Navigation Techniques of the 1940s

or How to Fly Long Legs without Modern NavAids.

By David Bitzer DCA-910

The goal of this note is to make some observations as to how to fly long over-water routes in FS2002 without benefit of modern navigation aids. In the hey-day of the DC-3 there were few modern conveniences and navigation instruments. Airmen had to improvise and use whatever they could to navigate between airfields. For those who want to experience flying the DC-3 when it was the newest, fastest, most modern plane in the hangar, this note may offer some insights. Included are recommended modifications to the instrumentation and fuel capacity to make the DC-3 appear and function as it did in the wonderful days of yesteryear.

This note is also for those who have wondered how aircraft navigation over long routes was done in the late 1930s and 1940s, especially as it applies to the DC-3 and similar aircraft, when there were no waypoints, or radio navigation aids (e.g. at sea) along the route.

Since there is good documentation readily available from Charles Woods at his site (http://www.navfltsm.addr.com/) and Peter Tucker in his tutorial adf_tutorial.pdf available from (http://dc3airways.com/ek%20gann.zip) on using NDBs to navigate, I will focus on the aspects of the flight that are out of range of an NDB. How the navigation aids that were available work is excellently explained by Peter Tucker (op. cit.). Another good source of information on navigation of the time is the book *By Dead Reckoning*, by Ralph Lewis. He mentions that during the early 1940s the Coast Guard maintained three ships equally spaced along the route between San Francisco and Honolulu to aid in guiding aircraft across the ocean by providing homing and communications facilities. This is good testimony to the fallibility of reliance on dead reckoning alone.

Simulated flying **long over-water routes** can be a lonely experience, full of boredom for hours on end, and then experiencing the stark terror of not finding the destination where and when you expect it. This note will shed some light on how to live to fly again. 4X or 8X speeds may be used at cruise altitude to shorten the flight. To help explain the steps a navigator would take to plan a flight I will use the following as an example:

A DC3Airways charter flight from Natal (SBNT) to Dakar (GOOY)

Date: 7 June 1942

BASIC PATH REQUIREMENTS

You first need the latitude and longitude for Natal (SBNT) and Dakar (GOOY). Then determine the Great Circle (GC) distance and initial bearing using the lat/long information and nautical navigation tables or the trigonometry formulae below:

These formulae came from Ed Williams’ excellent site at:

http://williams.best.vwh.net/avform.htm#Dist

The **great circle distance D** between two points with coordinates {lat1,lon1} and {lat2,lon2} is given by:

D=acos{sin(lat1)*sin(lat2)+cos(lat1)*cos(lat2)*cos(lon1-lon2)}

(Note: “acos” is computer shorthand for “arcCos” or “Cos^{-1}”
e.g. acos 0.5 means “the angle whose Cosine equals 0.5, which is 60 degrees.
Similarly, in the expression below:
“atan”is the same as “arcTan” or “Tan^{-1}”
“asin”is the same as “arcSin” or “Sin^{-1}”)

Course between points :
We obtain the **initial course, tc1**, (at point 1) from point 1 to point 2 by the following. The formula fails if the initial point is a pole.

tc1=mod(atan2(sin(lon1-lon2)*cos(lat2),
cos(lat1)*sin(lat2)-sin(lat1)*cos(lat2)*cos(lon1-lon2)), 2*pi)

Note: Here atan2 has the conventional ordering of arguments, namely atan2(y,x). This is not universal, Excel for instance uses atan2(x,y), but it has asin and acos anyway. Be warned. It returns a value in the range -pi < atan2 <= pi.

Fortunately, tables exist to do these calculations for us, and the Virtual E6-B (VE6B) will do the distance and initial vector. The VE6B is a download from the dc3airways site.

Next, using the method described by Peter Tucker in his tutorial for the EKGann Charter (op. cit.) break the path into segments to approximate the GC path. For Longitudes (lon) of your choosing, spaced about every 500 NM along the flight path, you can use the following formula (From Ed Williams op. cit.) to determine the Great Circle (GC) latitude:

Latitude of point on GC :
Intermediate points {lat,lon} lie on the great circle connecting points 1 and 2 when:

lat=atan((sin(lat1)*cos(lat2)*sin(lon-lon2)
--sin(lat2)*cos(lat1)*sin(lon-lon1))/(cos(lat1)*cos(lat2)*sin(lon1-lon2)))

(not applicable for meridians. i.e if sin(lon1-lon2)=0)

Note: All calculations and formulae in this note assume a spherical earth.

For each of these "legs", then you can use the V-E6B* to get the distance and initial heading. Note that for legs less than 500 NM the Rhumb Line and Great Circle distances are about the same, so we will fly Rhumb Lines for simplicity.

* This is a Virtual E6B navigation computer. It is available as a free download on the DC3 Airways web site

For north/south flights, or flights that stay near the equator, breaking the flight into segments of 500 NM is not needed since the Great Circle and Rhumb Line routes are similar.

Note that all these bearings are True North related. You must figure in the magnetic variation to get the compass headings needed. (And don't forget to add corrections for wind). The need for True bearings will be come more apparent as we discuss wind effects and celestial navigation below. The formulae above are provided for those who want to understand how the tables were made for use in the 1940s.

