial Navigation system are:

Super Celestial
Automatic Astrotracker.
Navigation Radar
LORAN
GPS

OMNI could be, except that inertial navigation systems are normally for transoceanic operations. Also, error increases with distance from the VOR. NDB is similar in that respect.

Any combination of these may be used, if appropriate.

The Astrotracker is an advanced celestial nav system that was integrated into the inertial navigation system in the mid 1960s to provide high precision position updates. It was discussed under the heading of Super Celestial & Automatic Astrotracker; the two Aero Nav systems were combined under Aero Nav system No. 22.

4. 26.4.3 In theory, there is no limit to the accuracy of an inertial system. Manufacturing precision and design are the only factors that limit the system accuracy. Absolute perfection is, however, impossible.

4.27 Submarine; Although Not Aero, There is Enough Similarity (including the Third dimension) & Technology to Justify Inclusion.

4. 27.1 Background

Submarine nav on the surface, & especially underwater requires unique nav systems (some state-of-the-art) & abilities. Submarine nav utilizes all available, practical nav systems. Of necessity, since Subs are primarily weapons of war, nav systems must operate in the stealth mode, & minimize risk of detection, including all outgoing signals, or noise. This is important even during times of peace. The use of outgoing energy, such as SONAR (acronym; for sound navigation and ranging), is minimized. Some nav systems used for other modes are also modified for stealth. The author was occasionally surprised to hear of "unexpected" Sub Nav systems as he discussed them with a retired Nuclear sub commander friend. It was made very clear that the information discussed was all unclassified.

Background & theory of most systems were discussed previously, but not SONAR. SONAR is essential for submarines for several reasons. Nav is only one of these uses.

4. 27.2 Theory

Submarine nav theory is as stated above. Theory of all applicable Aero Nav systems apply, except that all possible measures must be applied to improve stealth operations. Thus exposure above the surface must be limited.

SONAR has not been discussed previously, but is the most important sub nav system in most cases, except that Inertial nav is essential for making possible DR. SONAR is capable of measuring the speed of a sub relative to the water, or to the bottom; or in fact, velocity. Speed is obviously vital to nav.

SONAR work very well underwater. SONAR is a sound based system that is sometimes described as underwater Radar. It is used for underwater echo location & analysis of shapes, & distance from bottom profile & objects. SONAR is used in both active & passive modes. Sound propagates in water with its long wavelengths.

4. 27.3 Accuracy & Efficiency

Accuracy is the same as when used for Aero Nav except that some systems are the ultimate for its type; money is no object when saving American lives whether on ships or the sub; or even entire cities. Per Aero Nav system No.22, the Super Celestial system used for subs is actually accurate to 300 ft, as opposed to the norm for celestial of closer to 1 mile.

4. 27.4 Application

4. 27.4.1 The entirety of submarine nav is to obtain the most accurate possible position continuously, or at least for 1 instant in time, with minimal risk of disclosing location or exposure.

Reviewing the list of Aero Nav systems the following systems may apply to subs:

- DR
- Map Reading
- Celestial
- NDB
- Radar (when surfaced only)
- SONAR
- Drift measurement
- Super celestial
- LORAN
- Doppler
- Inertial
- GPS

4. 27.4.2 Inertial navigation

Inertial navigation is the primary sub nav system, since most others require surfacing; potentially in enemy territory.

Inertial nav is easier with the stability of a sub than that in an airplane which is subject to turbulence & rapid control movement. Ask any SCUBA diver how very smooth it is just a few feet under a rough ocean surface. The large mass of a sub combined with the resistance of water inherently stabilizes the sub much more effectively than the enormous mass of large surface ships. The author once demonstrated the stability of mass (Newton's Law; objects in motion tend to continue moving & those that are stationary tend to remain stationary) by carefully stepping onto a massive rope that moored a barge beside the Houston Ship Channel. Nothing happened, even with the leverage of a taut rope. See Note 1. After several minutes, movement was barely detectable, at which point he stepped off of the rope. Eventually the barge bumped the pier. This also illustrated, to a lesser extent, the resistance of water.

Note 1: Given a 15' long rope & a total sag upon initial load application of 3", the multiplication factor is 30 to 1. A 150# man would apply a 4,500# tension on the rope; or side load on the barge. Until the barge began to move, the 4,500# resulted in zero horsepower, like a jet engine when brakes are locked.

Inertial nav is, in fact, a vastly sophisticated DR system. Inherent drift of the Inertial nav system must be corrected by some other nav systems. DR is always essential unless another nav system provides a continuously updated position; an infinite number of fixes for any trip.

4. 27.4.3 Celestial

Manually operated & held sextants would be impractical for subs. The Astrotracker would be little better. The old WWII vintage periscope sextant shown in Figs 38 - 40 is capable of viewing only one star at a time through a1-3/8" in diameter shaft. It may have been practical for a pre nuclear sub, but not with increased concern for stealth; & the increased intelligence gathering ability of modern systems.

A moderate increase in size, & significant increase in complexity, permits the Super Celestial system to view the entire sky. Near instantaneous collection of data on as many as 11 stars simultaneously; even during daylight hours, with a fully automated computer based system permits obtaining a fix with very brief exposure for wartime operation. The updated inertial navigation system can operate with minimal error for several days. Time of exposure is important in wartime, so the very short collection time is essential.

Signature type RADAR, such as is used for space applications, including re-entry vehicles, is one of several types of Radar that is capable of detecting periscopes & even small nav or com antennas that protrude from the surface of the sea. Exposure above the sea surface of such antennas is limited to only a few seconds when there is a potential of enemy surveillance.

4.27.4.4 SONAR

SONAR frequencies vary from very low (20 Hz) to extremely high (10 MHz).

There are three forms of SONAR in use by subs:
- Active; high power
- Active; extremely low power
- Passive. No outgoing signal whatever; only sensing natural or manmade noises. These may be compared with an IR (heat) sensing night scope vs. one that emits light only in the IR band to illuminate ambient temperature objects.

Conventional high power SONAR can provide information on surface ships, friendly or enemy submarines, mines, sea-bottom mountains, & obstacles such as oil drilling or pumping platforms.

The ping of conventional (high power) active SONAR is very useful, but it is impractical for stealth operations.

Even extremely low power SONAR systems are capable of sensing bottom profile for "map reading".

Reflectivity of target materials differ, & provide valuable signature information to the active SONAR operator. The steel hulls of a surface ship or submarine are easily distinguishable from the ocean floor or other objects.

Map reading is used by subs for surface nav primarily by use of conventional marine visual markers; buoys lighthouses, & other marine nav markers.

For stealth operations an exceptionally low power SONAR, directed downward, may be used with reduced risk of detection.

Passive SONAR detects radiated energy, which also has unique characteristics.

Map reading seems practical if the bottom profile is adequately known. Since light penetrates water very poorly, viewing of the bottom would be nearly useless even if large portholes were provided. The author was stunned when his bright orange dive vest appeared to be deep purple at a depth of 90'; one reason he prefers 30'; for its color & beauty. As depth increases, it becomes darker & color recognition degrades rapidly. Color is lost because of filtration, similar to the atmosphere. Bottom evaluation by use of the limited field of view of a periscope would be impractical.

A SONAR variation of map reading is practical in subs, much like Radar map reading is in the air. A SONAR analysis of the bottom profile is automatically matched to the map in the onboard computer data base. This is much more sophisticated, but vaguely similar to an autopilot flying a plane by reference to VORs, LORAN, or GPS signals & preselected flight path. The computer is much like GPS in that its data base contains maps of the world, with precision profile areas, as well as the less detailed ones.

Who would map the ocean floors? It is important to many marine enterprises, as well as subs. Even the National Geographic magazine published a distinctive vertical profile map of the Atlantic Ocean floor as shown in Fig 95. This map appeared in the June 1968 issue of National Geographic as a supplement to the map of the Atlantic, & is published with their permission. Scattered very small areas are mapped to an extreme level of detail & accuracy & serve to calibrate sub nav systems, & update the inertial nav system. Details & locations are classified.

Hydrographic surveying techniques have been employed to map the ocean bottom contours. In some areas this has been limited, but in a number of areas the contour mapping was accomplished to an extreme; exceptional precision & resolution. Fathometers were used for portions of the contour mapping.

Subs update their inertial nav systems by use of the "extremely detailed bottom contour maps". These maps are not manually interpreted, but by use of passive or active SONAR. Bottom topography measurement is critical for deep water sub nav. Subs have occasionally collided with undersea mountains, other subs, or surface ships when SONAR was not active.

Drift, like in a plane, is measured when appropriate. Sonar is capable of measuring drift.

For reasons of stealth, subs use an exceptionally low power SONAR for bottom observations when possible.

Single frequency SONAR Doppler effect is capable of measuring the speed of a target; or of the sub.

4. 27.4.5 Influence of Water on SONAR

Water pressure affects sound propagation. When vessels move through water, they pressurize it somewhat, which increases the speed of sound in the immediate area. This results in the sound waves refracting away from the area where the speed of sound is higher. The mathematical model describing the sound waves refracting away from the area of higher propagation speed of refraction is termed "Snell's law".

A SONAR target is generally small, so the reflected signal is very low in power density. SONAR energy, like Radar, is weakened per the inverse-square law; both outgoing & returning. Even a very sensitive detector would only be able to sense a return echoes at a moderate range. Conversely, the original signal would have a much higher power density, even though it too was impacted by the inverse-square law (only once) so it can be detected by an enemy at many times the range of the sender (SONAR). If the range is 100 ft, the inverse-square law would reduce the power density at the target to 0.001 of the SONAR output, & the return echo power density would be 0.001 times that at the target.

Ocean water can experience thermoclines, which causes refraction. This Curvature deceives SONAR.

Noise and reverberation both limit the performance of active SONAR. Depending on circumstances, one of the two will dominate.

If noise dominates, conditions at initial detection is described by the following equation:

$S - 2P + T - (N-G) = D$
where S is the sound level, P is the propagation loss, T is the signal strength at the target, N is the magnitude of the noise, G is the system gain , & D is the detection threshold. Absorption impacts propagation.

If reverberation dominates, conditions at initial detection is described by the following equation:

$S - 2P + T = R + D$
where all factors are per the above, with the addition of R, which is the reverberation magnitude.

SONAR Performance is affected by variations in the speed of sound . The speed of sound in water is related to the bulk modulus and mass density of the water. The bulk modulus is impacted by temperature & impurities (if any), and pressure. At the temperature ranges of sea water the density effect is minor. The speed of sound (in feet per second) is approximately:

$K_1 + K_2 \times T + K_3 \times D + S$
where $K_1 = 4388$, $K_2 = 11.25$, T + temperature in degrees F, $K_3 = 0.0182$, & S = salinity given in parts per thousand.
4388 + (11.25 × temperature (in °F)) + (0.0182 × depth (in feet)) + salinity (in parts-per-thousand).

4. 27.4.6 LORAN; Vital for Sub Nav.

The sub can cruise underwater while trailing a long LORAN antenna wire very near the surface to obtain a fix with an accuracy of 60'. There is so little optical or radar signature of the LORAN antenna that the sub position is relatively safe from enemy detection. LORAN is a very valuable asset in that it offers an accurate fix with minimal risk of detection.

4. 27.4.7 GPS

Fig 95 Ocean Floor Mapping

Much like aircraft type GPS except that the collection time must be extremely limited. That is one beauty of the GPS. Acquisition of aircraft & automotive time is very short. It would seem that that time could be radically reduced when cost is not an issue.

4. 27.4.8 Doppler

Doppler, being Radar is not practical underwater, but SONAR does use the Doppler effect.

4. 27.4.9 Drift Measurement

The author has little information on drift measurement, but it is available with any nav system that offers frequent fixes. A major value of SONAR is that it can measure drift directly.

4. 27.4.10 NDB The author has no information on the ADF (or NDBs), but it seems that it would be possible. It would, however, take a large, compared with periscope size, loop antenna. Since LF & standard broadcast transmitters are so powerful it would seem possible. Accuracy would be limited by the standards of other sub nav systems.

4. 27.4.11 . Radar transmits electromagnetic pulses in very short wavelengths, which is rapidly absorbed by water. Saltwater is also a good conductor, & its absorbtivity exceeds its transmission of Radar electromagnetic energy. The dielectric constant of water is also inappropriate for Radar propagation, so underwater Radar is simply not practical.

4.28 Space; Although Not Aero, & Not Exactly Navigation, Space is accepted as the Last Frontier for "Aviation"

A Disclaimer: This is one form of Aero Nav that the author knows very little about, & has minimal comprehension of, but it seemed important to include the "final frontier" of navigation. Hopefully the below may be somewhat informative. A few discussions with Engineers who do understand such things as Orbital Mechanics did lend some credence to the following.

4. 28.1 Background

Of hundreds of examples of Spaceflight or rocketry, a few seem too interesting to neglect:

In 1232 AD the Chinese used rockets against the Mongols.

In 1926, an American named Goddard launched the first liquid-fueled rocket in New Mexico. He laid the foundation for a technology that would eventually take man to the moon and beyond. Fueled by liquid oxygen and gasoline.

During the 1940s the 46-foot German V-2 became one of the best known of all early missiles, with a 1,650 pound warhead. It also used alcohol and liquid oxygen fuel.

On October 14, 1947, Chuck Yeager became the first person to break the sound barrier in a rocket powered airplane, although a few WWII fighter pilots had brief, puzzling encounters with control reversal at transitional speeds.

In April 1961, Russian Cosmonaut Yuri Gagarin was the first man to experience spaceflight, although he actually bailed out at mission end since the spacecraft had no chutes of its own.

In May 1961, Alan Shepard, was the first American to make a Suborbital spaceflight.

In 1962, an Atlas rocket successfully carried John Glenn on an orbital flight aboard Friendship 7. On that flight they temporarily lost all communications because of an unanticipated electrical characteristic that caused all a great deal of concern.

In the mid 1960s NASA showed a classified movie (eventually released) to a variety of "Optical Engineers & Physicists" who were considered to be optical experts. The conclusion of most (all in the author's small optical Engineering group) was that the Russians had definitely faked the first known space walk. The assumption was that the space walk had taken place, but that the Cosmonaut had been killed on his return to earth, & a substitute was available for interviews.

In the late 1960's NASA began a series of missions to the moon. The astronauts initially explored the moon on foot only about 1,000 feet around their spacecraft. On the last three missions, they drove a small electric Lunar Rover, that permitted them to explore much more of the moon. The Lunar Rover was fitted with a directional dish type communication antenna. NASA issued an invitation to a series of "Optical Engineers" of repute to submit a design for a sight that would permit easy pointing of the antennas toward the earth. The author made 3 prototypes of his design (by hand) for his optical sight that was selected from among 8 competitive designs that were submitted to NASA.

John Young flew the first Space Shuttle in 1981. It was noted that he had a very low heart rate during that very high risk flight. The author was among millions who probably had much higher heart rate as they observed it on TV than John Young. The Space Shuttle made many highly successful launches after that, with two tragic endings.

Without the capability of positioning GPS satellites in space, one of the finest Aero Nav systems ever developed would never have been possible.

In June 2004, SpaceShipOne made the first ever privately funded manned space flight. This space plane was built by a private American firm & won the 10 million dollar "Ansari X Prize", similar to that won by Lindbergh.

Many thousands of beautiful photos have been taken from space over the decades. Among the most fascinating were actually published during Colonel Jeff Williams' second 6 month long stay; this time as commander of the ISS (International Space Station); ending in March of 2010. Among the several degrees that Col. Williams has earned was a Masters in Aero Engineering. Col Williams is a personal friend of the author & his wife. He has flown 2,500 hours in 50 types of planes, & has spent a full year in space. In May, 2000, on STS 101 alone he accumulated 4.1 million miles in 155 orbits of the earth, & performed a space walk. In 2006 he spent 6 months on the ISS. The many fascinating & beautiful photos were taken during his first stay in the ISS. He continued his passion for space photography on his second mission; taking many more photos. His book, entitled The Work of His Hands, was published by Concordia Publishing of St Louis, MO.

4.28.2 Theory

Unlike a plane that can be flown "by-the-seat-of-the-pants" if necessary, it is impossible for an Astronaut to look out of a windshield or side window to estimate distance off course; or to land by judgment of descent rate & altitude above a planet.

The basic ingredients of spacecraft navigation include spacecraft speed, distance measurement, angular measurement, & the "all important" orbit. Trajectory correction & orbit trim maneuvers are important, seemingly mysterious factors. Speed is the term used in this discussion, instead of velocity, since velocity includes direction.

A spacecraft on its way to another planet is in reality in orbit around the sun. The portion of a solar orbit that passes the launch point & also the destination is called the spacecraft trajectory.

4.28.3 Accuracy & Efficiency:

The best of Aero Navigators, or even instrument rated pilots on Precision approaches, never reach the degree of accuracy that is essential to most aspects of spaceflight.

An interesting example of just how critical nearly every aspect of space flight navigation is: A story told by a NASA contractor. An early unmanned exploratory mission to the moon involved several contractors. One contractor computed the assorted values involved, & specified to all involved the importance of all aspects of the inputs. He stated the exact position vector & velocity vector desired upon leaving earth orbit, as well as the point along the earth orbit that a rocket should fire. Someone with another contractor thought he should add a small safety factor, so added a little to the velocity. The spacecraft actually missed the proper entry point near the moon by many miles.

4.28.4 Application:

In the above case where the spacecraft missed the moon, it would be conceivable that rockets aboard might perform corrective rocket blasts. Obviously, had the controllers tried to fire steering & retro rockets to reverse course as it passed the moon, it would not have had sufficient thrust or fuel to do so.

Space nav is accomplished by orbital experts well in advance of the flight, & implemented by computer from the ground. Even corrections when the spacecraft is not positioned or directed correctly are usually implemented by computer.

Orbital Mechanics is not discussed in the usual Engineering terms of speed & direction components of Velocity, but only as Velocity.

Like in Aero Nav, the first step at every point along the flight path is to determine the parameters; position, & velocity vectors. Again, unlike typical Engineering, position is considered to be a vector. Flight path is not as usual.

Each portion of a space flight starts with a position vector & a velocity vector.

If a spacecraft is to approach another spacecraft to engage it while both are in an orbit, the overtaking spacecraft must adjust the velocity to gain on it. Realistically a high rate of closure is desired initially. To increase closing rate, it must be boosted by thrusters to place it in a slightly lower orbit. To change velocity the vehicle must first be oriented for optimum thruster orientation. It is the orbit change that influences orbital velocity; not booster proper. The closer to the earth, the higher the velocity must be to maintain orbit, since the strength of gravity increases as distance decreases. As distance between the two spacecraft decreases, a booster moves it further away from the earth to decrease velocity & thus closing rate. A few of these cycles are complete until the closure rate is tolerable for latch impact.

Unlike aircraft, a spacecraft is unable make large angular heading changes; or "course reversal". At 25,000 mph, the deceleration fuel requirement would be prohibitive. Just to launch the Space Shuttle requires over 6 million lb. thrust initially & nearly continuous thrust until near orbital altitude. It could never carry enough fuel to reverse direction while on orbit at 25,000 mph. Obviously the instant it started to slow, gravity would begin an inevitable pull toward the earth & it would quickly re-enter.

The first Lunar Lander used nearly the last ounce of rocket fuel when it landed on the moon.

In the case of spaceflight, position vector & velocity vector determine the orbit. Only minute changes of orbit are practical; by short precisely measured & directed bursts of thrust using small rocket motors.

Knowledge of the destination planet location & trajectory along the solar orbit & predetermined spacecraft trajectory orbit, are required to establish velocity changes that may be required enroute as the spacecraft drifts "off course" (orbit).

The orbital parameters & inherent motions of the earth, & planets that a spacecraft may be directed toward, are well known. Thus the determination of necessary trajectories must be determined & inserted into control computers. During the flight, measurements must be made along the orbit.

Earth trajectory can be converted into the heliocentric orbital parameters needed to describe the spacecraft trajectory along its route & around the sun. Important measurements of the spacecraft motion that can be made by Mission Control personnel on the earth include:
a. The relative velocity of the spacecraft vs. the earth; measured directly away from the earth. The earth vertical component of the velocity vector is usually much less than the absolute velocity.
b. The spacecraft position in the sky (earth).
c. If the spacecraft is equipped with an optical navigation system, it can send data on the RB (relative bearing) of various other planets & known stars from the spacecraft to Mission Control.
As with any navigation system the above measurements may be repeated as frequently as the systems can obtain & transmit them. The projected mathematical model will then be corrected & frequently updated to create a history of a spacecraft's location in three-dimensional space over time. The navigation history of a spacecraft is incorporated not only in planning its future maneuvers, but also in reconstructing its observations of a planet or body it encounters. This is essential to constructing SAR (synthetic aperture radar) images, tracking the spacecraft's passage through planetary magnetospheres or rings, and interpreting imaging results.

Earth based instrumentation such as Doppler monitor spacecraft position vector & velocity vector & compare that data with programmed trajectory to determine the need for corrections, & the optimum time & place to make such corrections.

Some navigation equipment is sometimes carried on board the spacecraft, such as Radar & optical imaging instruments. Optical navigation involves viewing a planet or body against the background stars.