FSNav and the Microsoft FS Flight Planner may be used to get Great Circle routes, distances, and initial bearings. Magnetic variation data is automatically added in at the endpoints on both FSNav and the FS Flight Planner. There are also calculators available to determine the magnetic variation. Ed Williams (op. cit.) has such a calculator available for download from his site. A useful variation graph is available at:

http://geomag.usgs.gov/MagCharts/wmm-gif/WMM-00D.gif

Back to the example:

The distance to Dakar is 1629 NM and the initial True bearing is 40 degrees, plus a West magnetic variation of 22W = 62 degrees Magnetic. The final true bearing is also 40 degrees, plus a magnetic variation of 11W = 53 degrees magnetic. There is no significant difference between the Rhumb Line and Great Circle routes as we are crossing the equator near midpoint. The easy way to find this is with the Virtual E6-B or FSNav or the Game's Flight Planner, or combinations thereof. To get the final True bearing, I used the VE6B in "reverse", declaring the destination to be the start, and vice versa.

Here is a word of CAUTION to those using FSNav for flight planning. There is a flaw in FSNav code that will sometimes give incorrect initial magnetic headings. Because of this, it is a good idea to cross-check your bearings with other sources.

[Norm Hancock, the DC3 Airways VP for Charters, has suggested an easy way to find the correct heading to fly using FSNav. 'Draw' the mouse along a short length of the proposed course line very close to the waypoint at each end of the leg and take the average heading. This procedure automatically includes the Magnetic variation correction.]

We are at 18 degrees West variation near midpoint, so let’s consider flying the magnetic average of 22 and 18 for the first half, and 18 and 12 the second half. 20 and 15 for average of 17.5, rather than the average of 22 and 12 which is 17 degrees. Since it turns out to be so close, let’s just maintain 18 degrees West variation over the whole flight.

We now have a basic route laid out, with a magnetic heading (or series of them) to fly.

The second step is to figure out how far you may drift off course during the flight, so you may plan for intermediate course corrections, or conducting a planned search for GOOY when you get close to your destination. Contributions to the drift include winds, airspeed inaccuracies, direction inaccuracies due to steering, or magnetic variation changes, or gyrocompass drift.

A good way to estimate the amount of drift or error that may arise using dead reckoning is described by Elgen and Marie Long in their book: “Amelia Earhart, the Mystery Solved.” It is called the 10% rule, and it says:

“For any range R, the error is within a circle of radius R/10.”

They also say this is accurate 9 times in 10.

Using the 10% rule, we would expect to arrive at the coast within 163 NM of Dakar. At a ground speed of 150 Knots, we could also be over an hour early or late arriving. To do a box search of an area of radius 160 NM, even with a 30 NM visibility, would be prohibitive. It would take 2 boxes, one of 120 miles on a side, and the second of 240 on a side to search it all. This is a distance almost as great as the trip distance. Of course, if the visibility is less, the search would take even more time and fuel to do.

CAUTION: The NDB at Dakar has a range of only 22 NM.

See the Appendix for more information on box searches.

Looking at the map for navigational features and NDBs near the destination, we see we will be approaching a definitive coastline, and if we are north, the coast line will run NE-SW. If we are south, the line will run NW-SE. There are NDBs roughly every hundred miles in both directions, with the ones to the south being more favorably positioned.

So, if we arrive at the coast, we would know which way to turn and would need enough fuel and daylight to fly up to 160 NM to reach GOOY.

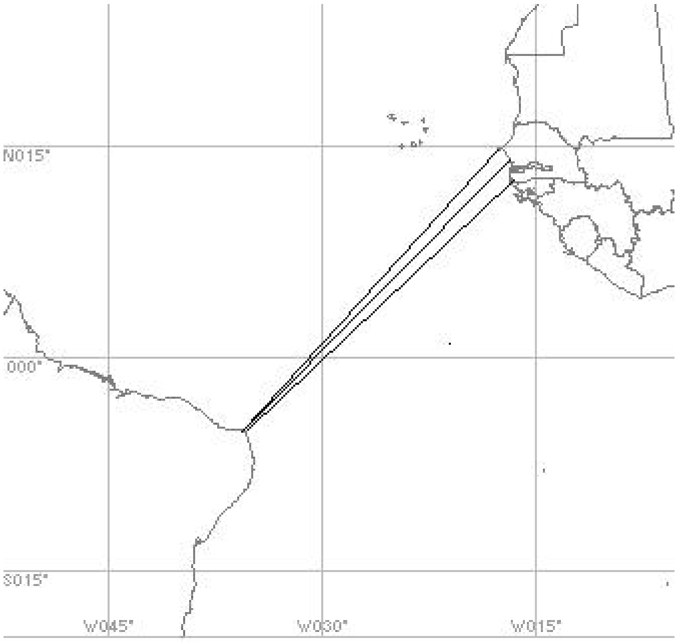
FUEL REQUIREMENTS

Let's take a first look at the fuel requirements. At an average of 2 NM per gallon, the flight would take 810 gallons for cruise, and an additional 60 gallons for take-off and climb, and 80 for the search, plus 80 for one hour reserve, or 1030 gallons in total.
In a 20 Knot headwind, it would take roughly 15% longer, or about 1200 gallons. We will sharpen this up when we know the forecast winds.

On closer inspection, the distance from Natal to the African coast, if we err to the north, is 2000 NM. Note that this adds over 300 NM to the trip, before starting the search. Because of this bad news, the aim point is adjusted to arrive no further north than GOOY, by taking a true track 5 degrees more southerly than GOOY. Then our maximum search occurs if we err to the south, and the max search distance is 326 NM. This says we can expect a maximum distance of 1955 miles. There is an airport 5 degrees to the south of GOOY named GOGS, that we could navigate for. Its distance is 1557 NM from Natal, on an average bearing of 63 degrees Magnetic.