Tracking type Doppler measurements provide the radial component of a spacecraft's Earth relative velocity, as well as relative to the planet of interest.

Spacecraft range from the earth is converted to range from other planets of interest.

Time of positions, & to reach critical points along the trajectory is very important, & must be determined with great precision.

Spacecraft velocity is determined with great precision to assure arrival at any critical points along the trajectory.

Angular measurements are another way to establish distances & position vector. Although the angular measurements are phenomenal by most standards (arc seconds), the accuracy is inadequate for determining a spacecraft velocity vector spaceflight for navigation for long range flights. Angular are measurements expressed in celestial terms; the angular quantities of right ascension and declination. Doppler shift provides usable distant spacecraft angular position vector, but interferrometry can improve accuracy further.

Interferometry utilizes DSN (Deep Space Network) radio frequency stations that are located many thousands of miles apart are interrelated. These two stations track the spacecraft continuously. Recordings of this data consisting of many simultaneous precision points in time. Both DSN stations are simultaneously directed at a star of known position. This involves triangulation. Data is compared to establish a highly accurate spacecraft position vector within an accuracy of 3 ft.

Differential Doppler is a variant of typical Doppler measurements that is capable of establishing a spacecraft position if it is orbiting a planet of known position. This involves more than one observer noting the Doppler effect (increasing frequency) as the spacecraft approaches & then moves away (decreasing frequency) from the observers.

Factors that require consideration for establishing the orbit of a spacecraft include a variety of different types of data that must be entered into a large computer programmed for complex 3 dimensional solutions. The computer entries must include a data base offering various types of navigation data, details on celestial bodies; including not only position in sky, but also the mass & planetary gravity field models, atmospheric friction, & even solar wind effects.

Even spacecraft orientation must usually be considered. Viewing ports for crew members, cameras, optical sensors, or other instrumentation may require changes in viewing direction. Some portions of the spacecraft may not be able to withstand the severe cold of deep space, or the direct solar heat.

4.29 GPS

4.29.1 Background

The first version of the GPS closely followed the first flight of the Russian Sputnik. Its purpose was multifold, including limited positional information.

In 1957 Johns Hopkins Applied Physics Laboratory researchers proved that they could determine the exact location of the Russian Sputnik satellite by measuring the shifts in the frequency of the transmitted radio signal as it approached or moved away from them; the Doppler effect. Conversely the same concept could permit determining any position on earth if the exact position of the satellite were known. Inadequate accuracy of time keeping systems was a limiting deterrent in 1957.

U.S. military needs for a more accurate & versatile nav system drove the development of a GPS. Time keeping accuracy slowed continued success until the development of the atomic clock, which provided time to an extreme accuracy. Time for signals to travel between the earth & satellites is critical for GPS to function well. The National Bureau of Standards (NBS; since renamed; new acronym; NTIS) in the USA built the world's first atomic clock in 1948 by using ammonia molecules, which have an appropriate resonant frequency. In 1948 the atomic clock was not yet practical. Success eluded Engineers until technological advances eventually resulted in an atomic clock that was satisfactory for GPS.

The first actual devoted GPS satellite was launched in 1978. It was not until 1989 that additional, more advanced GPS satellites were launched, & 1995 until the GPS system was fully operational.. The system grew to 24 & then 30 GPS satellites.

4.29.2 Theory

GPS theory is based on the 1957 Johns Hopkins Applied Physics Laboratory application of the Doppler effect. discovery mentioned under Background in paragraph 4.29.1.

In the U.S., "reference GPS receivers" were positioned at precisely known locations. GPS signals are received by both fixed & moving receivers. The usual GPS receiver uses time differentials to determine position. The reference receivers know precisely their location, so instead, reverse the process, & determine what the signal travel time should be. The difference between measured & theoretical times are applied as a correction factor. With that they can correct the GPS positional data & provide a more exact aircraft position.

4.29.3 Accuracy & Efficiency

Generally accepted GPS accuracy is 6 ft, but there are many factors & even options, as well as counter claims.

Several factors reduce the accuracy of GPS:

- Water vapor in the troposphere reduces propagation speed of GPS signals. Speed change results in distance error
- Charged particles in the ionosphere.
- Multipath, ephemeris errors, & the satellite atomic clocks also contributes to the errors.
- Noise alone can introduce errors of up to 30 ft.
- Atmospheric refraction can contribute significantly to overall error.
- Obstructions such as buildings can cause errors as large as 100 ft.

Methods of improving GPS accuracy are discussed under application.

Most GPS (& LORAN, too) read out in miles, so even 0.1 mile is over 500', & most do not read to hundredths of a mile. So resolution is generally the limit, vs. accuracy.

There is also a disparity in the accepted accuracies of GPS vs. LORAN. The modern panel mounted LORAN is capable of an accuracy of 60 ft, while GPS claims a 6 ft accuracy. Numerous credible comparisons have proven nearly the opposite, operationally. Some credible small commercial marine operators have reported that they can repeatedly return to a point using LORAN with no more than 20% of the error of the widely praised GPS. Published comparisons indicate that a commercial fishing boat could return to within 25' using LORAN vs. 300' with GPS.

GPS can be enhanced for greater accuracy by use of AGPS, DGPS, & WAAS.

4.29.4 Application

4.29.4.1 A typical aviation GPS displays separately or simultaneously a variety of valuable parameters, including:

- A moving map
- An integral CDI
- GS in kts or mph; selectable
- Ground track direction.
- A "GO TO" feature that allows an instantaneous heading from current position to any desired waypoint.
- Distance & course to destination
- Distance & course to nearest waypoint
- Distance & course to any selected waypoint
- VNAV feature; to optimize descent, as with LORAN VNAV
- Altitude above MSL
- Distance off course

4.29.4.2 The GPS is programmable for a large number of routes & way points. This does require effort. Generally each proposed waypoint must be entered by an official designator. That includes departure & destination airport, & each VOR if following airways. If flying a direct route, dog legs may be required to deviate around restricted airspace, large bodies of water, or national borders. If flying low, it may be necessary to deviate to avoid large cities or Class B airspace (surface to 10,000' MSL; or 4,000' AGL for Class C airspace, ARSA). Such dog legs would normally have an imaginary point at which a turn must be initiated. A "user entered waypoint" may be defined for any convenient purpose. The most convenient way to define a user entered waypoint is by direction & distance from the nearest VOR. A convenience of the GPS 195, & some GPSs, is the simplicity of establishing the return route. Simply call up "reverse route". If the GPS is IFR certified, instrument approaches should be included in the flight plan, in case the conditions require an instrument approach. In some cases it may be desirable to assign alter points for a change to an airport with VFR, or higher IFR ceilings & visibility.

Each VOR, airport, NDB, intersection, & some official intersections-alter points are available as GPS waypoints for use in Aero Nav. Victor airways & especially arrival & departure procedures (see Aero Nav system 30) identify pertinent points along a flight path, including alter points. Intersections are often where two airways intersect. Some cross; others simply join & terminate at that point. Alter points are typical in congested or mountainous areas to relieve congestion or avoid obstacles, such as mountain peaks. East & SE of Albuquerque V68, V291 & V 60 airways detour around some higher peaks. That portion of the ABQ chart is not shown in Fig 12. Likewise, the Kansas City, MO chart is referred to elsewhere, but not shown. There are several alters around the periphery of Truman A, Truman B, & Truman C MOAs (military operating areas). These simply expedite traffic as much as is reasonable around Whiteman Air Base from which the B-2 bombers flew many nonstop bombing missions to & from Iraq; amazing distances. Further West the same chart shows Victor 508 departing the TOP VOR near Topeka Kansas on a 288° radial for 20 miles before altering to a MC of 252° to MHK VOR. Nearby V 307 heads at 327° & alters only 8 miles before passing abeam of MHK VOR, to a heading (actually MC) of 009°.

The GPS data base includes all official airports, navaids, & even frequencies. A typical aviation GPS has a moving map, & offers a variety of features that prove very useful in flight. If interested in landing prematurely & unaware of nearby airports, a convenient feature offers "nearest airport". If that airport lies behind the plane, the next closest may be requested. Once the most likely airport is chosen, additional information may be obtained by a query. Everything available on the chart relating to the airport is available, including runway length & elevation.

Updates of GPS & LORAN aviation data bases need not be updated when Sectionals or enroute charts are updated for VFR flight, although frequent updates are recommended. If certified & used for IFR flight they must be updated every 56 days. IFR certification is possible only for panel mounted GPS units; not handheld. Fig 96 illustrates the Garmin GPS 195; one of the earlier full capability handheld GPS units with B & W moving map. The panel mounted GPS at that time looked much like the LORAN of Fig 86; some did have the addition of a moving map. Later GPS units diversified to include com & often a variety of Aero Nav systems. The more modern portable 7.25" x 5.25" technically advanced Garmin 696 offers a 7" diagonal, 800 x 480 pixel resolution color map. Its features include:

Fig 96: An Early Advanced Handheld GPS; Still Quite Useful

- Weather graphics
- Terrain alerts; & obstacles displayed
- Ergonomic controls
- Approach plates (preloaded; may be enlarged)
- Taxiway maps
- XM weather
- GPS derived simulated instruments

At $3300. each, it sells for over twice what the GPS 195 did when it also represented the latest technology. It is nearly as capable as panel mounted GPS, without the authorization to fly IFR, although it can be used unofficially to support IFR certified avionics. Conversely, OMNI & ADF are easily certified for IFR, & are nearly essential for IFR flight.

Fig 97 illustrates what some might consider to be the ultimate in modern GPS as part of a full glass panel. Some sophisticated technically advanced instruments are actually glass screen images. The only old type mechanical instruments shown in Fig 97 are the critical AS, AG, & altimeter, & they are only for emergencies since they are also represented on the glass screen. Although the claim, & primary object for the new glass cockpit is to reduce pilot work load, this panel does look somewhat overwhelming until each portion is studied. It should reduce workload for heavy jets, but seems to do the reverse for lightplanes. It actually does increase work load excessively. It occupies so much time that there is inadequate time for adhering to the age old critical flight safety commanded "See & be seen rule"; watching for traffic. Manufacturers & users also recommend that it be used only with autopilot turned on simply because the pilot is too busy to fly the plane. Instead of simply turning 1 to 4 knobs to set transponder code, for example, he must first select "transponder function". Then another step. Finally press "buttons" to select each number of the code. In turbulent air it is all too easy to press the wrong button, or hit it once too often, in which case he must start the procedure all over again. Push buttons are not conducive to turbulent air. They do not stabilize the hand when desired, & are too easy to hit accidently. With the conventional transponder (as with conventional Nav com frequency settings) he can select each knob by feel, without looking at them. He can rest his hand on the knob to be adjusted in turbulent air, so there is no need for looking at the knob until ready to turn it. Accidental change of code is very unlikely, & in the unlikely event ov over turning the knob, a simple one detectable click will correct it.

FIG 97: A Modern Glass Cockpit Included GPS & Much More

4.29.4.3 The above mentioned 100' mountain-building induced error is less serious for aircraft than for vehicular applications because of their large terrain clearance. Most important is that the GPS unit have a clear view of all satellites, & that each satellite has a view of the other satellites; not being on the opposite side of the earth.

Three separate systems were developed to improve the accuracy of GPS; AGPS, DGPS, & WAAS.

- AGPS is an acronym for Assisted GPS. It aids GPS in case of poor or even totally blocked reception. It actually obtains information from external sources such as a cell phone tower. A side benefit of AGPS is inherent knowledge of satellite orbit. Since the GPS no longer must establish orbit initialization, response time is reduced.
- DGPS is an acronym for Differential GPS. DGPS uses a fixed tower to relay information to the GPS receiver. DGPS enhances accuracy even more effectively by comparing the fixed location with the satellite, & corrects for the disparity before relaying data to the GPS. DGPS is even more effective when atmospheric attenuation is a concern.
- WAAS is an acronym for Wide Area Augmentation System, which was developed for the FAA, & is discussed in detail in Aero Av system No. 32.

4.29.4.4 Three satellites are considered a minimum, but if those three formed small angles of intercept, the accuracy would be measurably reduced. It is normal to utilize a large number of satellites, although obviously approximately half of the 24 to 30 satellites will be on the opposite side of the earth at any given instant.

Handheld GPS units have integral antennas, so in plane (or car) the satellite viewing area is very limited. They do actually work even under these conditions. An external plug-in antenna with signal cord is much preferred. In a typical lightplane, viewing angles are in the vicinity of 120° vertical & 175° to 230° horizontally if mounted as far forward under the windshield as practical.. This assures adequate reception, although external mount atop the cabin is preferred.

The GPS, like LORAN, has an adjustable GS update to preclude unreadable jittery numeric displays that would result from excessive frequency of updates.

4.30 Instrument Approach

4.30.1 Background

The text in several earlier Aero Nav systems mentioned IFR flying & approaches. Regardless of the Aero Nav system employed, the termination of any flight under IFR conditions is likely to involve an instrument approach.

Jimmy Doolittle's first demonstration of flight without outside reference required considerable skill, knowledge & courage, but it was soon followed by routine IFR flight & landings using the A-N Low Frequency Range.

As technology improved, & new types of avionics were developed, the usefulness & ease of operation facilitated instrument approaches at larger numbers of airports, & to lower minimums.

A typical VFR flight requires a 1,000' ceiling, & 3 mile visibility. In most of the country the FAA allows a 1 mile visibility. An instrument approach allows a landing in considerably poorer conditions, but rarely in zero-zero (fog). It merely improves the possibility of ending a flight under IMC (instrument meteorological conditions) at the desired destination. It does add tremendously to the versatility of an airplane.

That VFR minimum applies for the entire flight., so enroute IFR will require an early landing to wait for VFR weather. There is no legal limit to flying over zero-zero conditions as long as the destination or alternate will have sufficient minimums for the available approach.

Instrument Approach Plates are also now called Terminal Procedures; giving the procedures that must be followed for each type of approach & each airport & runway that has an instrument approach.

4.30.2 Theory

The instrument Approach is a continuation of the IFR flight, with similar tracking methods, & specified turns & altitudes that lead the plane to the runway at a moderate altitude.

Each instrument approach was carefully designed for safe terrain clearance & alignment with a runway at a suitable altitude. If the approach plate calls for flying at a heading of 090 for the descent, & the plane is 180° from the airport, it would neither be safe nor legal to descend while approaching from 180°.

The lower the ceilings, or the shorter the visibility, the more important & practical IFR flying will be.

Flying under IFR conditions is not beneficial unless a landing can be safely accomplished at the destination.

Most Aero Nav systems capable of IFR flight will also provide adequate guidance for IFR approaches.

Procedures were developed & adapted to assure proper alignment with the desired track & glide slope angle. There are several options for each. An ILS provides a distinct 3 dimensional, sloping line in the sky that may be followed to complete a nearly perfect flight. Other methods usually require the pilot to fly at specific descent rate to a specific point before continuing a uniform or interrupted descent.

4.30.3 Accuracy & Efficiency

Earlier instrument approach systems were low precision, but still acceptable. Low frequency range would still meet the needs of Genav if it were still available, & there were no alternatives; as might be the case if the GPS satellites were destroyed by a misguided terrorist.

The other instrument approaches are still active, & some are called "precision" approaches because they are suitable for lower ceilings & closer to the ideal path.

The ILS is extremely accurate. The ILS is a higher accuracy lateral positioning beam than VOR or other approaches. It is also accompanied by a similarly precise horizontal beam. The VOR approach offers no direct vertical guidance, & the lateral accuracy is governed by a beam that is broader in width than the corresponding beam of the ILS. Fig 98 shows the ILS version of the OMNI CDI instrument; or OMNI head.

Specific accuracies of the assorted instrument landing systems are, starting with the system capable of the greatest lateral accuracy:

ILS is the most accurate, considering 3 dimensions, so obviously falls under the umbrella of "precision approaches".
RNP. Described in instrument approach system No. 34. Overall approach accuracy exceeds all other systems.
ADS-B Described in instrument approach system No. 33 is not exactly an instrument approach.
WAAS: Described in instrument approach system No. 32. Positional accuracy nominally 10 ft.
LOC (localizer) The lateral portion of an ILS, except for lack of vertical information. It is not a precision approach only because of the missing vertical information.
LDA. An LDA involves a localizer, but not necessarily a glide slope. It is noted for approaches up to 30° off-centerline.
VOR Lateral information only, with 4 times the error of ILS or localizer.
ADF The oldest instrument approach system that is still in use; moderate accuracy, but quite precise if the NDB is located near the runway.
RNAV The most recently approved instrument approach system except for those described in instrument approach system No. 32 through 34.

If practical it is prudent to select approaches or airports with the lowest minimums in case ceilings are lower than forecast.

Most lightplanes do not have a glideslope receiver, so cannot land using the ILS, or operate at ILS minimums.

Fig 98: CDI - ILS

The ILS CDI is simply an OMNI CDI with the addition of a horizontal needle to provide information on deviation from vertical alignment with the horizontal ILS beam. The vertical needle responds to OMNI, localizer, or ILS signals. The localizer is the same signal that the ILS vertical needle responds to. Thus both OMNI & ILS vertical needle deflect 4 times as far on a localizer approach as on an OMNI (VOR) approach for the same distance (angle) off course. A 1 dot (division) deflection represents 0.5° when flying an ILS or localizer. On an OMNI 1 dot represents 2°. The dots show up much better in Fig 78 (OMNI CDI) than in the ILS CDI illustration.

4.30.4 Application

4.30.4.1 Instrument approaches are now called "terminal procedures" but for this course the old term is retained. The types of Instrument approaches available over the years since Jimmy Doolittle's first demonstration include:

- Low Frequency Range (A-N)

- Standard Broadcast Station - Radio Bearing Indicator
- NDB - Direction Finder
- NDB - Automatic Direction Finder
- GCA - Ground Controlled Approach
- OMNI - VOR
- Localizer Back Course
- VOR-DME
- TACAN; or VORTAC
- GPS
- RNAV
- RNP
- STAR/DP - Standard Terminal Arrivals & Departure Procedures

4.30.4.2 General requirements for all types of approaches

4.30.4.2.1 Before departure; preferably several days before**.**

- Review relevant aircraft & personal records to assure full currency for IFR flight.
- Carefully study anticipated approach plates & all likely options as well as for alternate airport.
- Verify terrain & obstacle elevation along intended route, including high elevation terrain. Note that this information will be on the chart, & also in the form of MEA, MRA, & MCA (on chart, also) to assure a safe flight.
- Verify terrain & obstacle elevation along the anticipated descent path
- Develop a plan for the departure & descent to landing to also assure adequate obstacle clearance.
- Plan descent procedure; such as orbiting instead of direct path if necessary depending on terrain profile.
- Plan approach proper.& safe corridor in which to descend.
- Verify descent minimums.
- Establish initial altitude so that the descent will be uniform & moderate per the values specified on the approach plate. He must know the correct altitude for two or more points along the approach. The pilot will, of course, read MSL values on the approach plate, & the altimeter.

He must check weather; usually several times before & during the flight.

If traffic is heavy at the destination airport he may be asked to enter & remain in a holding pattern at a specified altitude, & descend when advised to do so; sometimes stepping down through several altitudes. The author has very rarely been instructed to hold. Although with the enormous traffic at Airventure Oshkosh he once held at 8,000' in solid overcast for 48 minutes. On an ILS he & another plane were each told to expedite; meaning to speed up to reduce distance behind traffic ahead. A few minutes later he instructed both to make a 360 to the left. Neither knew whether he was following or leading the pair. Since both had increased airspeed significantly they had to slow down as quickly as possible to establish a uniform 2 minute turn. Any imperfections would have meant failure to align with the ILS beam, & possibly a missed approach & conceivably even re-entry into a holding pattern.. The 360 demanded a uniform speed, altitude, & turn rate. An estimated impact of the airspeed variation might have failed, but both pilots apparently estimated well. The author arrived back on centerline to his surprise. As he broke out of the overcast near ILS minimums (MDA) the author & his wife saw a similar plane, half a runway length ahead, at the same altitude. They touched down half a runway length apart. As is the norm at Oshkosh, neither pilot responded to instructions because of the exceptionally heavy traffic. Controllers, in fact, speak rapidly & with negligible delay. Nearly any other place & time the pilot is expected to respond to verify full understanding of all ATC instructions.

In poor weather the pilot may find that he will not see the runway at minimums. At some airports in the Philadelphia (Pa) area it is commonplace for pilots to descend below minimums without admitting it to Approach Control. That is not only illegal, but hazardous. The author & most others have always refused to violate minimums; just as he refused to take off over gross, which a few pilots also do. In fact, at high elevations his wife flew a Piper Tripacer in a flying club, & reported to him that it seemed incapable of adequate performance with only two passengers. After riding with her from a 4,300' elevation field he suggested she not fly it again, or if so, well below max gross weight. She agreed, & thereafter flew 65 hp taildraggers in the club. The little 65 hp Piper J-3 Cub flew fine at twice that elevation, as did their Cessna 140A soon after.