Redoing the fuel requirement to GOOY via GOGS; the distance to GOGS is 1557 NM, plus 326 max search to GOOY gives a total of 1883NM. We don't actually intend to go to GOGS first, but by aiming at GOGS, when we arrive at the coast we know to turn north and fly up the coast to GOOY. At 2mpg, that is 942 gallons, and at 150 kts tas, that is 12.5 hours. Figuring a 20 knot headwind all the way, this becomes 14.5 hrs, and 1102 gallons fuel. Plus 60 gallons for takeoff and climb, plus one hour reserve =140 more, or a total fuel requirement of 1242 gallons. This is still marginal, but better than the first route presented.

The chart below shows the flight offset 5 degrees south as proposed above. You can use the mass of the continent as a navigation aid, flying to the coast, and turning left to run up the coast to Dakar. The dotted line gives the 10% error, as 156 NM at the destination.



REDUCING THE SEARCH TIME

We have the good luck of a coastline to reduce the search area, but the geography is such that we still need to deliberately fly south of our target by 160 NM to make sure we don't miss it to the north. This is not good. The way to fix this is with some enroute "waypoint" that would let us make a correction in course, and reduce the error at the destination. For example, if we could determine our position at the half-way point, and it were say 80 miles north of our expected track (extreme case), we could say we were drifting 5 degrees north, and we would steer the remainder of the route with a southerly 10 degrees correction, and should arrive at our destination, instead of being 160 miles north. We couldn't entirely count on it, however, since perhaps a cross wind put us north, and the wind during the last half of the flight may change. But applying the 10% rule to the last half, we should steer toward a point halfway between GOOY and GOGS, and only have an 80 NM uncertainty to search out, instead of 160 NM. This would save 80 gallons fuel, and about an hour on the trip. So, how would we find our position at a halfway point over the ocean in 1940? At night with a view of the stars, celestial fixes are the answer. During daylight a more complicated procedure using the sun may work.

Conveniently, the flight chosen for this charter demonstrates this daytime solution. It was a flight the Longs (op. cit.) describe in detail. They explain how navigator Fred Noonan did what is called a "running Sunline Fix". It isn't as accurate as an NDB would be, so the 10% error growth with distance after the fix doesn't start at zero, but starts with some small error that has to be added to the total error budget.

HOW TO DO A SUNLINE

Let's examine how to do a sun line of position first. It starts with a measurement of the height, in degrees above the horizon, of the sun using a bubble octant, or a sextant.

(A sextant is more tuned to ship use, where a fixed horizon is available. The bubble octant is more suited to aircraft use, where the horizon may be obscured by clouds, haze etc, and where the horizon is "depressed" because of the altitude of the airplane.)

This angle defines a circle on the surface of the earth, at a given radius from the point on the earth directly "under" the sun – the “sub-solar point”, (Called P).

You need to know where P is, and this is found from nautical tables which provide the sun's lat/long for date and time. So, you can, using the table and the angle, know you are somewhere on that sunline.

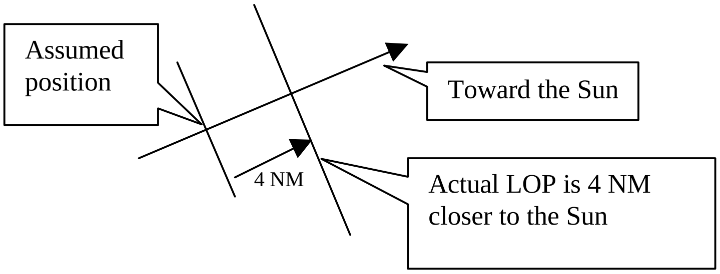
Long (op. cit.) says a measurement of 10 readings of the sun angle, averaged over a two minute period, will ultimately locate where you were 1 minute ago (at the midpoint in the measurement) to an error of less than 15 NM.

A standard way to plot this sunline on your chart is to assume a position near (within 200 NM) of your true position. The assumed position is on a line drawn through this point, at right angles to the direction to the sun. Using Ed Williams (op. cit.) formula for great circles, compute the angle (true direction to the sun) and the distance from your assumed position to the point P.

The angle measured with your octant is the elevation. The declination is 90 degrees minus the elevation angle. The great circle arc distance in NM from your position to P is conveniently 60 times the declination in degrees. Finally, find the difference between the distance from your assumed position to P and the calculated (from the sextant readings) distance. Move the assumed LOP away from or toward the sun by the amount of the difference. CAUTION, this is a flat earth approximation to the solution, so it is only accurate within a radius of roughly 200 NM of the true position. If your first assumed position is too far away, make another assumption on your position and try again. This method eliminates the need to have the point P on your chart, and measure long distances very accurately. This same procedure works on any celestial body, and is used at night for celestial navigation.

Back to our example, Noonan decided to make a sun shot when the sun crossed his true bearing of 40 degrees. This would give him an accurate ground speed, which he would need later. He looked in his tables and found that if he were near his dead reckoning position of N3.5 W25.7 at 12:40 GMT, the sun would be on an azimuth of 39 degrees, and have an elevation of 66 degrees, 27 minutes. He would draw his assumed LOP on an angle of 219 degrees through his assumed point. If he then measured the angle with his octant (a two minute average from 12:39 to 12:41) to be 66 degrees, 31 minutes, he would know his assumed LOP was 4 minutes of arc (4 NM) too far from the sun, so he redrew the line on the same angle, but 4 miles closer to the sun. (Had the measured angle been less than the table value, he would have moved away from the sun. This LOP is accurate to about 15 NM.