4.30.4.2.2 The typical Communication sequence for instrument departures, IFR enroute, & approaches include**:**

Before departure:
Weather (the author typically started checking weather a few days before a XC flight; & repeated occasionally)
Clearance Delivery
Ground Control
Tower
Departure Control
Center

Enroute IFR:
Center with occasional request to change to FSS frequency long enough for a check on weather

Before landing:
Weather
Center
Approach Control
Tower
Ground Control

4.30.4.2.3 Pilots flying on instruments must be alert for the possibility of VFR pilots who may possibly be flying in marginal weather. He should also realize that VFR plots flying completely wihin the law need to see him. If he reports his position in terms of instrument flying identifiers, those VFR pilots may have no perception of his location. He should report well known locations. Holding patterns or Departure procedure 1-2-3 are not known to VFR pilots. Nor do pilots from another state know where the xyz bridge is. Everyone knows where the airport is; so 6 miles NE; or better yet 6 miles 45° from airport, heading toward airport (usually use airport name or identifier instead of simply airport).

4.30.4.2.4 The instrument approach is one of the more demanding tasks in flying. It is a challenge, & it can be very rewarding; it can even be enjoyable, but it is not the time to check a pilot's handbook to refresh memory on how to perform any necessary activity, or familiarize one's self with the approach plate for the first time. The more the pilot knows about the plane, the avionics & the approach, the safer & more successful he will be.

4.30.4.3 Specific Types of Instrument Approaches

4.30.4.3.1 Low Frequency Range

The low frequency range is no longer used in the U.S., but several components are still important to most instrument approaches. It was a good approach, but the author cannot imagine using such a cumbersome approach; compared with modern options.

The low frequency range offered both enroute & Instrument approach capability. The Instrument approach was more demanding than following an airway enroute, including:

- Situational awareness was more critical & difficult than with more advanced instrument approach systems.
- The lateral position along the airway, & especially on the approach path, required greater precision than enroute flight. More recent IFR tracking & approaches generally have significantly greater precision than the old low frequency range.
- The progress along the enroute, & especially the instrument approach, was even more difficult, & less precise when flying the old low frequency range (A-N range).
- The third dimension, the altitude component, was equally difficult during instrument approaches for pilots flying the low frequency range.

Fig 99 illustrates a typical Low Frequency Range Instrument Approach Procedure that is based on the A-N range transmitters shown in Fig 51. Fig 99 does not show the profile that was a part of any Instrument approach, even in the 1930s.

Figures 48 to 51 illustrate the low frequency range. Fig 51 shows the fan marker that provided adequate position accuracy for safe Instrument approaches. Fig 50 was less definitive, but was also a contributor to Instrument approaches.

Fig 48 A-N Range General Layout
Fig 49: Circular Transmitted A & N with Overlap for Steady Tone.
Fig 50 Cone of silence (also called cone marker or Z marker)
Fig 51: General Layout of Signals Transmitted by an A-N Range Station.

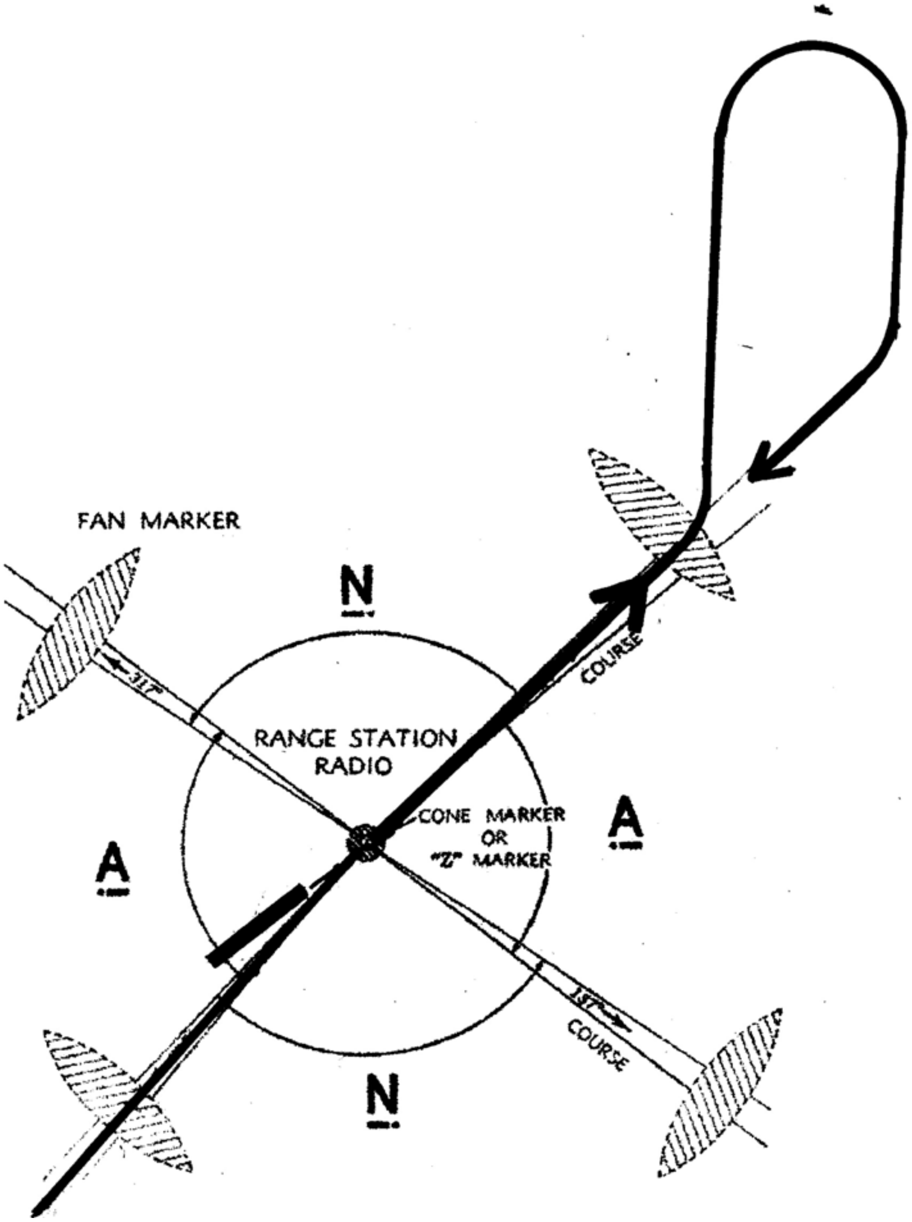


Fig 99: Low Frequency Range Instrument Approach Procedure

In the case shown in Fig 99, the pilot should, well in advance of starting descent from cruise on the Victor airway:

- Obtain from Center W/V (or compute it based on data gathered in flight: TAS, GS, & drift).
- Compute drift, & thus MH from desired MC for each leg of the approach.
- Document each MH (or CH) that is required to achieve specified MC
- Establish initial altitude, & points along approach where they should apply.
- A likely set of altitudes might be as those shown at the below bullets; given in MSL. For simplicity, assume airport elevation is very near SL. The pilot will, of course, see MSL values on the approach plate, & the altimeter:

To fly the approach he must (hypothetical representative values are listed):

- If airway crosses high level terrain that precludes safe descent to 2,000', plan appropriate alters that may be safely flown. Deviations from the approach plate are neither safe nor legal.
- If significantly above 2,000' when over cone marker plan a safe descent in a holding pattern.
- Begin the approach by flying on the 233° radial, flying MC of 53° (the reciprocal) toward the cone marker (cone of silence; final fix).
- Cross final fix at 2,000' when outbound during the instrument approach.
- Outbound at the final fix he must alter to a MC of 58°.
- Outbound at the final fix he must begin a descent to 1,500'.
- As he reaches the fan marker on the NE side of the transmitter, he must begin timing for the 45° left turn (actually well past position shown schematically at fan marker) & fly for 4 minutes on 58° MC.
- Enter a procedure turn by turning 45° (correcting for drift) to the left; flying 2 minutes at that heading; begin gradual descent during 45° turn. Descent rate should result in reaching 800' upon crossing the fan marker after inbound toward final fix.
- While flying inbound on a MC of 188° a highly experienced pilot will be able to estimate when to initiate his turn onto the inbound leg of the instrument approach by listening for the strength of the "N" (dash dot) tone, as the "A" starts to ease in (dot-dash); possibly before. He will also know better when to initiate the turn based on time than a less experienced pilot.
- Turn to a MC of 238°.
- Maintain airway centerline by keeping tone blended..
- Flying MC of 238°, but staying on the airway by keeping tone blended..
- Upon reaching the final fix he must descend to MDA (minimum descent altitude; typically 400' AGL) & immediately alter to a MC of 240° which aligns plane with the runway.
- If he sees the runway he may descend & land by visual reference.
- If he does not see the runway after the predetermined time has elapsed he should begin an immediate climb back to the altitude specified for a "Missed Approach" & turn to the heading assigned for a missed approach.
- He should immediately call to advise the controller that he is executing a missed approach.
- He may then request another approach; or he may be told instead to fly a specific heading, & climb to a specific altitude & plan an approach at his "alternate" airport.

If the approach heading (actually course) were more than 30° from the runway heading (course), the MDA was typically 600' for a circling approach. After a missed approach he should have climbed to 2,000' & complied with appropriate instructions. If fan markers were present they would have specified crossing altitudes. In many cases fan markers were the only means of establishing distance along the track other than the cone marker.

4.30.4.3.2 Direction Finder Approach

The first generation Direction Finder employed a manually rotated loop antenna to determine the RB (relative bearing) to a selected (manually tuned in, like a tunable portable radio) NDB.

The second generation Direction Finder is the same as the first generation except that it employed a manually controlled, electrically rotated loop antenna.

Neither is very convenient for an NDB approach.

Fig 100 illustrates a simple chart that facilitates entering a holding pattern; or an approach from any direction. In the "Direct" half of the circle, the holding pattern may be entered in a direct manner. Both teardrop & parallel entries are illustrated by dashed lines. Studying this aid to orientation before flight is preferred, but it is even more valuable in the event that an unexpected approach is necessary. As always under IFR conditions each turn should be at a standard rate; 2 minute turns.

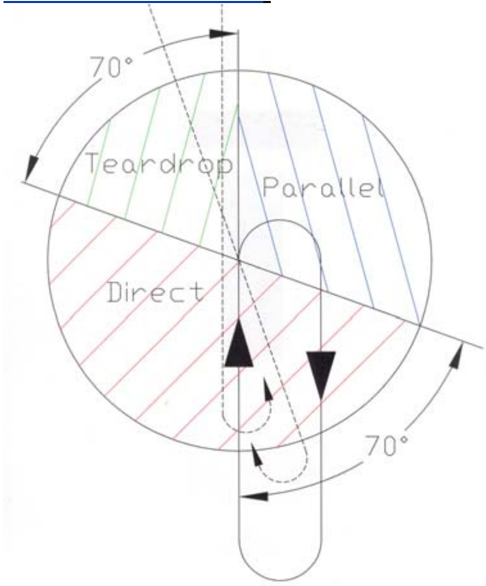


Fig 100: Standard IFR Entry

4.30.4.3.3 ADF (NDB) Approach

The next generation of the direction finder approach was the ADF (Automatic Direction Finder). The ADF automatically pointed either to or from the NDB, regardless of how the plane turned. Unfortunately the pointer might actually be pointing away instead of toward the NDB. Resolving the ambiguity requires one of several techniques. A moderate angle of turn will indicate whether the NDB is in front of or behind the plane. For a quick more positive identification, turn 90°. Both arrow head & tail will point 90° off-heading initially. If the pointer (arrow head) points to the left, & the pointer moves forward as the plane flies on this off-course heading, the NDB is to the right of the plane on this new heading. If it moves aft the NDB is left of the plane. Once resolved, this ADF is as effective as the newer version, with the major exception that it is possible for the pointer to reverse without the pilot noticing it as he flies over the NDB, which could be catastrophic. A turn toward the NDB leads the plane to it whether the arrow or tail points to it.

4.30.4.3.4 The true ADF Approach

The modern ADF was introduced to the market in the late 1960s. It has a solid state electronic loop that eliminated the ambiguity problem, & was even much lower profile; thus less aerodynamic drag. It only points to the NDB regardless of how the plane turns; without ambiguity. If the pointer moves aft without the Aero Navigator noticing the swing he immediately knows the direction to the NDB that is tuned in.

Fig 101 illustrates the NDB approach to runway 3 ((1)) a Alamogordo, NM. See Note 1. Note that the runway is close enough to the beautiful Sacramento mountains that a 3° glide path would not be safe for the more frequently used runway 21. Winds are often quite high favoring runway 21 in Alamogordo. In fact, the author once landed a taildragger that stalled at 45, with an honest 50 mph headwind (quite a challenge; only in an emergency). In 30 countries the author has never seen a mountain as beautiful as the Sacramentos immediately South of Alamogordo.

Note 1: See annotations that flag pertinent items of interest on the approach plate. These triangles were added by the author for illustrative purposes. Numbers on approach plate in triangle correspond to number in double parend in the below text. For example: 1 = runway number, 2 = actual runway direction, 3 = circling approach in table. Note also that the approach plate shows actual direction; 214°, while the runway number is the first 2 digits; 21.

If winds are too high for runway 3, a circling approach to runway 21 could be made; if ceiling permits. Circling generally means a 30 to 90° heading change; not 180°. Circling minimums vary with aircraft speed during the approach. Most lightplanes would fall into Approach Category B at 91 to 120 kts (104 - 138 mph). The higher the speed the higher the landing minimums, per the small table at the lower left of Fig 101. Circling minimums would be 4720' ((4)) with 1 mile visibility. That may sound like very high ceiling, but it is given as MSL. AGL is shown in parends as 520; rounded up to 600' per parend. Note that circling approaches require an additional 200' ceiling for that category airport. Straight in approach ceiling minimum of 4520' is shown above the ((4)) & 4720. It is certainly unwise to circle an airport in low visibility at 400'.

There is no IFR approach for the unpaved crossing runway (16 - 34), although it could be used unofficially, after reaching VFR conditions, as a circling approach.

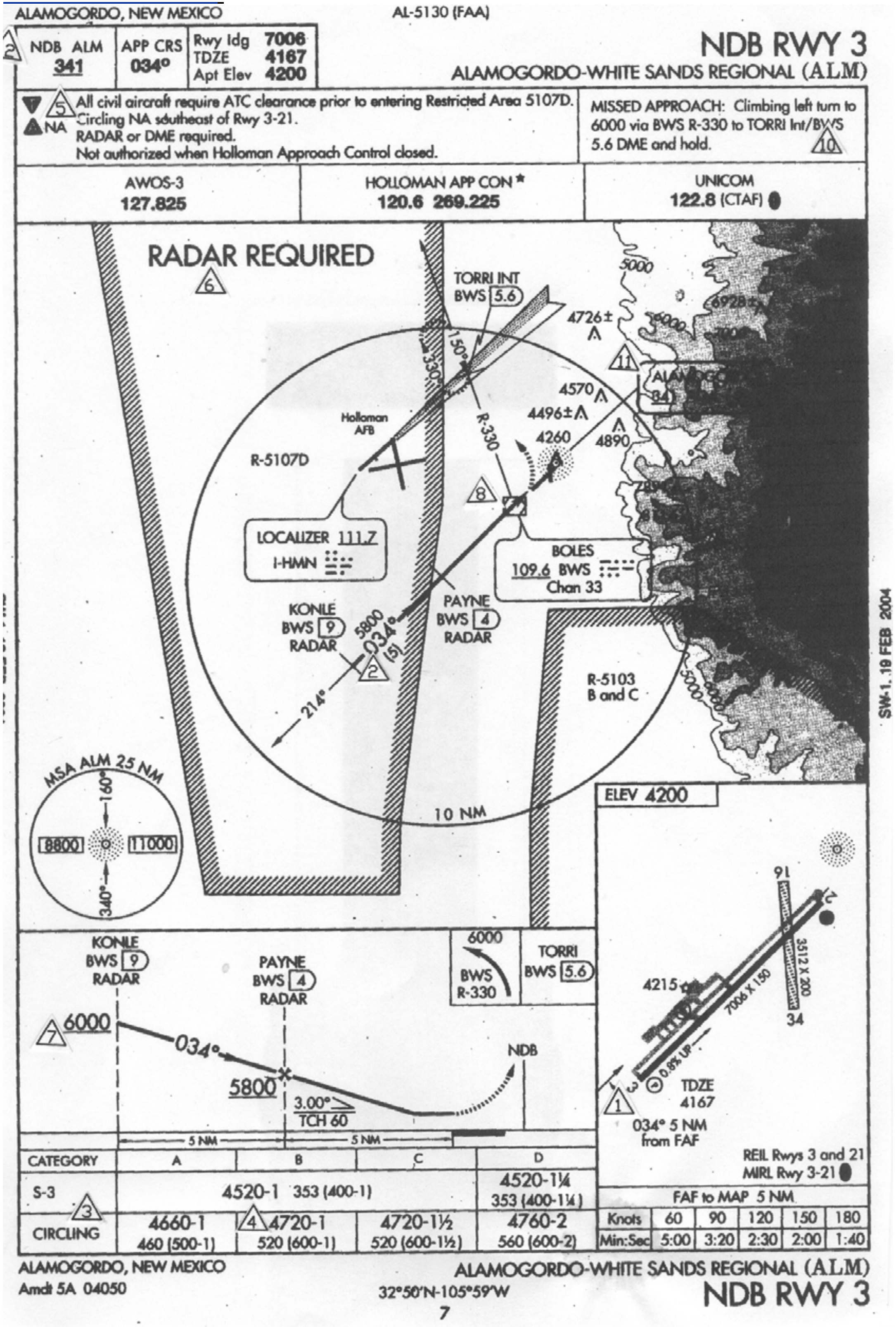
To the right of the landing minimum table is the FAF to MAP 5 NM table, which gives the time to fly the last 5 NM between these two points. Timing on Instrument approaches is critical in case a missed approach is necessary. In this case, the Sacramento mountains would prevent much of an overshoot past missed approach turn.

Note also that near the top of the approach plate ((5)) it states that ATC clearance is necessary before entering the restricted area; no. 5107D. The approach plate also calls for Radar ((6)). In the "profile" portion of the approach plate it shows that the initial point of interest for the approach calls for Radar & a 6,000' MSL altitude. "Radar" means that ATC advises of position along the approach path while inbound on the approach on a MC of 034° per ((2)). The next Radar fix is for 5800 MSL. The next Navaid is not shown in the profile because it is not a part of this instrument approach. It is shown ((8)) in the plan view as the Boles VOR (frequency of 109.6). Since this is an NDB (using an ADF) approach the NDB ((9)) is shown in the plan view. Note that although there is an altitude for crossing each of these two fixes there is no indication of the altitude at which point the plane should transition to level flight. That is because that altitude must be determined by use of the MDA table. The value, as stated above, depends on airspeed & type approach (circling or straight-in). Note that the profile is shown with uniform descent angle. Many pilots prefer to descend quickly to the minimum altitude for the "next" fix. That increases the opportunity to see the ground during level flight, but demands additional attention to prevent descent below minimums. If using that method, he would cruise at 6,000' until crossing KONLE fix, at which time he would rapidly (but safely) descend to 5800' & then level out until reaching PAYNE fix, at which time he would quickly descend to minimums, & cruise at that altitude until time to execute a missed approach. The NDB is immediately after the runway. If the cloud deck is too low & he does not "break out" he must execute a missed approach. Both views show the action required. The profile shows a pitch up & climb. The plan view shows a turn to the left. In this case, with mountains rising eventually to over 9,000' a turn to the right could prove disastrous. To determine exactly what to do upon executing a missed approach the information is given near the top right of the approach plate ((10)). It is obvious that the missed approach must be known & flagged long before the approach is initiated, since here is no time at that point to search for a small statement. The NDB frequency & Morse code box is partly obscured in this copy at the number ((11). The frequency is repeated at the top left ((12)); NDB 341 (Hz).

All instrument approach plates are boldly labeled at upper & lower right hand corners with type of approach & applicable runway; NDB RWY 3, with name of city or airport eliminates all doubt that it is the approach that is illustrated. Each approach plate also gives a few other details such as field elevation (4200'), runway layout, geographic coordinates. & pertinent frequencies.

The ADF approach is dreaded by most pilots, including the author. It is difficult & complex by comparison with most instrument approaches. As with other approaches, a crosswind adds to the difficulty; except to a greater extent than with most others. An unknown wind also increases the difficulty. Even if W/V is precisely known, correction is not intuitive, although a few minutes with an E-6B measurably simplifies the approach proper. Since wind changes with altitude the best guess or computation will still be imprecise. The approach proper is, however quite accurate.

Although the author has always taken pride in the fact that an FAA examiner & several CFIs, after flying with him, admitted envying his skill at landing a plane. He has only made one good ADF approach, & that, amazingly, was his 1st; during training for his instrument rating. The remaining 98 ADF approaches under actual IFR (most nearly



CATEGORY	A	B	C	D
S-3	4520-1 353 (400-1)			4520-1¼ 353 (400-1¼)
CIRCLING	4660-1 460 (500-1)	4720-1 520 (600-1)	4720-1½ 520 (600-1½)	4760-2 560 (600-2)

FAF to MAP 5 NM

Knots	60	90	120	150	180
Min:Sec	5:00	3:20	2:30	2:00	1:40

Fig 101: NDB Instrument Approach to Runway 3

to minimums) all left something to be desired. Nevertheless, all were successful.