Showing this on the chart below:

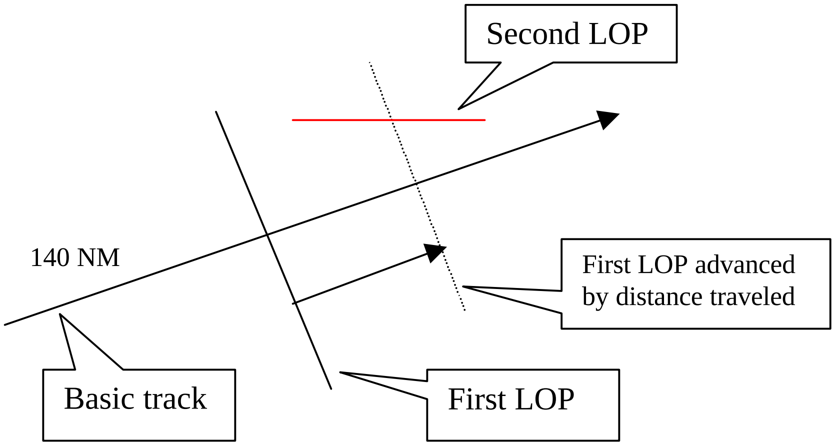


To get a running fix near the equator where the sun changes azimuth rapidly at noon, you get a sun LOP a little before noon, and another one a little after noon. Then you "advance" the LOP by your estimated ground speed times the elapsed time so that the first LOP is corrected for the time difference. The intersection of these two lines is your location.

Using the sun and an octant you can do a fairly accurate fix in this special circumstance because you are near the equator where the sun changes its apparent position overhead rapidly. A fix at 1240 GMT will give you a LOP of 120 degrees, and a fix 61 minutes later, at 1341 GMT will give you a LOP of 90 degrees. Advancing the 120 degree LOP by the ground distance traveled in that hour will give an intersection that is accurate to 15 NM in the n/s direction, and 30 miles in the 120 degree direction.

The Flight Planner shows that at 1240 GMT our assumed position is N3.53, W25.7 and at 1341 we will be at N5.0, W24.2, with 628 miles to GOGS. This assumes a 150 Knots ground speed.

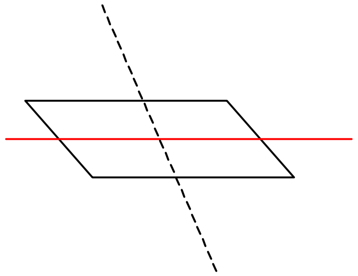
Let's draw a diagram to illustrate this:



The basic track is 40 degrees true (Map not to scale). At 1240 GMT, the sun is directly in front of the plane's track (the plane may be crabbing to compensate for wind), and the sunshot gives the first LOP at right angles to the track, as shown. It also specifies the distance to the start of the flight, from which the ground speed is determined to be 150 Knots. Take-off was at 0615 GMT, climb at an average of 800 ft/min for 10 minutes, at a TAS of 120 Knots gives start of cruise at 0625, 20 miles from Natal. The cruise time to the sunshot position is therefore 6.25 hrs. The sunshot says the first LOP is 805 NM from Natal.

After 61 minutes, the sun is directly to the north, and the sunshot provides the second LOP shown in red. Advancing the first LOP by 150 NM, we have the dotted line as shown. The point where the red line and the dotted line intersect is the "fix" at 1341 GMT. The distance to the left of the basic track is the drift due to cross wind. The speed (150 Knots), compared with the TAS computed from the IAS, the altitude, and the temperature (OAT) gives the amount of headwind or tailwind. Vector addition of the headwind and crosswind gives the wind speed and direction.

Next we look at the error in position which is represented by the parallelogram below:



The basic error in a sunshot is 15 NM, so we draw parallel lines 15 miles north and south of the red line. This represents the area in which the plane will be 9 times in 10. The dotted line east west error is a little more complicated, since it was taken an hour ago. At the time it was made, its error was also +/- 15 miles, but now, you have moved 140 NM, so the 10% rule says the error has increased 14 miles, so the total east/west error is 28 NM. As you continue to fly the same course and speed, the size of the box grows, but its shape doesn't change. After 3 hours, GMT is 1630, and the maximum probable north-south error is 57 NM, and east west error is 71 NM. Without the sun "fix", the error would have been 10% of the total distance, or 120 NM

Since the course is the key to this charter's navigation, our fix at 1445 means that the remaining distance is 620 NM, and we will arrive in 4h 24m, or 1909 GMT. Note that the expected cross-track error will only be 15+62 NM, so we can cut our search to 77 miles. We can set a course from whatever our position is to a point about 37 NM south of

GOOY, if the visibility is 30 NM, or 65 NM south of GOOY if the visibility is 2 NM. Our distance 620 NM and true bearing 19 degrees were obtained from the VE6B. Also note that our speed line is stale, dating to 1240 GMT. The error in time of arrival has grown for 6.5 hours, which at the 10% rate is about 40 minutes. We plan to make the correction when reaching 550 nm from GOGS, at 1415.

When the sun direction is at right angles to the true course (40 degrees), a sunshot will provide no information on ground speed, but will provide an accurate measure of whether you are to the left or right of your intended course. The sun is in such a position (if we are near our assumed position) at 1518 GMT. We expect to be at N9.1 W20.0 at that time. If we were to make a series of octant readings at that time, the "on course" angle would be 66 degrees, 35 minutes (of arc). For every minute of arc above 35, the flight is left of course by one nautical mile, and below 35 minutes would be a mile to the right. (This is because the sun rises at 67 degree azimuth, heads NORTH, and is at 310 degrees when the course LOP is taken). If a correction to come back to the course line is made at 1539 GMT, we have about 3.5 hours to go, and our error in cross track could be reduced to less than 70 NM.