Likewise, those who compliment him on his landing skills seem to be much less impressed by many of his other flying skills, such as simply holding altitude & heading. See Note 1. below. Even the simple take off seems to him to be more difficult than landings. He has, over the years, made hundreds if not thousands of practice zero-zero take offs; with a trusted safety pilot in the other seat, & under VFR conditions. Needless to say he has never made an actual zero-zero take off, nor would he consider doing so. There is a dichotomy regarding TO & landing minimums. An airliner is not allowed to T.O. under zero-zero conditions, but generally under very low minimums. If fully certified & current for Category IIIc they may land under zero-zero conditions; but obviously not on an ADF approach. An instrument rated commercial or private pilot may T.O. in a lightplane under zero-zero conditions, but require higher ceilings & visibility to land than an airliner. Taking off in a lightplane, under zero-zero conditions, is considered by most pilots to be foolhardy. In the case of a twin, an engine failure soon after T.O. is critical, even if the pilot is at peak in proficiency. It is safe for such a legally proficient multiengine pilot. A single engine lightplane has no opportunity to avoid obstructions under zero-zero conditions, when an off field landing is unavoidable.

Note 1. An important proficiency & confidence builder that is taught during instrument flying & often before, is simple. If a pilot accepts a heading within 5° of correct, or an altitude deviation of 100', he will soon find that his deviations are quite large. If instead he demands of himself 1° & no altitude deviation he will actually find that it is easier.

The succeeding approaches & approach plates are similar to the NDB approach, so are not described in such great detail.

4.30.4.3.5 GCA - Ground Controlled Approach; Later called Precision Approach Radar (PAR)

4.30.4.3.5.1 The Radar fixes on the above NDB approach are similar to the GCA. The GCA was an approach directed solely by a Radar operator by communication with the pilot. The Berlin Airlift was possible only by use of the GCA. No other approach system at that time was sufficiently accurate for the task. Planes passed extremely close to tall buildings, to literally save the lives of Berliners. The GCA could have been conducted without vertical information since the GCA operator knew the proper altitude for the entire approach path. He could advise pilots of the proper altitude periodically during an approach.

4.30.4.3.5.2 The term "GCA" was obsoleted many years go, but controllers often direct pilots by the same method; generally only to expedite a portion of an approach. Similar methods are used for flight in & through congested areas.

The modern day GCA is called Precision Approach Radar (PAR), & is much the same as the operation used during the Berlin Airlift. PAR is usually directed by Approach Control. A PAR also occasionally involves several turns to avoid or blend into traffic. It may follow a specific approach, or the controller may simply direct the plane in what appears to be random turns, & even altitude changes. The "key phrase" is "precision approach". Often Approach Control will request a specific descent rate. In critical portions of the approach, the controller will follow the standard ILS or old GCA concept by specifying actions such as "slightly or well above glide path". Although the pilot must usually read back instructions to assure full comprehension, during the PAR he should never do so.

The author has made quite a large number of GCA - PAR approaches; most under VFR conditions. For a pilot who is accustomed to being under control, it is a little unsettling to rely on someone else to bring the plane down" to minimums, if the ceiling is that low. A former WWII P-39 Aircobra pilot told the author that he landed a F-84 in England when he did not see the ground until he stepped down off the wing; WOW.

4.30.4.3.6 The ILS Approach

The ILS systems have Several Distinctively Different Types of Transmitters (if lights can be considered to be transmitters); Localizer, Glideslope & MALSR (lighting).

4.30.4.3.6.1 The ILS Components:
A unique merit of the ILS is that if there is absolutely no alternative, such as fuel exhaustion or serious engine problem, an ILS could be flown to the ground. This would neither be legal nor wise, if avoidable, but it is an interesting challenge to practice zero-zero ILS approaches under VFR conditions, & with an alert CFI in the right seat.

- The "ILS localizer transmitter" provides precise azimuth information, much like the VOR. The main difference is that it also has a glide slope beam. The ILS glide slope transmitter emits a beam that is much like the localizer beam, only rotated 90° about the ILS centerline. It slopes up from the runway threshold at a 3° angle. That feature alone makes it a "Precision" approach. The lateral positioning beam is 4 times as accurate as OMNI. The VOR beam width is 22° (full deflection; left to right), & each dot (on the face of the CDI) needle deflection represents 2°. Thus the localizer beam width is 5°; only 1/4 as wide, & thus much more precise than OMNI. An indication of the beam width may be seen on the ILS Approach plate for Runway 1 at Ronald Reagan airport at Washington DC; Fig 102. The extreme length arrow head represents the lateral portion of the ILS beam. That arrow head terminates at the threshold of runway 1 (rounded off direction of 7°).

- The ILS signal is much like the OMNI, with another difference being in the method of controlling the needle. The ILS localizer is selected by an ILS frequency & responds only to the signal, without regard for the OBS setting.

The nav receiver electrically disengages the OBS from the needle when tuned to an ILS frequency. It is good practice to set the OBS dial to the ILS direction per the approach plate; simply as a reference or reminder of the nominally correct heading.

With an OMNI it is possible to turn away from the original course, & track it in at a different angle per any desired OBS reading. The localizer has only one correct bearing; in this case the 187° radial with reciprocal heading of 007°. The ILS localizer - OMNI needle responds to off-course lateral positions such that correction requires turning toward the needle. If the needle is to the left, the plane is to the right of course. Turning toward the pointer; to the left, brings the plane back on center.

Preparing for an ILS requires, as with any instrument approach, be fully aware of what is expected, & have all numbers set or at a minimum, plainly visible for use when called for. He should know that he will should be prepared for anything the controllers might ask him to do. The most likely entrance to an ILS approach is either:

1. By vectors to intercept the ILS (most likely near the FAF {LOM} & on the ILS, heading inbound), or be instructed to fly the full approach. Or:

2. The full approach, which requires him to fly directly to the Washington, VOR shown at the point of the extended arrow point; identified by the name with the frequency of 111.0; & DCA (the identifier). The line under the 2500' & 1600' altitudes shown on the profile indicates a minimum permissible altitude. A line above would indicate the max permissible altitude at that point. A line above & below would indicate that only the listed altitude is allowed. He should fly over DCA at or above 2,500' (per the profile; the altitude at which he should cross Pisca intersection, the outer fix, which is obtained by tuning in a second VOR to Nottingham (OTT) at a frequency of 113.7). From DCA he should then fly outbound on the front course of the ILS (in this case, a heading of 187°, remembering the reverse CDI indication) for a minimum of two minutes beyond the outer marker, or possibly past. Pisca is the feeder fix, which represents the starting point of the instrument approach.

He should then execute a procedure turn as illustrated at the lower right of the tail of the long arrow head. The procedure turn is understood to be a 45° turn to the left, followed by a 180° turn to the right, which is then followed by intercepting the ILS, & turning inbound. Altitude is to be per the approach profile at the lower right corner of the approach plate. The profile slope is shown much steeper than the glide slope controlled 3°. The approach plate calls for an altitude of 2500' or higher over Pisca intersection. It is obvious that if too high, it would not be possible complete the 3° ILS. Oxonn (LOM) requires a minimum of 1,600'. The line under the altitude indicates that the stated value is a minimum altitude. A line over the altitude would indicate that the stated value is the maximum altitude for crossing. There are three other variations of the crossing altitude.

- A "glideslope transmitter" beam-signal can have "lobes" that could deceive an inattentive pilot while flying an ILS approach. These lobes are somewhat like a spurious response; or second order, third order, etc diffraction

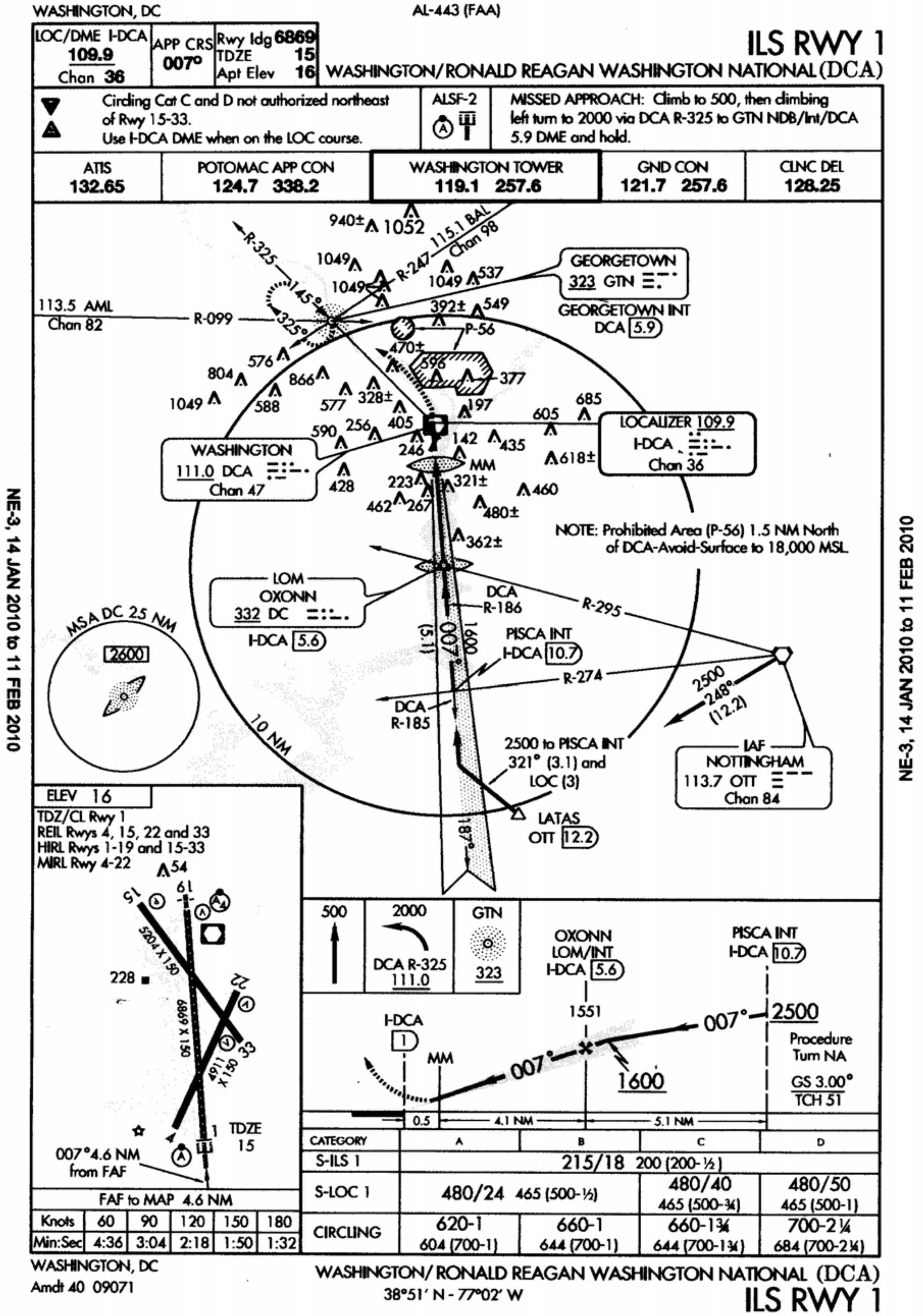


Fig 102: ILS Approach Plate for Runway 1 at Ronald Reagan airport at Washington DC.

color spectra from a diffraction grating or prism. They replicate the true laterally horizontal plane of the glide slope beam at progressively larger angle above the horizontal. Three degree is the nominal slope for a glide slope beam, but there is no obvious way to determine, sitting in the cockpit, that the plane is on a 3° glide slope; rather than a 4°, etc. These lobes are beams that appear normal, but extend upward at a larger angle. The plane could fly an ILS until reaching the bottom of the cloud deck without ill effect as long as the descent rate can be reduced before the plane actually touches down. That would usually be practical in a lightplane, but not necessarily in a heavier plane. Since the lobes extend upward, but not downward, this hazard can be prevented by approaching the glide slope from a lower level; so that it is intercepted from below. The glide slope is never magically in place, but the pilot must fly to it. That may be by performing a normal entry, or by following controller instructions. If the intercept is flown from below the glide slope, the needle will be pegged against the top of the instrument, telling the pilot that he is too low. As he approaches the beam the needle will begin to drop from the top. When it is centered he simply drops the nose enough to keep it there. Another way to assure that the plane has not intercepted a false lobe is to refer to the approach plate to find the correct altitude for the FAF (final approach fix). With the altimeter setting correctly set the two numbers should agree when over the FAF. The FAF is normally at the outer marker on ILS approaches. These items may be seen on the ILS Approach plate for Runway 1 at Ronald Reagan airport at Washington DC; Fig 102; ILS RWY 1.

Not shown here is the "ILS RWY 1 (Cat IIIc)" approach plate which is nearly identical to that in Fig 102; ILS RWY 1. The major differences are in the lower right profile - MDA window. It contains only 1 line; S-ILS 1, with RA 163/16 - 150DA 165 instead of the three lines; top line having: S-ILS 1 - 215/18 - 200(200-1/2); over localizer & circling approaches. In addition that window shows: Category IIIc ILS - Special Aircrew & Aircraft Certification Required. Although the ILS 1 is a precision approach, the Cat IIIc ILS is even more precise. See 4.30.4.3.3.5.2 below. The Cat IIIc is neither a simple nor a common approach. It is generally limited to airlines; or at least the very serious & wealthy pilots.

● Outer, middle and inner marker beacons are similar to the fan marker from the Low Frequency Range. In fact, they are a remnant from same. The inner marker is used only for Category II operations, so is not installed on smaller airports. Each marker beacon has a different tone, & in some receivers, color of the light. At the Outer Marker, a single "dot" deviation indicates a distance from the centerline of 500 ft. At the Middle Marker, one dot indicates 150 ft off course. It obviously indicates the progress along the glide path, & actual distances are shown on the approach plate. Not so obvious is the fact that they also indicate altitude; a good safety check; & again, redundant information. Marker beacons transmit on 75 MHz.

● Approach lighting systems. Should the ILS glideslope component be out of service, the approach reverts to a non-precision LOC approach with corresponding MDA altitudes.

MALSR (medium intensity approach lighting system with runway alignment indicator lights), if installed, would reduce visibility minimums for an ILS approach to Category **I**. MALSR is an acronym for, & is an unsophisticated approach lighting system, but it does improve visibility for approaching aircraft, which permits operation at lower minimums.

A missed approach, like on an NDB, is shown as two curved arrows & details are given on top right of the approach plate.

4.30.4.3.6.2 Category of ILS Approaches in Terms of Approach Minimums

Standard straight-in ILS, S-ILS

Circling - When the approach magnetic course differs from the runway magnetic course by more than 30°

CAT I - Category I landing with a minimum ceiling (or DH; for Decision Height) of 200 ft & Runway Visual Range

(RVR) of 1,800'.

CAT II - Permits landing with a DH of 100 ft & RVR of 1,100'.

CAT IIIa - Permits landing with a DH of 50 ft & RVR of 650'.

CAT IIIb - Same as IIIa plus automated roll-out after touchdown, but requiring the pilot to take control during the roll-out. Permits landing with a DH less than 50 feet; or without DH, a RVR of 250' A runway guidance system is required.

CAT IIIc - Same as IIIb, except zero-zero.

In entering the ILS the intercept angle of the vertical localizer beam should not exceed 25°. One FAA examiner put this rule-of-thumb to the test to see how well the candidate could handle the unexpected during instrument check rides. After a few apparently random heading changes a pilot loses situational awareness in terms of position, so the instrument rating candidate had no idea of his position. He would direct a candidate toward the ILS at 90° off-heading. The response was usually a heroic attempt to turn, as soon as he realized that the needle left the peg (full scale) & moved much more rapidly than it should have, with a bank much steeper than recommended. Other candidates would announce that they were making a 270° turn away from the on-course heading in an attempt to intercept the radial correctly; not a bad idea. Still better were the ones who announced a missed approach, & simply started over with a proper series of turns. On an instrument check ride the norm is to shoot at least one VOR approach, but using only one VOR. Identifying a cross radial & changing back to the VOR he was tracking was a little difficult. Another trick the examiner sometimes pulls is to alter the norm. The usual holding pattern consists of a racetrack pattern flown with right hand turns, But he may ask Approach Control in advance to casually call for left hand turns, or to hold on the side of the holding fix that would require left hand turns. The examiner pulled that on the author; a good lesson on listening carefully to ATC; which he failed to do.

A seemingly small thing in the ILS approach is to know the nominal descent rate. This provides another way to assure that the plane is flying the correct ILS lobe. A simple approximation for the proper is to divide the TAS by 2 & add a zero. If cruising down the ILS at 120 mph, he should be descending at (120/2) x 10 = 600 fpm on the ROC indicator.

4.30.4.3.7 Localizer Back Course Approach

The back course is also called a localizer approach. It is simply the "back side" of an ILS. It is just as accurate, but lacks the horizontal beam & CDI needle. It thus lacks any direct indication of altitude or glide slope. The only differences between the localizer course & VOR are the direct vs. reverse indication & accuracy.

4.30.4.3.7.1 There are several variants of the localizer, including the lateral information portion of the ILS. All localizers transmit along the nominal runway centerline in both directions. An approach can then be shot from either direction. The reverse is identical to the ILS except for the reverse CDI indication. Some avionics corrects for the reverse CDI indication. If not, the back course approach must be flown by reversing response to needle deflection. Just another way to keep a pilot sharp. The author thoroughly enjoyed his frequent Hobby R 22 back course IFR practice with a missed approach & reversal to ILS 4, until Hobby (Houston) was declared a Class B airspace. He shot several of each type approach in much less time than a normal complete circle around the field while practicing only one of the two approach types.

4.30.4.3. 7.2 HSI (horizontal situation indicator)

Since the HSI has a feature that is very useful for the back course, it is an appropriate place to discuss other features & uses of the HSI. The HSI combines several instruments into one. See Fig D7 in appendix D.

The back course is only one of many applications where the HSI is very useful. It was the only way to eliminate the reverse operation of the CDI pointer until the glass cockpit was introduced. This does require a variation of the normal procedure. While flying outbound on the localizer front course rotate the HSI course arrow 180° from the intended course. It is essential to point the HSI arrow to the intended inbound course if flying the ILS.

The vertical hash mark is called the "lubber line". It indicates aircraft heading. In the case of Fig D -7 heading is 175°. Typical of compass-type instruments, the compass rose has minor divisions in 5° increments.

Typical conical card type compasses have no simple way to indicate heading changes of any desired heading change. In this case, the fixed outer marks indicate 45 & 90° turns. Some have more such marks. In this case, a

90° turn to the right would result in a heading of 265°. Although obvious, & even easy for odd headings such as 349°, there is always a risk of adding incorrectly in the "heat of the battle" to fly a complex plane in a complex series of turns under turbulent instrument conditions. Reference marks do facilitate turns to new headings.

An important feature of modern instruments & instrument panels is that manufacturers have standardized location on the instrument panel, & location & color of such things as reference marks. This is very much a safety feature since the pilot knows where to look on the panel for any given instrument, & where & what to look for any given feature on an instrument when he is flying a "strange" plane. This is important for many, including club members, renters, or corporate pilots whose employer leases or owns several planes.

The knob on the lower right rotates the "heading bug" which is shown aligned with the 12 (representing 120°) on the rotating inner scale in Fig D -7. The unusual shaped symbol on the knob matches that of the heading bug. The heading bug may be set to the desired heading as a reminder, & reset when heading should change; such as per ATC instructions.

If the plane is equipped with an autopilot, the autopilot will fly the heading based on the heading bug setting.
A very important feature is the course selector (shown as a yellow arrow) that is pointing to 205°. The course selector is a three part line that is rotated by use of the knob at the lower left. The reverse end of the course selector serves as a handy reciprocal indicator for times when a 180° turn is required.

When tracking a VOR, the mid length portion of the course selector acts as a CDI to indicate the direction off of the preset course. Just as with the conventional OMNI head (CDI) shown in Fig 77, the plane must turn slightly to the left, if the CDI pointer moves to the left. This is also true on an ILS. A point of confusion is that if flying 90° from the heading bug, the CDI bar will be horizontal rather than vertical.

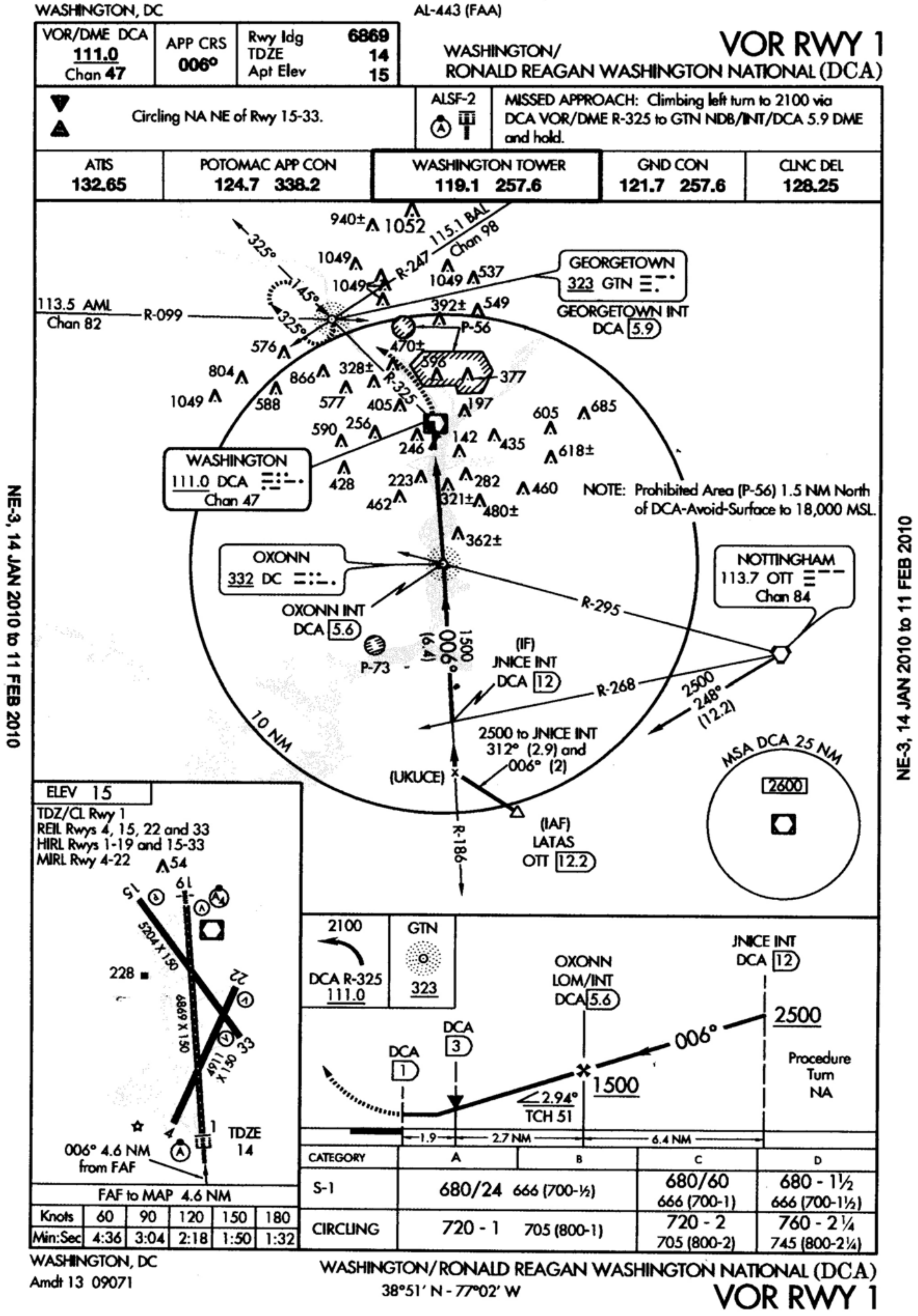
The short yellow trapezoidal bars on each side of the compass rose are dual glide slope indicators. These trapezoidal bars move down when you are above the glide slope & vice versa.

The white triangular indicator near the center provides "To - From" information.
The HSI also serves as a slaved DG. The sensor is like that in the author's Remote Compass; in the tail cone, where there is much less EMI. The sensor unit is more accurate than conventional compasses. Since it is slaved there is no need for manual setting, so no knob for same.
Resetting the heading bug does not change the compass rose, since it is directed by the heading of the plane.

4.30.4.3.8 The VOR Approach

4.30.4.3.8.1 The VOR transformed IFR approaches, & for that matter cross country flying, from a tiring, difficult, & quite possibly a frightening experience, to nearly leisure activities. Some pilots, including the author, really do enjoy a low stress OMNI approach, as long as he expects to "break out"; or even if not, if there is an alternate airport that will serve the purpose, if the reason for the stop is fuel, rather than home. Even a 6 hour Victor airway flight under genuine IFR conditions is more of a joy than a challenge. It does, though, serve well for proficiency building, which the author certainly did need; being well aware of the fact that there was no such thing as a perfect approach.

The VOR approach shown in Fig 103 proves that although it is a good & accurate approach, it does not compare with the ILS, much less the ILS Cat II. Fig 102 shows that the best ILS approach (straight in approach) has minimums of 465' ceiling, while Cat II (not shown here) has a 150' ceiling minimum for the same runway-airport. The VOR approach, per Fig 103, has a minimum ceiling of 666'. Although the difference between ILS & VOR approach is only 200', that may prevent making an IFR flight in some cases if ILS is not available.



FAF to MAP 4.6 NM					
Knots	60	90	120	150	180
Min:Sec	4:36	3:04	2:18	1:50	1:32

CATEGORY	A	B	C	D
S-1	680/24 666 (700-½)		680/60 666 (700-1)	680 - 1½ 666 (700-1½)
CIRCLING	720 - 1 705 (800-1)		720 - 2 705 (800-2)	760 - 2¼ 745 (800-2¼)

Fig 103: VOR Approach

Near the top left of the approach plate the Potomac APP Con advises that approach control is 124.7. Approach control is the frequency he will use for some time before & during the approach. To the right it shows the tower frequency of 119.1. The VOR frequencies of both VORs are given; 111.0 & 113.7. The NDB frequency is listed in the box as 332 KHz.

4.30.4.3.8.2 The ideal VOR approach involves two VORs since a fix is required rather than simply a LOP. The main VOR on the VOR Rwy 1 approach is aligned with the runway of interest, which is excellent. The other VOR is to the side such that a radial crosses the first VOR, & others can be received from a portion of the main approach path. No crossing radial is shown at the airport or the primary VOR; probably because that VOR cannot be received from ground level. The pertinent fixes must be identifiable for the best possible approach. The GS must be established before passing the last fix; Oxonn, at the 295° radial of Nottingham VOR (OTT). Without that he would not know when to execute a missed approach if necessary; or when to expect to see the runway. Actually, though, Oxonn can be established by use of the OTT VOR or the 332 KHz low frequency beacon; as from the old low frequency range marker. It would be prudent to tune the ADF to 332 KHz & also the VOR No. 2 to 113.7 to have redundancy. Never miss an opportunity for redundancy. The VOR needle should be centered as the plane passes Oxonn intersection, & simultaneously the ADF pointer should swing 180° & point to the rear. As busy as the pilot would be, he should reset hi OMNI No. 2 from 268 From to 295 upon passing the 268° radial. Most important, the approach must be timed, & the MDA should not be violated. He should cross Jnce intersection (R 268) at or above 2,500' & immediately start a descent to 1,500', at which point he should quickly descend to the 680' MDA , & hold that altitude until he sees the runway; or it is time or execute a missed approach.

4.30.4.3.8.3 Less than ideal VOR approach? Remove the OTT VOR from Fig 103 & leave the Oxonn DC NDB & the result would not be much different, except that the only fix would be over Oxonn NDB. The approach would not be practical at all except that it is simple to overfly DC VOR & fly outbound directly over DC NDB. Time a procedure turn & return for the same approach as shown except that the only fix would be inbound at the NDB. That would reduce the quality & accuracy, so would result in higher minimums. Such an approach could not be flown using this approach plate because it would not be an authorized procedure. Since it had not been proven safe by the FAA by performing the entire approach it might result in flying into an obstruction. That is most likely to be the reason for the 2,500' minimum altitude for crossing Jnce intersection.

4.30.4.3.9 VOR-DME & TACAN

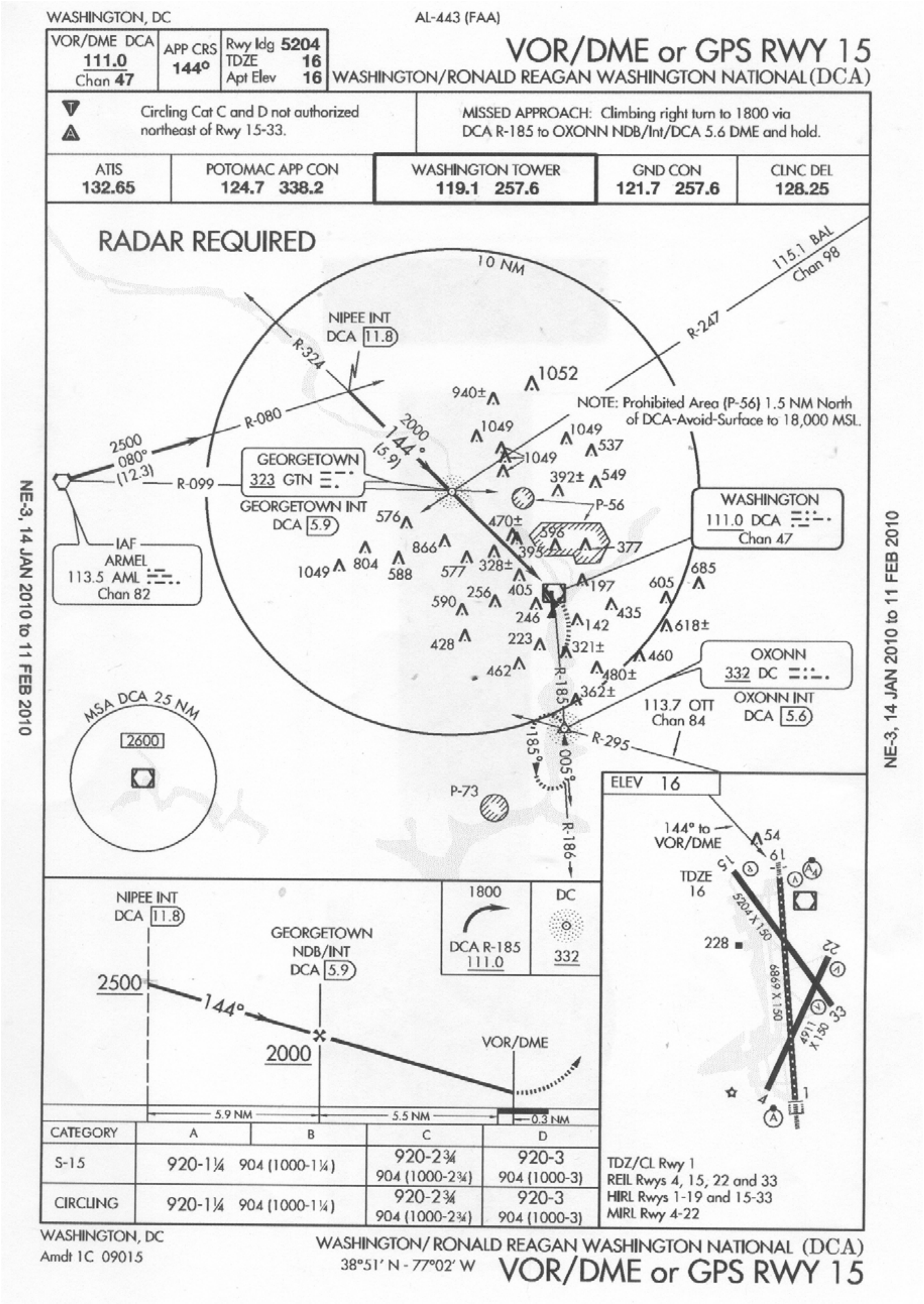
Fig 104 illustrates a VOR-DME approach that is shared with a GPS approach. Both require Radar, also.

Note that the minimum altitude is actually higher than for the VOR approach to the same airport; but a different runway. It is possible that a portion of the justification for the difference is the obstacles or other factors between the two runways. Runway 15 is shorter, but nearly in perfect alignment with the approach direction. Runway 19, which has its own approach, would require a 40° turn from this approach; constituting a "circling approach", which increases the minimums.

The VOR-DME annotations have the addition of mileage. In the plan view of the airport the distance from Armel VOR to Nipee intersection is 12.3 NM. That intersection is 11.8 NM from the VOR; just past the runway threshold. The profile also shows the DME distance from the VOR to the two fixes as 11.8 & 5.9 NM. A matter of minor concern is the "slant range" issue. Since minimum altitudes are specified, & excessively higher altitudes would not be practical (would result in need for excessively high descent rates) the slant range would be very close to those distances given.

Note also that two VOR radials & the NDB all identify the "Georgetown DCA NDB" fix. The DME ranges of import are from the primary VOR-DME.

There are actually more GPS than VOR approaches in the US because the VOR approaches are only convenient if a VOR is located nearby, & preferably aligned with a runway. Some low powered VORs are added to an airport solely for the purpose of instrument approaches.



CATEGORY	A	B	C	D
S-15	920-1¼	904 (1000-1¼)	920-2¾ 904 (1000-2¾)	920-3 904 (1000-3)
CIRCLING	920-1¼	904 (1000-1¼)	920-2¾ 904 (1000-2¾)	920-3 904 (1000-3)

Fig 104: VOR-DME or GPS Approach

4.30.4.3.10 RNAV (GPS)

The GPS can provide altitude information, but not with sufficient accuracy for precision approaches. They are improving as testing & improved procedures are implemented. GPS approaches share procedures with other types; Fig 104 is such a case.

The GPS is capable of flying the same approach by measuring distances & bearings from any fix; VOR, NDB & intersections. Some intersections consist of a crossing point of LOP from each of two Navaids.

Note that Radar is required, & that the minimums are the same as for the VOR-DME approach.

In 2008 GPS-based approaches in the USA surpassed the number of VOR-based approaches, although VOR-equipped planes outnumber GPS-equipped IFR aircraft. There are more GPS approaches because they do not require nearby VORs. There are more VOR equipped planes because nearly all panel mounted VORs are IFR capable, while most panel mounted GPSs are not certified; if even certifiable. Since the bulk of factory built lightplanes are older than 25 years. Nearly all have VORs, but many have never been upgraded to newer higher priced panel mounted GPS.

4.30.4.3.11 LDA - DME Approach

The LDA approach utilizes an ILS, but is, by definition, a circling approach because the ILS is more than 30° off-runway alignment. As a result it has higher minimums.

4.30.4.3.3.12 RNAV **LNAV is** "lateral navigation" for RNAV systems that lack VNAV.

4.30.4.3.3.13 MLS (Microwave landing system)

This precision landing system was expected to replace the ILS. It had some merits, but was actually rarely installed, & with limited success. Although less expensive to install than ILS, the WAAS proved superior without the need for ground equipment space & cost. MLS continues to be of some interest in Europe, where concerns over the availability of GPS continue to be an issue. A widespread installation in the United Kingdom is currently underway, which included installing MLS receivers on most British Airways aircraft, but the continued deployment of the system is in doubt. NASA does land the Space Shuttle by use of a MLS variant called Microwave Scanning Beam Landing System.

4.30.4.3.3.14 Airborne Radar Approach

Although it is not an accepted instrument approach, it is possible to use some types of airborne Radar to make a successful instrument approach.

Airborne Radar is somewhat like a blend of Radar navigation & the GCA. With the GCA, there is no ambiguity regarding the Radar target. As discussed earlier, identification of ground targets is much less natural when relying on Radar. It should only be attempted as a last resort; in an emergency. Anyone operating in remote areas that has no Navaids suitable for an instrument approach should consider practicing an airborne radar approach frequently; but only under VFR conditions, & with a safety pilot in the other seat. A safety pilot is defined as a pilot who is fully qualified to fly the plane under the conditions that it may encounter.

An airborne radar approach should be supported by all possible avionics, including GPS, LORAN, OMNI, GCA or ADF.

4.30.4.3.3.15 STAR/SID; Standard Arrival & Departure Charts

Fig 105 Illustrates Rober One Arrival; one of several procedures for flying to Kennedy International airport. A similar chart gives the procedure to back track Rober One Arrival; its title is similar except ending with Departure instead of arrival .

Each frequently used arrival or departure route for major airports (& many lesser airports) has a distinct published procedure. The below description of Rober One Arrival eliminates any doubt of the justification for this concept. Lacking Rober One, the communication exchange between the pilot approaching JFK from Kennebunk & ATC or Center would be something similar to the following:

4.30.4.3.3.15.1 Communication "Lacking" Rober Arrival:

Cessna Citation Jet: Kennedy Center, Cessna Citation 7786U requesting clearance from Kennebunk to JFK International; level at flight level 28, 15 minutes North-East of ENE.
JFK Center: Cessna Citation 7786U, Kennedy Center, fly Rober Arrival; state ETA to JFK International.
Cessna Jet: Kennedy Center, Citation 86U negative Rober Arrival
JFK Center: Citation 86U, this is Kennedy Center, (he wanted to say "you have got to be kidding; do you even have approach plates for JFK", but instead said): "Standby to copy routing to fly Rober Arrival; expect delay; hold at ENE until JFK center is ready to read clearance; state ETA to JFK airport after departing ENE.
Cessna Jet: Kennedy Center, Citation 86U ready to copy Rober Arrival clearance.
After a few minutes delay; JFK Center: Citation 86U, JFK Center, "Standby to copy routing to fly Rober Arrival; expect delay; please readback instructions & state ETA to JFK International after departing ENE".
Cessna Jet: JFK Center, Citation 86U; understand; hold at ENE until JFK center is ready to read clearance; three two minutes ETA to JFK airport after departing ENE.
JFK Center: Citation 86U readback OK. Citation
Cessna Jet: JFK Center, Citation 86U ready to copy Rober Arrival
JFK Center: Citation 86U cleared to JFK International as follows: ENE VOR to Aspen intersection to PVD VOR to Trait intersection to Parch intersection to CCC VOR to Rober intersection to JFK International.
Cessna Jet: JFK Center, Citation 86U cleared to JFK International as follows: ENE VOR to Aspen intersection to PVD VOR to Trait intersection to Parch intersection to CCC VOR to Rober intersection to JFK International.
(In fact several requests for clarification are likely, & these would clutter up the frequency excessively)
JFK Center: Citation 86U readback OK. Citation

Note: the clearances would be copied in a convenient aviation shorthand by the already busy pilot with a small triangle indicating "intersection", circle, arrow or arrow heads indicating something else.

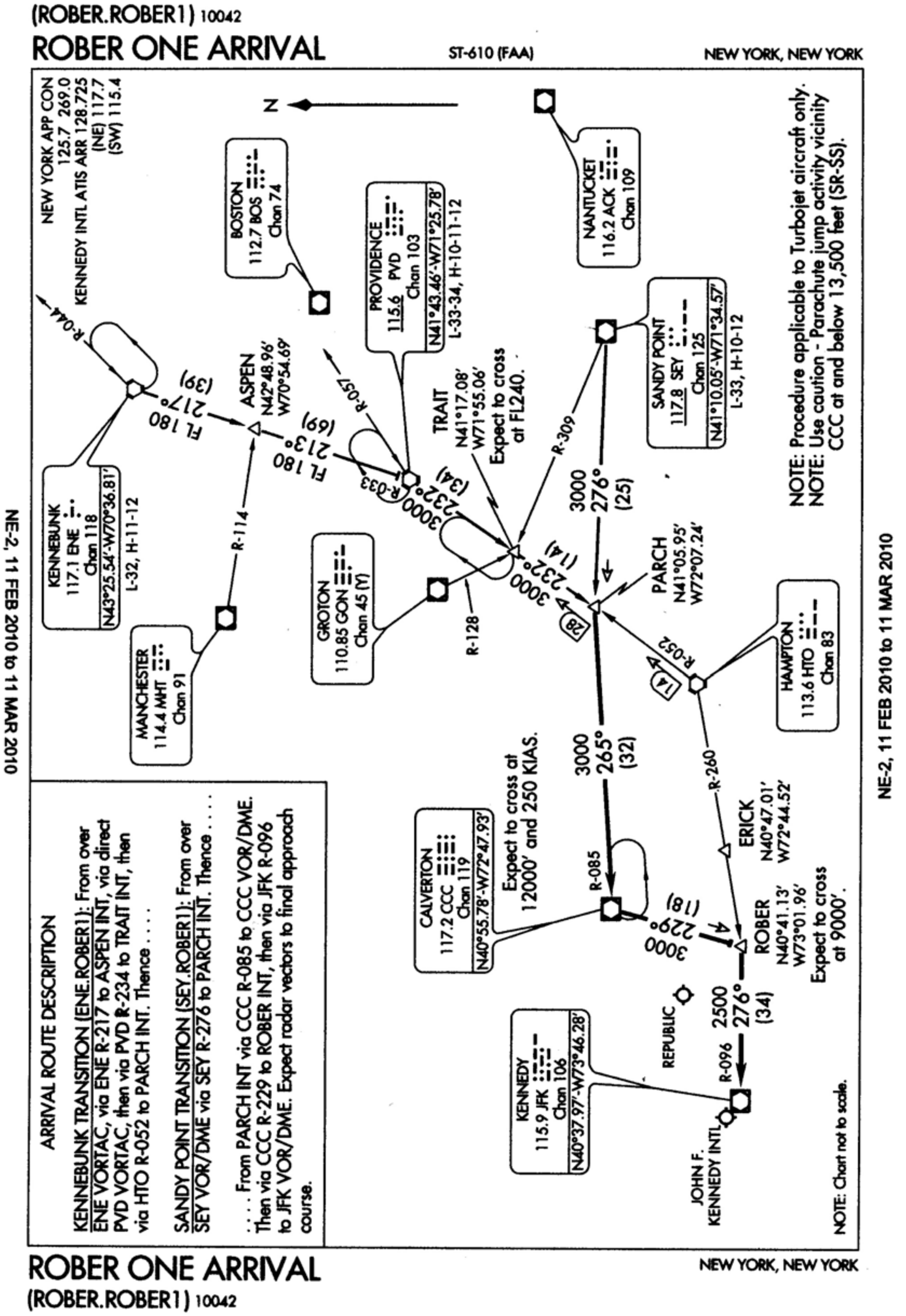
4.30.4.3.3.15.2 Communication "Using" Rober Arrival:

Cessna Citation Jet: Kennedy Center, Cessna Citation 7786U requesting clearance from Kennebunk to JFK via Rober Arrival; level at flight level 28, 15 minutes North East of ENE.
JFK Center: Cessna Citation 7786U, this is Kennedy Center, Cessna 86U clear to fly Rober Arrival; state ETA to JFK airport.
Cessna Jet: JFK Center, Citation 86U cleared to JFK via Rober Arrival.