So, how does one simulate a LOP based fix in FS2002? Hopefully a gauge designer will come to our rescue and provide a solution soon. I have floated a design idea by one of the premier designers, and he is interested. It would let the user input a sun azimuth and an estimated Lat and Long, and the gauge would provide the proper distance to advance or retard the estimated LOP to get the true LOP. The gauge would work with the moon and other stars as well. In the meantime, what I have been doing is using tables of sun (or star) positions vs date and time, or looking up their position on the internet at:

http://aa.usno.navy.mil/

It gives the azimuth and elevation to the sun and other celestial bodies for assumed times and positions on the earth. I try to choose azimuths to either be parallel to the flight leg, (speed lines), or perpendicular to it (course lines). Then I "peek" at the HUD (the heads up display in red at the top of the panel) to get the true lat/long of the aircraft, and I advance the LOP from the assumed position to go through the true location of the aircraft, maintaining the same angular orientation. I then try to forget where the point was on that line, as the sun line does not give you that point. To get a point fix, you need another LOP at a different angle, and the intersection of those two lines will give you the fix.

TIME MANAGEMENT

In the original example flight the Lockheed Electra used by Noonan cruised at 130 Knots TAS for maximum range. The Company Aircraft cruises at 150 Knots TAS, and could be slowed, but the trip is long enough as is, so the time is adjusted to make the "running fix" occur about where and when it did on Noonan's flight. Sunset at GOOY is about 1830 cockpit time, 1930 GMT. We want to arrive at the coast in time to search the maximum of 163 NM before sundown, so the faster speed facilitates that.

Redoing the GMT planned times, the Departure is at 0710, first fix is at 1247, the second at 1341, the change in course is at 1415, and the third sunline is at 1609 instead of 1630. ETA at GOGS is 1804. Remember that these are no-wind conditions. If you have forecast winds aloft, you need to adjust your takeoff time so that you will reach your assumed position for the sunshot at 1240 GMT. The 10% rule assumes you have factored in the best guess for the wind.

This might be a good place to mention that if you see you are going to run low on fuel, the Company Aircraft also cruises well at 2.6 NM per gallon, by slowing to 120 KTAS.

PUTTING IT TOGETHER

If the distance of any leg exceeds 10 times the expected visibility in the vicinity of a landmark, or range of the destination's NDB, we should manually add more waypoints along the great circle route at distances using geographical features or star shots. This can be done by editing the *.PLN files created by the FS flight planner. Usually, you can just fly the average magnetic bearing between waypoints, half way between the initial and final bearings to do a “magnetic Rhumb Line".

From the several discussions above we ended up with a fuel total of 1160 gallons, so we need 4 Fuselage Tanks, and we need to reduce our maximum cargo weight by 6X360=2160 pounds to stay with our maximum gross weight, or redo the navigation with a higher gross take-off weight. Let’s go with 1160 unless last minute head winds aloft forecasts exceed 20 knots. The appendix shows how to add the Fuselage Tanks and reduce the Gross Dry Weight of the aircraft.

The flight starts at the Active Runway at Natal (SBNT) at the proper time to get a celestial fix near half way near local noon. The plane has 1160 gallons fuel loaded, and is at its normal gross landing weight. Real weather has been downloaded and edited and installed in the flight. You may find the wind conditions for Natal by temporarily turning on the HUD.

Upon departure, it is important to get to the cruise altitude of 8000 ft quickly, and get on the bearing 60 degrees Magnetic, so you can then use the technique described by Peter Tucker (op. cit.) of finding and crabbing out the wind drift (at 8,000 ft) before you get out of range of the NDB at SBNT. You don't want to crab out the wind at 4,000 ft and then later move to 8000 ft and not have an NDB to help you adjust for the cross wind. At 8000 ft, and a constant 150 Knots TAS, you are sacrificing a bit of range for ease in navigation. Achieving absolute maximum range involves flying higher and slower as you burn off fuel, but the improvement in range is less than 5%. This is a good trade in a dead reckoning environment.

Under way, it is important to maintain constant course and speed. If you are using the trusty Sperry autopilot, (or using the Control+H key), you will need to reset the gyro hourly to line up with the magnetic compass by pressing the D key. Failure to do this will result in your flying a ballistic course and ending up too far north, in the example flight. Also, FS2002 sets the clock at GMT -2, at Natal and when you cross the W30 meridian FS2002 will advance the clock to GMT -1. The clock is your lifeline, so you need to be aware of this jump, which will occur about 0730 Natal time. In general, FS2002 will make cockpit clock jumps on the meridians spaced every 15 degrees. Also, since you are below the equator at the start, the sun will rise to your right, cross in front of you about 1240 GMT, and be highest in the sky to your north at 1340 GMT. The position of the sun is critical to your navigation, as explained above. You also need to maintain a constant true air speed, which means watching the OAT. The Sperry autopilot will maintain a constant pressure altitude, so if your weather (OAT) changes, you will need to adjust your IAS to maintain your TAS at 150 Knots. Use of the VE6B is a handy way to manage these changes. The modified Instrument panel provided has an enlarged magnetic compass and bigger clock with properly functioning hour hand, fewer radios, and an OAT for your convenience. See the Appendix for details.

WHEN THINGS GO WRONG

It is important to know when you have missed your waypoint. This means keeping accurate logs of the times of passage of each waypoint, and any deviation from the planned magnetic headings, or deviations from the planned indicated air speeds or density altitudes. Outside air temperatures are also valuable to dead reckoning navigation. Your virtual E6B will be a big help in computing the true airspeed, and from it and the forecast winds, the ground speed.

If you miss the NDB, the procedure varies depending on circumstances. The NDB may not be broadcasting, your receiver may not be receiving, or you may be out of range. If you are off course enough to be out of range, information on other NDBs in the area is very valuable, so you may try to receive other stations. Perhaps you can get a sunline, or a celestial fix.