The availability of approach & departure procedures obviously saves a great deal of time, & nearly eliminate the otherwise inevitable delays & communication problems.

4.30.4.3.3.15.3 Specific minimum requirements to fly a Cessna Citation for personal purposes (not for hire) under instrument conditions:

- Private pilot's license with Instrument rating.
- An Instrument rating is essential for practical purposes, but not actually mandatory, even for jet aircraft flying under VFR conditions.
- A checkout is all that is required to transition into most planes, but for those heavier than 18,000 lb, or for any Jet or turbo prop, a Type rating is required. This requires demonstration of piloting & aircraft knowledge, & skill to fly the particular type plane.
- Training on all systems in the Citation
- Physiological training. The FAA does not require a "chamber ride" where the candidate experiences several effects of hypoxia & decompression.



NOTE: Procedure applicable to Turbojet aircraft only.
NOTE: Use caution - Parachute jump activity vicinity CCC at and below 13,500 feet (SR-SS).

ARRIVAL ROUTE DESCRIPTION

KENNEBUNK TRANSITION (ENE.ROBER1): From over ENE VORTAC, via ENE R-217 to ASPEN INT, via direct PVD VORTAC, then via PVD R-234 to TRAIT INT, then via HTO R-052 to PARCH INT. Thence . . . .

SANDY POINT TRANSITION (SEY.ROBER1): From over SEY VOR/DME via SEY R-276 to PARCH INT. Thence . . . .

. . . . From PARCH INT via CCC R-085 to CCC VOR/DME. Then via CCC R-229 to ROBER INT, then via JFK R-096 to JFK VOR/DME. Expect radar vectors to final approach course.

NOTE: Chart not to scale.

Fig 105: Arrival Procedure for JFK

- Single pilot operation is rarely permitted for jets, or on large, heavy planes. Most of these do require two pilots; generally both must be fully qualified to fly the particular plane. Single pilot operation is allowed on the Citation; quite an important selling point.
- Currency to include BFR, & recent experience complying with specific time, number of landings & instrument approaches per FAA minimums.

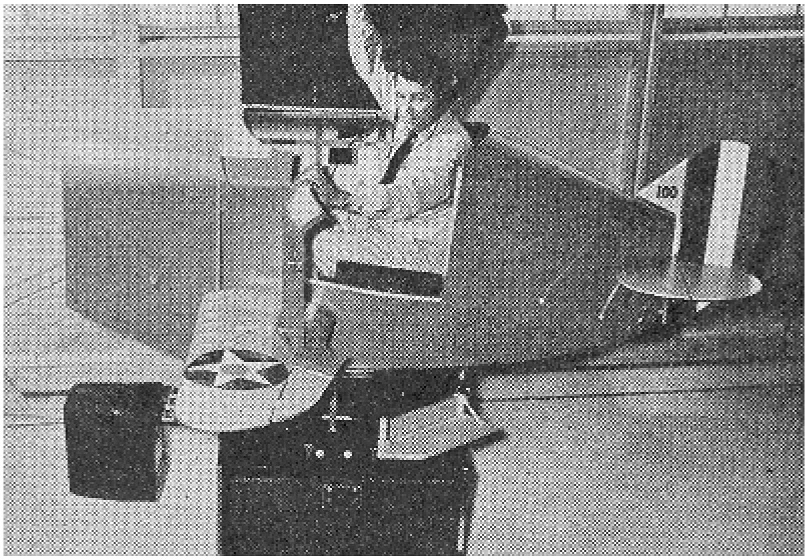


Fig 106: The Early Link Trainer for IFR Training.

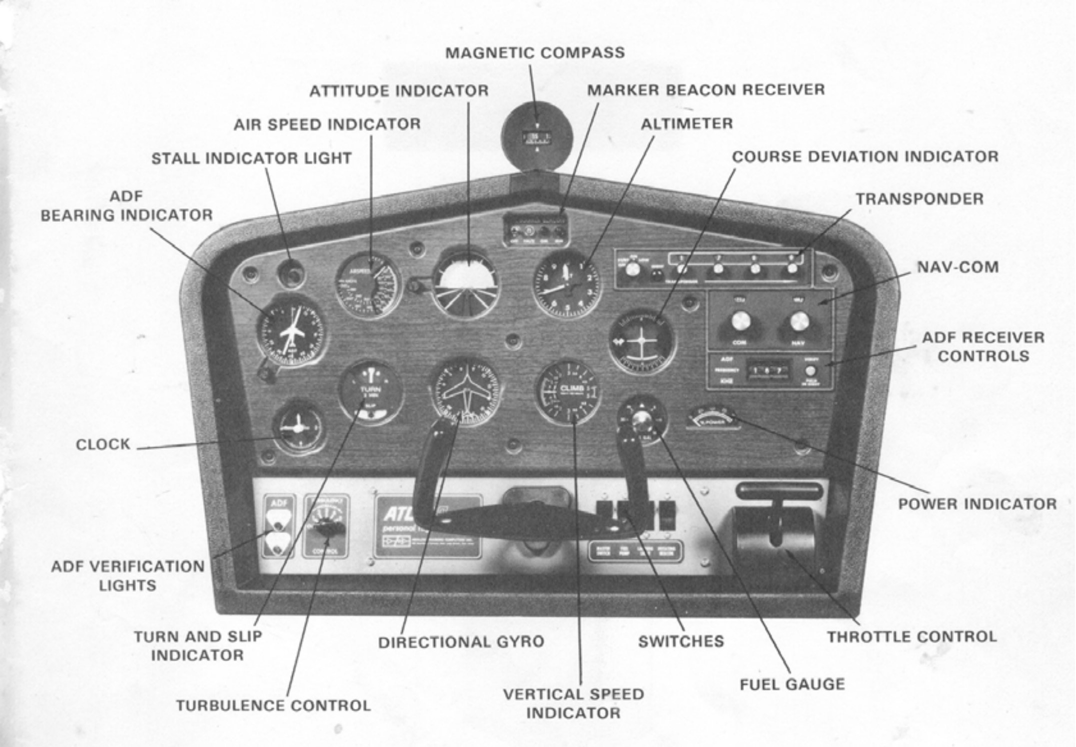


Fig 107: ATC 510 Flight Simulator

4.30.4.3.3.16 Flight Simulators

4.30.4.3.3.16.1 The earliest flight simulator was made by Link in 1930 after development in 1929. Instruments responded to stick, rudder & throttle, with limited pitch, roll & yaw action of the mini plane. Shown in Fig 106. This was used during WWII for a portion of the instrument flying training of fighter & bomber pilots. Actual flight was still necessary. After the war it was used for civilian pilot training & proficiency. More recently major advances were made in flight simulators.

4.30.4.3.3.16 .2 The ATC 510 & 610 flight simulators were introduced long after the above Link, & before the introduction of PC based flight simulators. Generally flight simulators must be attended by a CFII for flight simulator time to be logged. For unofficial IFR practice they were quite helpful. The author found his ATC-510 to be much more difficult to fly than the family Cessna because it lacked the "feel" & motion. With the turbulence selector set to "max turbulence" & no seat or panel movement or vibration, the only indication of rapid pitch or roll change, a constant instrument scan was much more important than on the Cessna. Constant instrument scan is always essential when flying IFR, but aircraft motions are sill useful. Moreover, the instruments deflected much further & more frequently than the Cessna in any weather that it should be flown in. The unit could be flown on a standard flight, with missed approach & quick return to FAF if desired. It fit in well in the family room, & served him well, although he found that a few approaches each week end in the Cessna was still valuable. In fact, the FAA allows only a moderate percentage of logged IFR time be simulator if it is to be used to meet minimum IFR proficiency requirements. IFR proficiency requirements changed near the millennium. An extension of the frequent practice (or actual IFR) is the BFR (biannual flight review). The BFR applies to all aspects of flight skills & knowledge for all pilots. An instrument rated pilot must demonstrate IFR skill during his BFR if his intent is to continue flying IFR.

4.30.4.3.3.16.3 Over the years flight simulators became so realistic that some airline pilots say they must continuously say to themselves "this isn't real" as the instructors add 1 "emergency" after another, until he could no longer control the plane. They are a very effective way to keep pilots sharp without the risk of an actual crash. Fig 108 illustrates the actual panel of a typical Cessna Citation biz jet. The flight simulator used to train & confirm proficiency looks exactly the same, & vibration & movement are so realistic that it is convincing. Flight training centers are readily available, for a price; but such training is much less expensive than proficiency flying in the real jet.

These simulators are now available for smaller planes, too, & many pilots enjoy the "unofficial" PC based simulators. Some are used by small flight schools to supplement their training planes.

Fig 108: The Cessna Citation Instrument Panel; or a Flight Simulator? It could be either.

4.31 Area Navigation (RNAV)

4.31.1 Background

Aero Nav under

IFR flight in the U.S. has always involved positive control, meaning that ATC must know where each plane is at all times so that adequate separation of aircraft could be assured. This was practical only with Radar coverage or positive positional information. Radar does not cover the entire length of Victor airway, but intersections & OMNIs served as reporting points. Pilots were required to provide an ETA to several points along the route. Radar does not cover the entire surface of the U.S., so the only practical method of assuring separation has been to require that all IFR traffic fly only on airways, & advise the ATC of time of passage over each VOR, & often also at some intersections. As the system improved ATC stopped asking for position reports at intersections, & eventually at VORs. As more flexible & accurate Aero Navigation systems became available the concept of "area nav" became practical. With only OMNI & ADF, fixes were convenient for pilots & ATC only at VORs & in some cases intersections. VORs only provided continuous LOPs; not fixes.

Inertial nav had been used by large jets; largely for international flights. RNAV was evaluated experimentally in the 1970s, but was unsuccessful. The FAA denied approval.

4. 31.2 Theory

With the introduction of LORAN, & later GPS, each pilot had continuously updated fixes, ATC could call & immediately receive an accurate fix from any IFR traffic. It was practical to allow virtually all IFR traffic to fly directly between any two points without risk of collision. In converging areas such as major airports ATC had radar coverage to monitor all traffic, & vector any out of the paths of others when justified. Officially called RNAV, it is based on "free flight", which is another term used to describe AREA Nav.

4. 31.3 Accuracy & Efficiency

Accuracy depends on specific Aero Nav system used, but both GPS & LORAN were exceptionally accurate regardless of location or proximity to VORs or major airports.

Airways are much more efficient than freeways, but direct flight is even less wasteful. The East coast is particularly inefficient in terms of distance, & even more so in terms of time. The frequent trip by the author mentioned before indicates the benefit of area nav. His flight from T41 (Houston area) to GUP (Gallup) is 900 air miles. By freeway with I - 10 to I - 25 to I - 40 is 1200 road miles. Headings are a constant 300° by air vs. roughly 285°, 360° & 285° by road; very devious.

4. 31.4 Application

RNAV is of great value, not only because it permits direct routes between any two airports, but because it reduces flying time & distance.

LORAN & GPS permit all types of planes to fly between the smallest airports in the country; or the largest. Remote locations are as easily accessible as congested ones.

RNAV approaches are usually terminated with GPS approaches.

4.32 New Concept A (WAAS)

4.32.1 Background

The familiar conventional GPS lacks the precision for low minimum instrument approaches, & is not otherwise as precise as desired. Several factors introduce errors into the GPS network. Water vapor in the troposphere slows the signal. Charged particles of the ionosphere also contribute. The atomic clocks that finally made the GPS possible are still imperfect. With electromagnetic signals traveling at the speed of light, timing errors of a few microseconds are still serious.

Testing began for methods of improving GPS by means of an external reference system.
WAAS was commissioned by the FAA in 2003 for use in Instrument approaches. It is still unknown in most aviation circles.

WAAS (Wide Area Augmentation System) was developed using a similar principle as DGPS (Differential GPS), but covers a much broader area.

4. 32.2 Theory

The developers of WAAS theorized that Ground based links would be capable of measuring the errors, applying corrections, & rebroadcasting the necessary corrections to improve the overall GPS system.

In the U.S., "reference GPS receivers" were positioned at precisely known locations on the ground. GPS signals are received by both fixed & moving receivers.

The usual GPS receiver uses time differentials to determine position. The reference receivers know precisely their location, so instead, reverse the process, & determine what the signal travel time should be. The difference between measured & theoretical times are applied as a correction factor. With that they can correct the GPS positional data & provide more exact aircraft position.

The error information is sent to two master stations (one on the U.S. east coast, one on the west coast) which calculate correction algorithms and assess the integrity of the system. A correction message is uplinked to the two WAAS satellites via a ground uplink system.

The two satellites are in geostationary orbits. These satellites then transmit the correction information back down to the GPS user on the GPS frequency. The GPS receiver then decodes this information and applies it to its calculated position to significantly improve the accuracy.

4. 32.3 Accuracy & Efficiency

Although users & manufacturers quote a wide variety of accuracies, GPS is generally considered to have an accuracy of roughly 30 ft.; some claim 6'. Resolution in aircraft GPS units is much larger.

The WAAS system results in location of an aircraft within 10 instead of 30 ft. This level of accuracy is not important for cruising IFR on a long flight. It is, however very important for instrument approaches.

WAAS permits landing with lower ceilings & visibility, thus increasing the versatility of any plane equipped for WAAS.

4. 32.4 Application

Aircraft that are equipped for WAAS are capable of high precision instrument approaches as well as more accurate enroute navigation.

This revolutionary system greatly extends the value of GPS Aero Nav & instrument approach capability.

The plane must be equipped with a WAAS capable receiver; not a separate, special receiver.

4.33 New Concept B (ADS-B)

ADS-B is Automatic Dependent Surveillance Broadcast

This system, like Instrument approaches, is not actually an Aero Nav system, per se. But, like Instrument approaches, it does cover the final stage of any IFR flight, although it is also useful under VFR conditions. If IFR the airport is out of sight, so some form of Aero Nav is required to locate & fly to the runway.

The FAA realized the need for major improvements in the air traffic handling & control & initiated search &

4.33.1 Background

development aimed at what they call the Next Generation of the Air Traffic System.

The FAA wants improved information on location, altitude, & velocity (heading & speed) of all enroute & " local "air traffic. The solution proposed involves increased use of a modern satellite-based system; for the Next Generation of the Air Traffic System. The current system is, for the most part, decades old, with a few serious weaknesses. Radar is excellent, but the line of sight limits range & coverage area severely. With Radar, ATC knowledge of air traffic is seriously lacking. The only information on nearby traffic that is available to pilots is whatever ATC elects to provide to them, via voice communication, which is already overcrowded. Information is limited to areas covered by Radar; generally near large airports.

The FAA recognized the need to:
- Improve situational awareness.
- Increase traffic volume.
- Reduce the risk of mid-air collisions.
- Improve communication.

The cost of procuring, maintaining & staffing Radar sites is excessive considering the moderate amount of coverage.

Radar does not cover the entire country, even at high altitudes, much less at the surface.

America is such a large country, with three large mountain ranges, that it is impossible to provide Radar coverage over such a large land mass to the critical lower altitude.

Enormous portions of the U.S., including that serviced by airlines as well as lightplanes, are beyond Radar coverage near the surface. Radar is important, but not mandatory for IFR approaches. Since airliners file IFR for all flights, many of their approaches, in all types of weather, are accomplished without Radar.

The Williamsport, Pa (IPT) airport is only 125 miles from New York city, & has Radar coverage only above 4,000'.

The Northwest coast of the U.S. (Oregon) has very little Radar.

The Jackson airport in Wyoming only has Radar coverage above 13,500'. Alaska has similar coverage; only high level in many areas.

Fewer than half of the instrument approaches to non tower airports under the control of "Houston Center" (Texas) have Radar coverage. Note that the "Center" covers large areas; not just, in this case, Houston.

Only a moderate percentage of the airports included under the umbrella of Houston Center have Navcom. VHF, like Radar, is line of sight, so has limited coverage. That is one advantage of flying Victor airways; nearly certain to have communication

Improved weather information availability is desired.

WAAS had been implemented, but it was limited. RNP is in the early planning stage.

4.33.2 Theory

Provide continuously updated position, altitude, & velocity information to & of all planes & ATC within a specified distance from each; a seemingly impossible task. Provide this by interrogation & integrating of GPS information. Provide in form of a cockpit screen much like a moving map or Radar display. The voiceless communication routes are illustrated in Fig 109.

4.33.3 Accuracy & Efficiency

The GPS based velocity & position information is more accurate than required for operational separation.

Better & more accurate information improves the ability of ATC to blend all enroute & landing traffic to & from points of interest with minimal interference or deviation from the shortest route for each plane; especially to the active runway.

The value & efficiency of having all ADS-B equipped planes & ATC (or Tower or Approach Control) fully aware of each plane in the air, including location & direction of flight is enormous. This information is even more valuable in the event of IMC.

4.33.4 Application

4.33.4.1 FAA Involvement:

In 2006, the FAA approved funding for ADS-B at eight sites.

ADS-B provides improved knowledge, of altitudes, locations, & velocity of all traffic by all traffic; to all planes & ATC.

FAA releases also say "pilots for the first time will see the same kind of real-time traffic displays that are viewed by controllers" to improve situational awareness. This will dramatically improve pilots' situational awareness, since they will know where they are in relation to the runway, other aircraft, weather and obstructions. Full implementation over the entire continental US will take 20 years.

With its combined increases in safety, efficiency, and capacity, and reductions in cost, ADS-B is critical to the agency's Next-Generation Air Transportation System.

ADS-B is one of the most important technologies for the modernization plan that the FAA developed.

The FAA issued approved standards for ADS-B avionics for Genav planes in December 2009.

4.33.4.2 Testing Activity:

Alaska is typically ahead of the crowd, as they were with RNP (Aero Nav system No. 34). In the case of ADS-B Alaska was the first to implement test stations when they led the way for ADS-B in 2006 with the initial testing of the system. UPS voluntarily equipped its aircraft with ADS-B cockpit displays, and is saving time and money on flights to and from its Louisville hub due to the improved efficiency available with satellite technology.

Alaskan pilots & ATC personnel proved that ADS-B is affordable technology & destined to serve aviation there & elsewhere well into the future, improving general aviation safety & FAA operations.

4.33.4.3 Capability:

This technology is already showing benefits in safety. There was a substantial drop in the accident rate of aircraft equipped with ADS-B avionics in Alaska.

In addition to improved safety in the sky, ADS-B will help reduce the risk of runway incursions. Both pilots and controllers will see the precise location on runway maps of each aircraft and equipped ground vehicles, along with data that shows where they are moving. These displays are clear and accurate, even at night or during heavy rainfall.

ADS-B will also increase the ATC system capacity by allowing aircraft to fly safely with reduced time & distance between them. Because ADS-B accuracy also means greater predictability ATC will have better capability to manage the air traffic arriving and departing from congested airports, resulting in even more gains in capacity.

It offers both pilots & ATC improved situational awareness while providing very high precision surveillance, including traffic & weather information.

ADS-B surveillance is much more informative with long range & 1 second updates, vs. 6 to 12 second sweep time & short range of radar surveillance. It is also superior to Radar with respect to discrimination between aircraft.

Aircraft transponders receive GPS data from other aircraft & use that data to determine the aircraft's precise position in the sky, which is combined with other data and broadcast out to other aircraft and ATC.

ADS-B receives full GPS positional information (real-time) from each aircraft in the surrounding airspace, & provides all information to each pilot as well as to ATC. It will provide situational awareness in controlled & uncontrolled airspace; enroute & throughout instrument approaches, including clear visual displays of traffic.

ADS-B updates transmissions from all aircraft every second, giving position, altitude, identification, velocity & other information.

_ADS-B affords "line of sight" surveillance with ranges of the ground stations as great as 250 NM

ADS-B actually began saving lives during the proof-of-concept period.

ADS-B can be employed in primitive & remote areas even in third-world countries

ATC surveillance can be provided in locations where Radar is not justified; even if only because of cost.

An ELT often fails, & transmission may also be obstructed, such as in a canyon. ADS-B will alert ATC of a problem simply by vanishing. Recordings can be reviewed immediately to permit retracing flight path for determination of probable crash or landing site.