If this doesn't work, a box search may be necessary. Keep close control of the area of uncertainty as it grows, and the minute that you believe you have missed the NDB (not the point where you are well beyond its range), start the search. Box searches can take a long time and use a lot of fuel. If the dead reckoning distance you have travelled is 1000 miles, you need to search a box 100 miles on a side. You need to plan for and have fuel for the search. Don't slow to maximum hover time power settings during your search. You aren't waiting for the weather to clear. You want to cover as much ground as you can. The centre of the search box should be your best guess as to where the NDB is. Since a large proportion of things going wrong is due to unknown wind, the faster you fly the less effect the wind has, so searching a box at maximum cruise is a good idea if you have the fuel.

A sun LOP (or any LOP, using the moon or a star) will be a great help, even if you can't get a fix by the intersection of two lines of position. The LOP will greatly reduce the area of uncertainty that needs to be searched. The Longs state (op. cit.) that if you know your position to within 200 miles, and the time to within a minute, and have the pre-computed nautical tables, a two-minute average of about 10 shots with a bubble octant will get you a LOP within 10 miles of error. Ideal for simply flying down it until you pick up the NDB. The trick is to pick your flight time to arrive at the destination when the sun is where you want it. (Noon for an east-west flight, Dawn or Dusk for a North-South flight.)

SUMMARY

To use the material presented above in Microsoft FS2000 or FS2002, the easy way is to select the aircraft and bring up the flight planner, (from File on the Tool Bar), and create a plan, following the prompts. Enter the start and destination airports and select “gps” and enter. Select the edit tab, and turn off all the element displays except airports and NDB points. On the graph use the mouse to pull the red course line to selected NDB transmitters, about 50 to 100 miles apart. When you are finished, review the navlog and edit it as necessary. This will give you the navigation data needed. NDBs closer than 50 miles apart are usually not needed, and if they are more than 150 miles apart, then the dead reckoning aspect of navigation applies while out of range. From the above, we can see that distances up to 500 miles are probably ok. For longer distances, divide it into segments and plan being there at the proper time to take advantage of celestial fixes or sunlines, or geographical features as waypoints. Print out the map to make a chart that you can draw celestial fix measurements on. The FS flight planner gives headings and distances and flight times. These headings and times must be corrected for wind but they are already corrected for magnetic variation. If you want to adjust the speed, you need to change a parameter in aircraft.cfg. See the Appendix below for instructions for FS2002. Select a start time and date, and get celestial data for assumed positions and times. Cross checking the data is always a good idea. You may do this using your VE6B on each leg, obtaining the true bearing and distance. Then use the magnetic variation given in the World Magnetic Chart to check the FS Planner.

FS Settings for 1940s long range simulation:

No use of HUD except at airports, or once per hour for LOP plots.
No use of GPS
No use of the game map with the aircraft position on it except at airports (I find that printing out a FSNav or Flight Planner map pre flight so I can add the LOPs is useful)
No unlimited fuel
No automixture. Not leaning the mixture manually may result in up to 20% range reduction
Use Real Weather from the internet to add some uncertainty to the flight
Use a Gauge (now in development) to obtain sextant lines of position rather than HUD

Autopilots are a big help, but use of a more modern autopilot than the Sperry is discouraged as not authentic. CAUTION: Sperry, and more modern autopilots are gyroscope based, and have to be reset to magnetic headings frequently. Note that you may have problems even with the realism setting for the gyro set to no drift. This is because as you fly long distances, the magnetic variation changes, and if your flight plan is based (as it should be) on compass bearings along the route, the gyro will not automatically change the bearing to track the magnetic variation. You will need to press the "D" key to reset the gyro. I like to do that hourly.

The position of the sun, moon, and stars in the game are reasonably placed, but not accurately enough to be used for long range navigation.

The cockpit clock will "jump" by an hour when you cross a time zone (defined by Microsoft, not always realistic). You need to use Zulu time. It would be nice to use a clock set to Zulu time, if one could be found.

ACKNOWLEDGEMENTS

The methods, procedures and data for this note draw heavily on the books “Amelia Earhart, the Mystery Solved,” by Elgen and Marie Long, 1999, Simon and Schuster, and “By Dead Reckoning (Recollections of a Master Navigator)” by Ralph Lewis, 1994 Paladwr Press.

Many thanks to Peter Tucker, DCA-196 for his encouragement, suggestions and extensive editing help.

APPENDIX

- USEFUL LINKS:

http://aa.usno.navy.mil/
http://williams.best.vwh.net/avform.htm#Dist
http://geomag.usgs.gov/MagCharts/wmm-gif/WMM-00D.gif
http://www.navfltsm.addr.com/
http://dc3airways.com/ek%20gann.zip

- ADJUSTING THE FS FLIGHT PLANNER SPEED.

The Microsoft flight planner is sensitive to whichever aircraft has been selected when the planner is invoked. You can change the planner's no-wind ground speed by selecting a different aircraft. You can also edit the aircraft.cfg file for your selected plane, within limits, to change the airspeed the planner uses. You should look for the [piston engine] section, and look in that section for the item “max_rated_hp=”

Changing that item does not change the horsepower of the engine. It may control the engine sounds, so don’t vary it too much from the engine specs. Changing it will move the speed used to compute the time of flight in the planner. A little trial and error will result in the proper speed. An example of the code I am talking about is shown below. If the "max_rated_hp" line isn’t there, just type it in as shown, anywhere below the number of cylinders.

```
[piston_engine]
power_scalar=1.450
max_rpm_mechanical_efficiency_scalar=1.000000
idle_rpm_mechanical_efficiency_scalar=1.000000
max_rpm_friction_scalar=1.000000
```

```
idle_rpm_friction_scalar=1.000000
cylinder_displacement=140.750000
compression_ratio=8.000000
number_of_cylinders=11
max_rated_rpm=2708.000000
max_rated_hp=800            // was 1350.000000
```

For the Company DC-3, changing the max_rated_hp to 550 yields 139 Knots ground speed, 800 yields 158 Knots ground speed, and 1000 hp yields 169 Knots ground speed. Of course, to change this you need Bill Rambow’s or Roy Chaffin’s permission, other than for personal use.