4.33.4.4 Plans for the future:

ITT has a contract that calls for an ADS-B system ready for commissioning by 2010, & sufficient stations available by 2013 to replace all existing airport Radar stations with ADS-B.

The FAA expects to mandate installation of ADS-B avionics in some airspace by 2020 (presumably only in class B airspace; much broader limitations would devastate some segments of Genav).

As of early 2010 Alaska, Houston, & Florida have operating ADS-B stations. Louisville, KY & Philadelphia are planned for implementation in the near future.

4.33.4.5 Potential Limitations:

Cost may limit many who might benefit from ADS-B. Neither the FAA nor ITT have disclosed an actual cost for each plane. Only test units have been distributed; & to a selected few.

The FAA reports that they have not estimated cost per-aircraft for ADS-B avionics, but consider it relatively low. Also, "Everybody equipped is everybody best served. If most aircraft are equipped, our entire system runs better."

To receive all of the benefits of ADS-B, the planes must be equipped with new, appropriate avionics.

That Fokker Triplane, & the Wright Flyer "may not" be suitable for such equipment. ADS-B tests have, however, proven that the system functions well in lightplanes.

4.33.4.6 Summary (FAA official list of ADS-B Benefits):

Provides air-to-air surveillance capability.
Provides surveillance to remote or inhospitable areas that do not currently have coverage with radar.
Provides real-time traffic and aeronautical information in the cockpit.
Allows for reduced separation and greater predictability in departure and arrival times.
Supports common separation standards, both horizontal and vertical, for all classes of airspace.
Improves ability of airlines to manage traffic and aircraft fleets.
Improves ability of air traffic controllers to plan arrivals and departures far in advance.
Reduces the cost of the infrastructure needed to operate the National Airspace System.
The FAA spokesman declined to state a cost per-aircraft figure for ADS-B avionics, though he said the figure was relatively low. "Everybody equipped is everybody best served," he said. "If more aircraft are equipped, our entire system runs better".

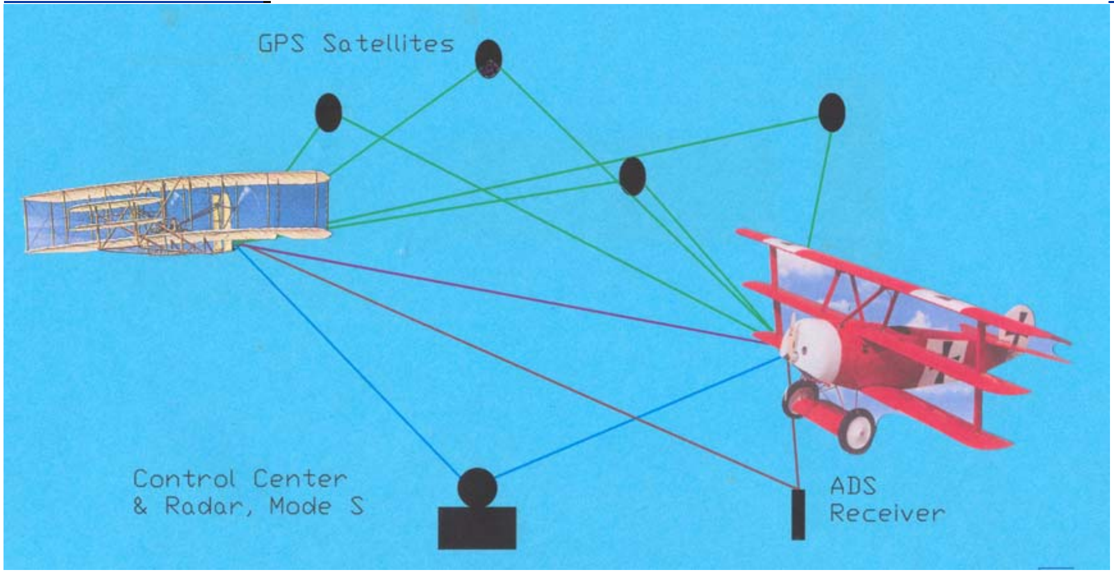


Fig 109 : Vintage Aircraft Fitted with Advanced Avionics; ADS-B

The ADS-B system in operation is schematically shown in Fig 109.

- Green lines represent GPS signals from all satellites within view of planes; for reception by planes.
- Magenta line represents signals sent by each ADS-B equipped plane toward all other ADS-B equipped planes within range; & received by same.
- Blue lines represent signals sent by each ADS-B equipped plane toward control center radar.
- Red lines represent signals sent by each ADS-B equipped plane for reception by ground based ADS-B receiver.

4.34 New Concept C (RNP; Required Navigation Performance);

Revolutionary Extremely Precise & Versatile Aero Nav-Instrument Approach System. So new that only 11 of several hundred airports were equipped for it by mid 2009.

4.34.1 Background

As aircraft capability improved, the need for improved systems & procedures increased, many airports were severely limited by unfriendly terrain such as mountains.

In the case of RNP it was an airline pilot (Captain Steve Fulton) who realized the need for major improvements in instrument approaches in mountainous areas. The ILS, being the most precise instrument approach, requires a long straight approach at a moderate slope angle, so is not suitable for turns near the runway to avoid mountains. Alaska Airlines & many other, were forced to use low precision instrument approaches on some runways, which resulted in more aborted flights during poorer IMC conditions. A need existed for a system that permitted turning while on the approach, but with the precision of the ILS.

The FAA ATC system fell progressively further behind with obsolete ATC electronics & procedures. Their search for equipment & methods to improve the airspace system resulted in the development & perfection of WAAS & ADS-B.

Captain Steve Fulton with Alaska Airlines conceived & demonstrated a system that would permit flying any curving path that may be necessary to complete an instrument approach in mountainous terrain.

When fully implemented WAAS & ADS-B will fulfill only a portion of the above FAA goals. RNP will represent a major improvement in the overall ATC system, including FAA goals. It will also provide an enormous increase in capability to safely handle larger traffic volumes to satisfy another important FAA need.

4.34.2 Theory

Given data from enough GPS satellites with 3D data base, including a full model of all mountains, & other data entered into a sophisticated computer, a plane can be flown on a devious course with multiple descending turns for an instrument landing with previously impossible precision, & complete safety. The computer could precisely predict the optimum path & glide slope to reduce time & distance between start of descent & touchdown. As development continued, the addition of full glide & traffic avoidance capabilities were added.

4.34.3 Accuracy & Efficiency

RNP Accuracy & Versatility are unsurpassed. RNP is one of the few cases where the autopilot controls the plane so very well & accurately that a pilot simply could not compete. Further the complex computer can track exactly midway between two mountains at each level & location more accurately than a pilot could in VFR weather.

In terms of cost & time savings RNP is truly unsurpassed, & indeed, revolutionary. The efficiency results in saving many millions of dollars in fuel cost annually. Freedom from ground based Navaids allows flying the ideal ground track rather than flying between a series of Navaids such as VORs. The ability to fly a series of alternating gradual left & right turns to equalize clearance from several mountains on each side not only increases efficiency but allows operation where no other instrument approach is possible. In one case the VOR minimums were near 2,000' & 3 mile visibility, an approach thet required spiraling down into a canyon, while RNP has a direct curving path with 250' MDA & 3/4 mile visibility.

4.34.4 Application

4.34.4.1 The concept:

The RNP was conceived in 1992 by Captain Steve Fulton. He immediately began developing RNP. After developing 30 different approaches, the first RNP landing was demonstrated in Alaska in 1996. In February 2003 Captain Fulton, Alaska Airlines Captain Hal Andersen, & Dan Gerrity founded Naverus to formalize RNP. It did require some very unique sophisticated avionics, including dual integral computers. Naverus revolutionized instrument approaches in difficult mountainous regions. The FAA evaluated & certified these approach procedures. Advanced avionics are used, & special crew training is required. The initial goal was to permit safe instrument approaches where mountains prevented conventional ILS straight in approaches. It simply is not possible to design an ILS approach with a series of turns; or even one turn. Multiple turns are practical & safe. Some of these Alaskan airports were also located in remote areas where Navaids were limited.

4.34.1.2 Implementation:

Before RNP was practical an exceptionally detailed & precise data base was required. Three dimensional data on each mountain was essential; not a simple plan view or profile; but a true model of each mountain in the vicinity of each RNP approach. RNP procedures rely on onboard avionics to keep an aircraft within specified bounds. As usual for Engineering & aviation, avionics must include redundancy throughout. Most important will be the Flight Management Systems (FMS) consisting of dual interrelated exceptionally complex computers with advanced dual GPS receivers. RNP must track obstructions, including terrain, such as mountains, & other air traffic. It must continuously update all information. Each FMS must establish & continuously update positions, & select optimum track, including altitude, throughout the entire approach. The FMSs must communicate & advise the pilot if there is a disagreement between the two. They must also notify the pilot in case of failure to maintain specified accuracy.

The RNP includes an inertial navigation systems to assure availability of precise positional information in the FMSs in the event of total loss of both GPS receivers. The Flight Management Computer algorithms also include the radius of each turn & the performance capability of the plane at any likely gross weight, in level flight, & in descent or climb, at any bank angle that might be required to fly any particular approach, & for any possible temperature or wind. The Honeywell Enhanced Ground Proximity Warning System (EGPWS) is important to assure adequate terrain clearance, but with the necessary turns that must be made, the EGPWS may issue a warning when flying directly toward a mountain. RNP approaches are flown by the FMC directed autopilot both vertically & laterally; not manually.

RNP is so precise that the desired track is typically held within 1,000'. Some who tested the system report it as 100'. The GPS positions are actually good to 12'. RNP approaches are identified by accuracy in decimal NM;

0.11, .15, 0.25, etc.. A 0.11 indicates 0.11 NM; or 669'. The computer is capable of analyzing & applying information to determine the shortest & fastest optimized route from any position (such as start of descent) to the runway based on all available information, & idle engines when practical.

Information & action required includes the best known 3 dimensional information for the descent path including:

- W/V from plane position to the runway.
- Plane.
- Intended runway.
- Each obstacle along the route to the desired runway per GPS Data Base.
- Each potential obstacle in terms of Radar Altimeter & collision avoidance sensors.
- Position of each plane in the vicinity.
- The expected changes of all other air traffic.
- The actual changes in any of the above must be detected & corrected.

The computers "continuously" update relative locations of all of the above fixed & moving objects. It also predicts these relationships & adjusts accordingly.

Important: The FMS units monitor all sources of information, & immediately notify the pilot if accuracy is out of spec., or if the two FMS units disagree.

The computers (FMS) must determine the shortest optimum route, with optimum deviations, from the aircraft position at the start of descent to the runway, based on all information; including real-time highly precise navigation information, relevant traffic, 3D obstruction models, & "idled" engines, when practical.

Idling engines on most approaches actually will save several million dollars worth of fuel per year for any major user airline.

To optimize RNP, many parameters had to be considered to accomplish the necessary goals. These included all aspects of aircraft performance; weight, speed, & winds from the surface to cruising altitude.

4.34.1.3 Examples of RNP approaches

The developers quickly realized that RNP had considerable merit for use in congested areas as well as in mountainous terrain. A series of approaches & departures from a large airport in the same high density area also constituted "obstructions"; just moving & of a different nature. RNP has the capability of maintaining separation in areas like NY City.

The RNP approaches and departures in several high traffic areas in the U.S. were simulated by realistic multicolored lines following curved paths in a promotional illustration by Naverus; representing a short period of time. The number of lines were amazing.

Reagan Washington National Airport is an example of an airport that has no mountains, but does have "no fly" (Restricted) areas nearby. The Reagan Airport RNP approach is illustrated in Fig 110. Although it shows a 10.7 NM straight line final approach, as it would with an ILS, it may actually be flown with a very long sweeping curved path. The direction of this path would then be the most efficient route from some point on the path that the plane is arriving from. All RNP approaches are routed for maximum efficiency, for the lowest possible fuel burn, & time expended. Properly performed, the plane would actually glide the last 50 to 100 miles of its flight.

The RNP approaches and departures not only allow Alaska Airlines to operate more safely into airports that are surrounded by high, rough mountainous terrain, but they also allow lower approach ceiling & visibility minimums for landings, & even reduce takeoff minimums. Lower minimums reduce the number of flight cancellations & improve the airline "bottom line"; income vs. cost. Another benefit is "happier airline passengers".

The FMS permits flying the shortest, but also the least obtrusive approach path. This permits reducing separation & thus time between landings. The number of flights per hour can be increased significantly; in some cases, twice as many operations per hour at any given airport. Each plane can follow a precisely optimized radius of curvature path.

Since Alaska Airlines developed RNP & obtained FAA approvals, they took the lead in expanding RNP in the lower 48. They operated in Alaska & elsewhere while other airlines stood idly by waiting for an opportunity to follow Alaska's lead; even in Alaska.

Alaska soon developed a RNP procedure for the Palm Springs CA. airport, which had very limited instrument approach capability. Some runways had no instrument approaches at all; others had excessively high minimums.

Alaska Airlines was able to obtain approval for airports that were lacking instrument approaches, or had excessively poor minimums, & reduce minimums from as great as 1,800' to only 250 ft. & 3/4 mile visibility. Truly an amazing & beneficial improvement. Alaska Airlines quickly saved several hundred thousand dollars per year in cost on that Palm Springs route alone. The difference between 1,800' & 250' obviously had an enormous impact on flight cancellations. At another airport RNP permitted reducing minimums from 971' to 340' by displacing its localizer approach.

Several foreign countries are noted for their exceptionally difficult or dangerous airports. China has one that is particularly difficult & hazardous. Chengdu Shuangliu International Airport in Tibet actually has an elevation of 14,200' (approximately 57% of the S.L. atmospheric pressure), with many nearby mountains, including one at 25,000'. For adequate terrain clearance the approach must be started from above 24,000 ft. The airport is far below the surrounding mountain peaks, so the approach follows a torturous path that bends around the mountains repeatedly during the descent; in "passes" as narrow as 1 NM at several points, & making a sharp 90° turn at one place. Turn radius must be precisely correct each time. Considering the fact that the turn radius to bank angle relationship is dependent upon TAS, & the radius must be planned over the ground, the algorithm must account for any wind changes; including head vs. tailwind. The bank angle must significantly exceed the norm for airline flying at times. The runway is obviously not in sight until near the end of the flight. Part of the curving is in following a typical mountain river, the meandering Yaluzangbu River. Although the pilots are unable to determine the proper ground track they can watch it all unfold by watching the typical GPS moving map screen.

Flying the devious descending route into Shuangliu International, under VFR conditions would be somewhat stressful for most pilots when operating at an altitude that limits performance significantly. Programming a conventional GPS for such a flight would nearly be impossible because each turn must be approximated by a series of short straight lines with many waypoints; probably more than memory would accommodate. Flying that

GPS flight plan by GPS would certainly be stressful. If that program had included a separate altitude reference on a spread sheet that was essential for that descending approach, the thought of flying it under IFR conditions might well result in a cancelled flight. A wait for VFR weather would be the logical choice if the author were faced with it.

Even with RNP the "snaking" descending approaches under IMC would frighten most pilots.

In the late 1960s the author built up his courage, after which he occasionally flew into a nice long high elevation downhill runway at Ruidoso NM where the VFR approach required a normal Downwind leg, with a mountain blocking the view of the runway at times along two legs. Terrain permitted a normal 90° turn onto the first Half of a Base leg from which a 45° turn was required. Midpoint in what would have been a normal Base leg that 45° turn placed the plane on a "Semi-Final". A second 45° turn was required to align with the runway; for the short Final. There was no IFR approach to that airport. It simply was not possible. Were that airport still there, RNP could provide a safe approach, but with an even narrower route than at Shuangliu International; tooclose for comfort at best. The Ruidoso approach by RNP would still discourage most pilots. There are many similar & vastly more difficult approaches around the world. Alaska has its share. An example is one where RNP provides the degree of precision necessary to deviate around assorted mountains & descend to an IFR minimum altitude of approximately 200' AGL.

A factor in obtaining approvals for RNP at any airport in the U.S. is that the FAA must be involved in the demonstration of each new approach at each airport.

4.34.1.4 RNP benefits:

RNP is the system that will provide the FAA with the greatest advance; is leading them into their new Trajectory-Based Operations (TBO), as part of the FAA NextGen (Next Generation) Goal. TBO is part of Performance-Based Navigation. The FAA authorized development of the TBO concept, including arrival procedures with vertical profiles optimized for continuous minimally curving descent beginning with transition from cruise to let down, & continued to touchdown.

Testing proved that RNP will result in reducing annual fuel cost by many millions of dollars per airline.

For RNP to function, a greater degree of precision is required. RNP includes the ability to turn closer to the runway, which is essential.

Proposed RNP routes into Los Angeles International direct aircraft to glide down to the runway following a large radius curving path that is optimized for the particular route (departure airport location direction), with the last 70 miles in a glide.

Another merit in RNP is the fact that total engine failure, although extremely rare, would not prevent a safe landing, since the glide path should not be changed. If necessary small drag reductions could be implemented, & even then the FMS would assure the proper glide angle.

RNP saved DFW $10 million per year on departures alone per initial analysis.

RNP saved Atlanta $34 million per year on fuel during departures alone per initial analysis. Departures also benefit by using RNP.

At PHX, RNP will reduce the time that aircraft remain in level flight by 38%, resulting in a savings of $2 million on fuel per year.

RNP improves safety, access, capacity, & predictability. RNP improves operational efficiency, enhances reliability & reduces delays.

An FAA news release stated that San Francisco can land 60 planes per hour in good weather, but only half that with reduced ceilings or visibility. RNP can greatly reduce fuel burn, noise & flight time by improving approaches. Their typical descent and approach takes 33 minutes, 40 seconds and burns 367 gallons of fuel. The RNP approach reduces time by 9 minutes & reduces fuel burn to only 120 gallons.

Although RNP is very costly, & requires special pilot training, the added cost will be quickly offset by fuel savings, reduced aborted flights, & passenger satisfaction. Although RNP is obviously not appropriate for small lightplanes, it will be justified by many in the general aviation fleet. UPS & FED X are involved in testing.

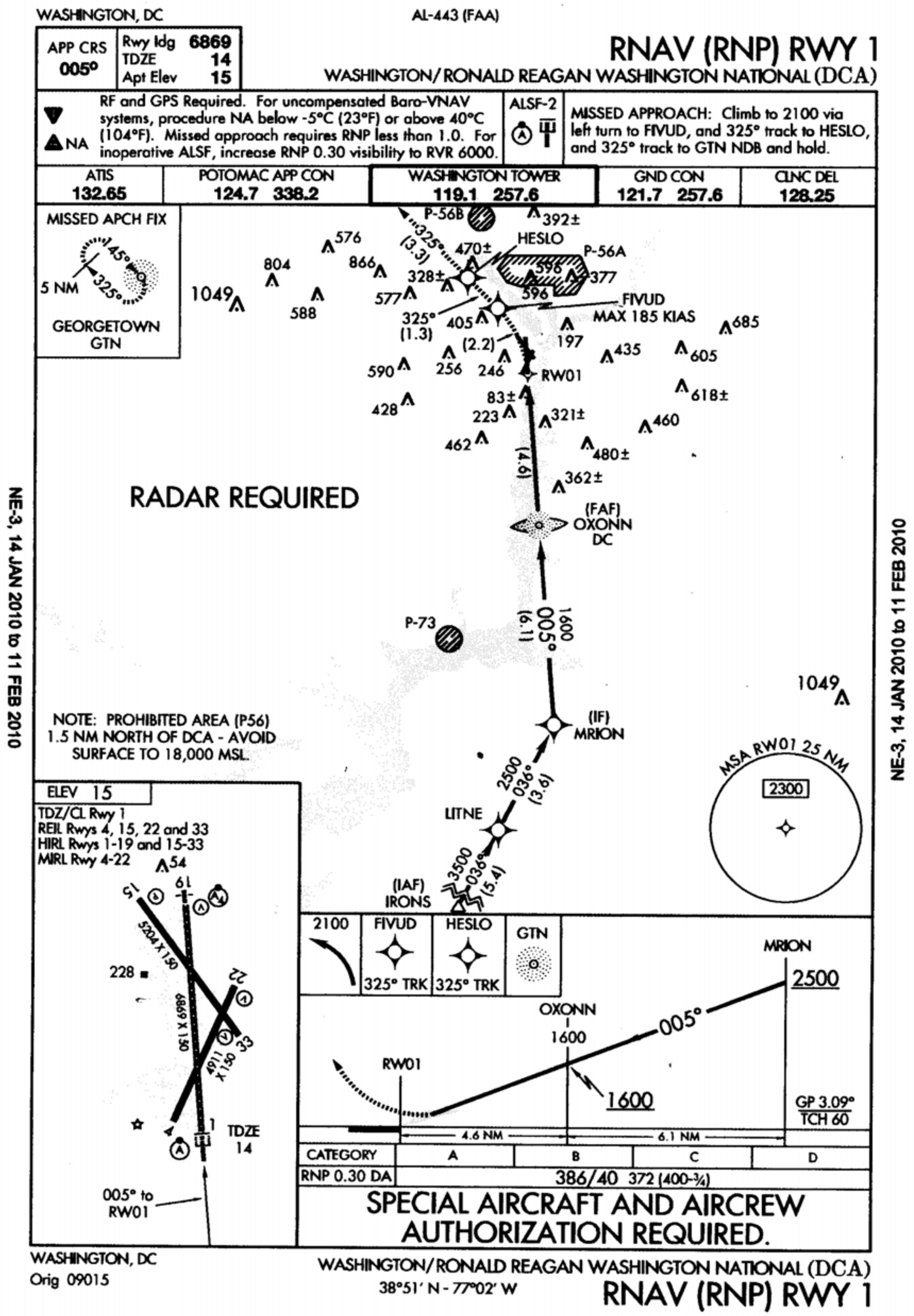


Fig 110: RNP Approach

Fig 111: RNP Illustration of High Density Traffic In & Out of a Major Airport

Fig 111: RNP illustrates congestion & inefficiency before RNP at a high density airport.

Southwest airlines, the largest (carries more passengers than any other airline in the entire world), most respected airline in the U..S., was the next to obtain approval for RNP. By mid 2009 Southwest had proven the possibility of saving many millions of dollars per year on fuel alone. It permits them to improve on their already unexcelled record of on-time flights. One reason for their popularity is their exceptional attitude toward customer service. Another is that they are employee owned, which virtually eliminates baggage theft.

FAA states that RNAV procedures can provide benefit to planes in all phases of flight, including departure, en route, arrival, approach, and transitioning airspace. This includes:
- Increase predictability of all operations
- Reduce controller/aircraft communications
- Reduce fuel burn with more uniform descents
- Reduce the number of miles flown in Terminal Radar Approach Control (TRACON) airspace

4.35 Fully Automated - Manned & Unmanned Aircraft - & What Does the Future Hold?

NASA & GAMA (General Aviation Manufacturer's Association) are proposing fully automated travel by lightplanes. The FAA proposed a fully automated, unmanned, single passenger carrying commuting helicopter. This is not being received well by pilots who trust their own flying skills more than the best of fully automated systems; besides, most fly for the "love of flying".

4.35.1 Background

4.35.1 The autopilot was the first step in fully automating flight. The first aircraft autopilot was developed by Sperry Corporation in 1912, although it is doubtful that it was installed in any except the larger planes. Since very early aircraft were quite unstable they required continuous attention in the air, so the autopilot was welcomed by some pilots. As aircraft matured, & became more stable the autopilot had merits in difficult modes of flight, or for long range flight. Some planes, such as fighters & serious aerobatic types still require close attention, because stability reduces the essential maneuverability, but autopilots are not justified in such planes. Most pilots who fly for pleasure prefer to do all of the flying rather than leaving that up to an autopilot.

Early autopilots were limited in the number of controls they manipulate. The buyer can still select the level of help he prefers; or the amount of money he is willing to spend. Single-axis autopilots only control the roll axis, & are often referred to as wing levellers. They could well save an inexperienced pilot who inadvertently flew into IFR weather, but his reliance on a wing leveler is likely to cause even greater risk in the long run. They are actually controlled by linking to a T&B or Turn Coordinator gyro, which senses yaw instead of roll. Since roll produces yaw, that works well. Autopilots that control pitch & yaw are directed by AG & DG gyros. Some autopilots also manipulate the throttles. Some automate different phases of flight. A very useful & popular feature of more complex autopilots is Navaid tracking capability. They track OMNI, GPS, etc., so keep a pilot from drifting off course The most extreme case of control by the autopilot was described in the previous Aero Nav system; RNP. Autopilots use mechanical, electrical, or hydraulic devices to manipulate controls. Some small autopilots on lightplanes control only trim tabs rather than the actual control surfaces, which require so little force that model airplane servos provide the necessary force & travel. Most lightplanes are flown solely by the pilot, so have no autopilot. Many small airliners are not fitted with autopilots; particularly commuter planes that operate only for short periods of time. One might expect an autopilot to reduce pilot work load under intense IFR flight, but the reverse is true. Autopilots often lose stability in severe turbulence or large angles of roll or pitch. Icing build-up can result in mixed messages even for a sophisticated autopilot, & cause excessive contradictory control movement to the point of loss of control. There are conditions when a pilot must retain control & "feel the control forces". Some autopilots oscillate excessively; including the Boeing 737. An ATP once said that the 737 can cycle from 500 to 2500 fpm during climbs or descents; much more rapidly than passengers would like. For that reason he does not use the autopilot during those phases of flight. Under extreme weather conditions some airports, pilots, autopilots, & planes must actually be qualified for CAT III, which was discussed under instrument approaches; in paragraph 4.30.4.3.3.5.2.

More sophisticated modern autopilots actually integrate avionics & computers to control the aircraft. The computer determines the current position of an aircraft, & directs the FMS (per the RNP system) to control pitch, roll, yaw, & often even power, to optimize the flight path & TAS. Some autopilots are more effective at minimizing fuel consumption than pilots.

Fully automated short run trains are operational for such things as transfer of people between airport terminals, but these are very simple compared with planes.

4.35.2 Theory

To fully automate the flying of a plane from TO, climb, navigation, descent, & landing, would require a fully integrated complement of computer, Aero Nav systems, 3 axis control gyros, power integrated with elevator especially, & a 3 dimensional navigational data base with information on Navaids & geographic positions of all, along with land mass profiles. The computer would of necessity be required to adjust for unusual circumstances, such as an engine failure. An autopilot would otherwise slow the plane enough to stall it in trying to maintain altitude after an engine failure.

4.35.3 Accuracy & Efficiency

To be safe a plane flown without any form of direct intervention by a pilot must be extremely accurate. The best example of this is the capability of making a hands-off fully automated Cat III landing.

There is one remaining factor. Jumbo jets are not flared like lightplanes to "kill the sink" immediately before touchdown, for several reasons. If pilots were to attempt to "grease" every landing in heavy jets they would use excess runway. Another reason is that it is much more difficult to judge height above a runway when sitting 50 ft above it than when only 3 to 6 ft high. The failure to flare results in a high sink rate upon touchdown; thus an exceptionally hard landing. Most ATPs flying a jet are exceptionally competent, but few "grease them on"; they instead "drop them in". No pilot would be pleased with such a hard landing in a lightplane. In fact, some planes would be damaged by a typical airliner touchdown. To be successful at fully automatic landings the sensing of height must be exceptionally accurate, & the sink rate must be reduced to a very small value, without "floating" to the end of the runway.

4.35.4.1 Application; Fully Automated Man Carrying Flight

4.35.4.1.1 The next step in aviation, although many years in the making, might be fully automated flight by a "mere passenger" who flips a switch, selects the destination & rides along where he wants to go. A chilling thought for pilots, but probably not as frightening as climbing into a spacecraft. The author has never enjoyed just riding along, even in the right seat, but he is especially uncomfortable when he knows those up front are violating common sense or FAA standards, as in flights to points in Mexico & Honduras. A fully automated lightplane might cause a little tension, unless it included a manual over-ride, & he were qualified to fly that plane. He has often been uncomfortable riding with more experienced pilots whose flying was not what he preferred. He would be more comfortable in airliners if he knew more about the pilots. Conversely, if the pilots were suddenly, incapacitated, & he were the only other pilot aboard, he would not feel capable of landing such a plane, even if a pro were on the radio to talk him through it.

The FAA released its fully automated single passenger personal commuter VTO composite plane concept on Fox News in 2010. It was reminiscent of the Osprey in that it was capable of vertical T.O. & landing, as well as horizontal flight. Computer generated demonstration flight showed rotors opening up & spinning for ascension, transition to level flight, & then reversal of the process to land. It mentioned using UAV technology.
A Popular Mechanics magazine article covered the same plane.

4.35.4.1.2 A variety of successes may lead one to assume that a fully automated man-carrying plane could be possible, The nearly routine fully automated flight including landing of large airliners, carrying hundreds of passengers, by use of Cat III, proves the concept of fully automated flight. A major difference in this case is the fact that there are two fully qualified pilots monitoring the panel just in case something seems to justify aborting a landing. If a second officer flying a similar approach made a mistake that justified a go-around, the Captain would do the same. These pilots also make numerous decisions & corrections, & control transitions from one phase of flight to another. Automation to eliminate pilot involvement would represent enormous technological advance.

Certainly the Predator drones must have influenced the FAA., which is staffed largely by pilots, but still decided that fully automated flight is was a worthy goal.

Several $4 million Predators have been lost to enemy fire, but saved many lives in the war against irrational, cowardly terrorists, & greatly reduced the loss of American pilots & ground troops.

The Predator has been controlled from the U.S. by use of a satellite, while flying over Afghanistan.

Predators have performed commendable tasks against the influx of criminal illegal aliens at the borders.

RC model planes ranging from those so small that they can literally be flown in the home, to quarter scale models, have proven the possibility of remotely controlled flight. Some also have autopilots.

For decades the military operated radio controlled target drones. The small McCullough 65 hp 2 cycle 4 cylinder engine powered drones cruised 250 mph & cost as much in 1960 as a 4 passenger Cessna that cruised at half that speed. Before that, during WWII, drones even included the plane that became the cute but hot little Culver Cadet.

Occasionally nearly irreparable WWII bombers were loaded with high explosives & remotely flown for the purpose of crashing into major targets.

"North Dakota deployed its unmanned aircraft to monitor flood" was the title of an AOPA on-line news release to members 3-18-'10. It was actually the University of North Dakota that provided the camera equipped aircraft. Nonetheless, none of these were fully automated for cross country flights without human input.

4.35.4.1.3 Some of the operations required to fully automate all aspects of just one flight would require consideration of many complexities. Multiply that by many thousands day & night all year every year & a few requirements might include:

●● For fully automated plane.

- Develop an exceptionally versatile computer & link to autopilot & digital communication with ATC & NWS. Safety would dictate redundancy, or even triplication .
- Autopilot should be equipped with aerobatic-dog fight type gyros to eliminate loss of control in severe turbulence.
- Install a 3D data base for terrain clearance & Aero Nav.
- Automated weather analysis with go--no-go data decision.
- Install a standard Radar altimeter or one that is more accurate at low levels for landing, as well as for operational terrain clearance; preferably duplicate or triplicate.
- Install software to provide all inputs that a pilot might conceivably provide from TO to landing.
- Develop a non verbal automatic communication system that will respond to automated ATC instructions.
- Develop automatic power & fuel management systems including automated altitude selection & continuous GS vs. distance & fuel analysis; & fuel stop selection.
- Most pilots would insist on selectable pilot over-ride & voice com capability.

●● For ATC system.

- Develop a fully automated link from ATC to NWS for weather information.
- Provide a fully automated identification system capable of controlling entire country; presumably based on current 4 digit transponder code (which may require increased capacity transponder to allow full likely compliment of available planes).
- Develop an enormous fully automated 3D radar complex to blanket the entire country & identify all planes within the entire country by segments, track, determine optimum efficiency of deviation of potential conflicts, & direct planes as necessary via automated communication system.
- Develop automated hand-off from sector to sector.
- Develop automated hand-off from sector to sector communication system that will respond to automated ATC

Another serious concern with such automation would be situational awareness identification, communication, & interaction with ATC. NASA & the FAA are considering such complexities.

Weather detection & avoidance would seem to be a concern.

4.35.4.1.4 A possible scenario for an automatically controlled man carrying plane or helicopter is illustrated in Fig. 112:

Plane of Helicopter with:

●● Control Panel with:

- Method of selecting destinations from quick access preference list, or from large list
- On & Go switches
- Off switch
- Emergency communication system
- Conventional flight sensor displays for information only
- Pilots would say a full set of controls with autopilot override & default to autopilot upon release, but that is not the current FAA goal.

● ●Autopilot with:

- Link to GPS
- Link to compass
- Link to pressure altimeter
- Link to Radar altimeter
- Link to collision avoidance system (aircraft)
- Link to collision avoidance system (obstructions)
- Link to ATC
- Link to NWS
- Link to Video camera
- Link to throttle
- Link to fuel remaining
- Link to fuel requirement to reach destination
- Link to flight controls

● ● Plane inclusions:

- Conventional power plant
- Conventional flight controls
- Conventional flight sensors linked controls
- Radar altimeter
- Collision avoidance system (aircraft)
- Collision avoidance system (obstructions)

- ● GPS with:
- Link to Radar altimeter
- Link to aircraft collision avoidance system
- Link to obstruction collision avoidance system
- 3D data base with terrain fully mapped including man made structures
- Aviation data base (airports, VORs etc)
- Link to Video camera
- Link to throttle
- Link to flight controls
- Automated alternate airports including fuel stops & weather alters per ATC

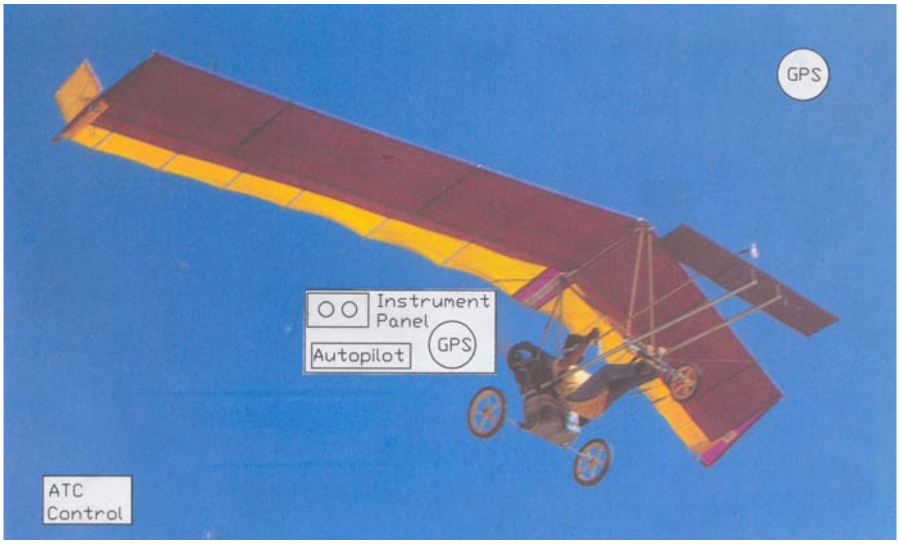


Fig 112: Fully Automated - Man Carrying Aircraft Schematic

4.35.4.2 Application; What Does the Future Hold?

The revolutionary WAAS, ADS-B, RNP, & fully automated man carrying planes all have, or will contribute greatly to the U.S. air space system. But there are other projects under way that also have potential to boost the efficiency, versatility, & most important of all, the safety of the system.

4.35.4.2.1 The Airborne Laser Scanner (LSA)

LSA is under development with great potential by Russ College of Engineering and Technology, NASA, & Ohio University were involved in testing & development.

LSA is a terrain-referenced aerial navigation system. Terrain-referenced Aero Nav started with the Wright brothers, & advanced over the years with Aero Nav systems described in courses G295 & G296.

With the assistance of a high resolution database LSA position ambiguity is virtually eliminated.

The LSA is self contained & independent of the usual Navaids.

Testing proved that over 90% of instrument approaches meet CAT IIIb 2D (no altitude) accuracy requirements, but vertical accuracies were expected to be improved with continued development. LSA was proven capable of measuring aircraft position within 3 ft.

Terrain database permitted achieving exceptional accuracy. Testing proved that extremely fine terrain data information could be stored & rapidly accessed using moderately priced equipment.

A January 2005 demonstration by Ohio University proved the capability of the LSA precision approach system.

LSA algorithms were proven by NASA tests to be capable of providing real-time position information by making 10,000 terrain measurements per second. Even building shapes were included in the data base.

4.35.4.2.2 A New Concept ATC System Developed by Oregon State University is Under Study by NASA

Early studies, per the following, were theoretically able to reduce airport congestion by 50% or more.

A great aviation news source, GAN published this new concept March 18, 2010. It was proposed by Kagan Tumer of Oregon State University, & is being evaluated by NASA. GAN immediately authorized the author to publish their article per the below: "You have permission to reprint the article entitled "New ATC System Could Save Billions". Per: [[Published with permission from General Aviation News. "New ATC System Could Save Billions. Authorized Mar 18, 2010 05:55 pm, Posted by Janice Wood © GAN, 2010 GeneralAviationNews.com)".]]

Engineers at Oregon State University and NASA have created a new system for air traffic control that could significantly improve congestion in the airways – a problem recently determined to cost the United States economy up to $41 billion a year.

The system, developed over five years of research, was recently adapted to make it even more flexible for voluntary use by air traffic controllers, and should be able to improve system wide performance by as much as 20% – a potential savings of billions of dollars, researchers say.

The concept is designed to leave control of aircraft in the hands of experienced controllers, but give them additional advice they could use at their discretion to improve the flow of aircraft on a regional and national basis. With some additional work the approach could be ready for its first test, researchers say.

“It takes a decade and billions of dollars to build a major airport, and with the growth of air traffic in the U.S. it’s pretty clear we’re never going to be able to build our way out of this problem,” said Kagan Tumer, an associate professor in the School of Mechanical, Industrial and Manufacturing Engineering at OSU. “What we can do is improve the efficiency of air traffic control, by giving controllers better information to make complicated decisions that benefit not just their airport but the region or nation as a whole — and our approach will do nothing to interfere with the safety of the existing system, which is extremely high.”

Existing approaches, the scientists said, are absolutely safe — they’re just inefficient, largely because it’s not practical for a controller to be landing planes in Chicago while worrying at the same time about a weather delay in Kansas City, mechanical problems in Miami, and a growing bottleneck in Los Angeles. But sophisticated computer systems and monitoring devices using advanced algorithms developed in the new research can do exactly that.

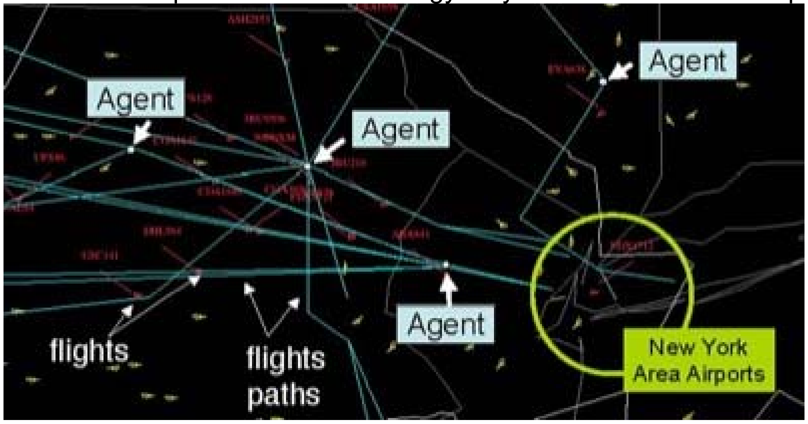
“The technology may sound complex, but it’s actually nothing more than sometimes telling aircraft to speed up or slow down to maintain certain spacing, or sometimes delaying a takeoff a few minutes, things like that,” Tumer said. “This is already being done to some extent, but only on individual and local levels, not with an approach that rapidly considers changing conditions and new developments over entire regions or the whole nation at the same time. That’s where advanced computer systems can help.”

Right now, Tumer said, thousands of air traffic controllers at more than 5,000 public airports are making their best judgments on more than 40,000 flights a day with limited data and little in the way of a support system. The new approach would have aircraft constantly monitored by new technology, and make optimized suggestions that can instantly reflect multiple issues – congestion at one airport, bad weather at another, planes that have to be routed around thunderstorms.

Early studies were theoretically able to reduce airport congestion by 50% or more, the researchers said, but that presumed that air traffic controllers would implement every computerized suggestion. The new system is more realistic, allowing experienced controllers to have much more influence on the process and hopefully be receptive to what it can offer.

“In effect, we’re trying to balance what computers will offer with the need for air traffic controllers to remain in full control of the situation,” Tumer said. “The computer has to make suggestions that humans can live with and are not too radical a departure from existing approaches. But even having made those concessions, we think this new system could cut congestion by up to 20%.”

In this system, a computer, in effect, will suggest “here’s what I would do” as aircraft become bunched up on a certain line of flight. Air traffic controllers can consider the recommendations and then do whatever they wish. The approach balances the interplay of humans and computers to improve overall performance, in an effort to transcend the problem that technology may have advanced more quickly than the trust that it will work.



“New approaches are difficult when something has always been done a certain way, and there’s a suspicion the new technology may not work,” Tumer said. “And it must be acknowledged that air traffic controllers have a remarkable safety record, which is not something anyone wants to jeopardize. Also worth noting is that nothing in this system would change the most critical aspects of air traffic control, at takeoff and landing. We have to be respectful of this existing expertise and work toward improved systems as a partnership.”

Early work on this was supported by the Next Generation Air Transportation Systems Program at NASA, and new studies are funded by the Cyber Physical Systems Program of the National Science Foundation. The latest findings on this research project were reported last year in Advances in Complex Systems, a professional journal.

The stakes on these problems are high, experts say. Air traffic in the U.S. is expected to triple in the next 20 years. A 2008 analysis by the Joint Economic Committee of the U.S. Congress indicated that domestic air traffic delays in 2007 cost the economy $19 billion in increased operational costs for airlines, and $12 billion in lost time for passengers.

Air traffic congestion, experts say, now costs more than the average damage done by all the hurricanes hitting the U.S. each year.