- AIRCRAFT INSTRUMENT PANEL MODIFICATIONS

You may modify the design of the cockpit main instrument panel to remove all the post 1940s period gauges, improve the visibility of the clock, and fix its hour hand movement. A simplified radio tuner helps de-clutter the Instrument Panel. Also you may add an OAT gauge and change the heading indicator to a large whiskey compass, because the outside air temperature and compass are very important to dead reckoning navigation. There may be a DC-3 panel.cfg and a main2.bmp included in the example flight that may be substituted for the current one, for personal use only.

- FUEL TANK MODS:

The DC-3 is capable of increasing its fuel capacity from 804 gallons to 1604 gallons by adding from 1 to 8 100-gallon fuselage tanks. It is easy to change the Company DC-3's fuel capacity. I modified the aircraft configuration file to include 8 fuselage tanks for long range flying. They show up as increased capacity aux. tanks on the fuel quantity gauge. The main tanks still show the gallons remaining correctly, but now when the aux tanks needle shows 50%, it is reporting 600 gallons/tank instead of 200 gallons. It increases the capacity of the aux tanks, adds fuel in the fuselage over the wings, and reduces the dry weight of the aircraft by 2400 lbs. Note that if fuel beyond 1200 gallons is loaded, the plane will exceed its gross landing weight. The changes in the moments of inertia due to fuel are done automatically. Example code is shown below:

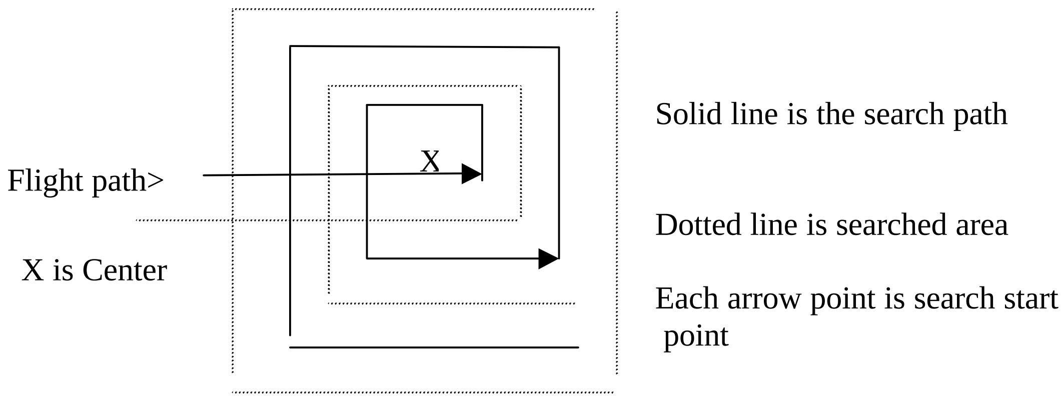
```
[WEIGHT_AND_BALANCE]
max_gross_weight=26900.000
reference_datum_position=0.000000,0.000000,0.000000
empty_weight_CG_position=0.000000,0.000000,0.000000
max_number_of_stations=50
station_load.0=2600.0,0.000000,0.000000,0.000000  //was 0
empty_weight=14068.0                    // was 19068.0000 lbs.

[FUEL]
LeftMain=0.000000,-16.666667,0.000000,202.000000,0.000000
LeftAux=0.000000,0.000000,0.000000,600.000000,0.000000        //was 200 gal
RightMain=0.000000,16.666667,0.000000,202.000000,0.000000
RightAux=0.000000,0.000000,0.000000,600.000000,0.00000        //was 200 gal
```

```
fuel_type=1.000000
number_of_tank_selectors=1
```

- BOX SEARCH DESIGN:

This may be a good time to mention that for an NDB with a 50 mile range, the maximum practical search box size is 200 miles on a side. It will resolve 150 miles of uncertainty, limiting the leg size to 1500 miles worst case. To fly this box, fly on past your best dead reckoning position by 100 miles, turn left 90 degrees for 100 miles, turn left again to backtrack for 200 miles, turn left again for 200 miles, and end with a left turn and 200 miles more on the original track. This adds 800 miles to your fuel requirements, for a total of 2300 miles. The Company DC-3 has a range of about 1500 miles at normal cruise and 800 gallons. This range can be extended 15% by flying slower (125 knots). That range can essentially be doubled by adding 800 gallons in long-range fuselage tanks (this requires editing the [fuel] section of the aircraft.cfg file, and you need Bill Rambow’s or Roy Chaffin’s permission to do that, other than for personal use).

CAUTION: While some NDBs are reported to have up to 80 NM reception range, the NDBs on the west coast of Africa seem to only have a 22 NM range. This requires modifying your search box sizes to 80 NM on a side for the first box, and 160 NM on a side for the second box.



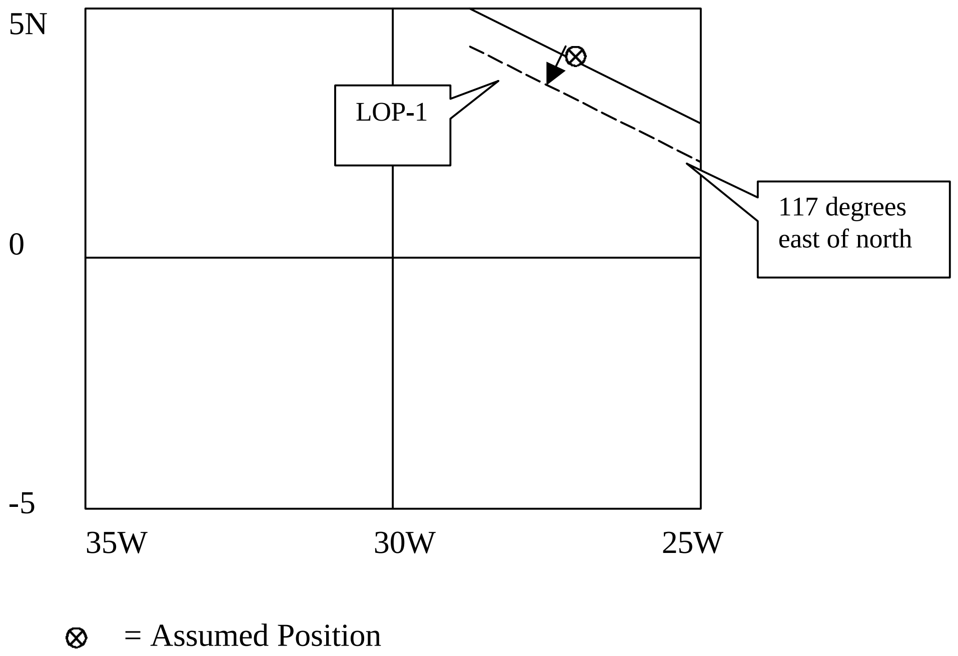
- RETURN FLIGHT FROM DAKAR TO NATAL:

Sometimes a second example is useful. Looking at the return flight from Dakar to Natal, step by step, as follows: We start by observing that the NDB at Natal has a 60 NM range. Our planned ground speed will be 150 Knots. Remembering the 10% rule, we assume that a position fix within 600 NM of Natal will put us in range of the Natal NDB. Using the FS Flight planner, we see GOOY to SBNT is 232 degrees magnetic and 1628 NM. Since we will be flying west, the sub-solar point is moving only at 750 Knots instead of the 1050 Knots relative to the aircraft that we had on the previous leg. This means that although we get more daylight, we can not get as good a LOP angle between sun shots one hour apart, so we will plan to take shots 90 minutes apart. Recalling that 1 degree of latitude is equal to 60 NM, we can use the track on the Flight Planner to choose the two points roughly 90 minutes (225 NM) apart, ending about 475 NM from Natal. Since the sun moves most rapidly in azimuth near local noon, we will choose the local noon to be at 28.5 degrees longitude. This makes local noon about 1351 GMT. The times for the LOP measurements are therefore 1306 and 1436. 475 NM at 150 Knots is 3H 10M, so the ETA at Natal is 1746. This sets the take-off time at 1628/150=10H 51M earlier, or 1746-1051=0655 GMT. The next step is to pre-compute the assumed positions and sun angles for the sunshots. The table below shows what was chosen, and computed. The Sun data was obtained from the US Naval Observatory:

GMT	**Lat**	**Long**	**Sun EL**	**Sun AZ**	**LOP**	**Dist to Go**
1306	N4	W27	68.6	27.3	117	700
1436	N0	W27	65.6	339.6	250	475

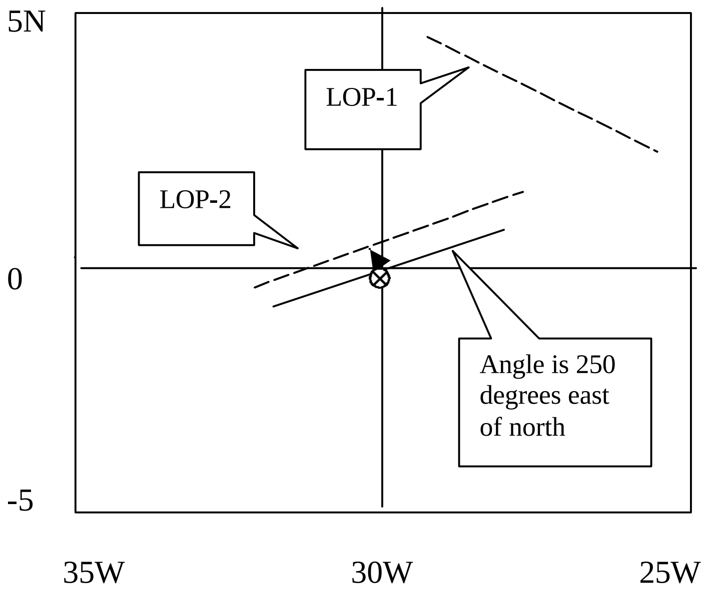
Next we get a weather forecast, and adjust airspeed and fuel load if needed to maintain 150 Knots Ground Speed. The winds at 9000 ft are expected to be East at 13 Knots for the first half of the trip, and 15 Knots for the second half. Using the E6B, the correction is 4 degrees left, and 8 Knots reduction in TAS to maintain 150 Knots ground speed. The initial magnetic heading is therefore 228 Degrees. Take-off at 0655 on runway 36 into a 15 Knot surface wind from the NorthEast. We want to get to 8500 ft quickly to use the NDB to confirm the wind effects. After take-off we will make a gentle climbing turn to the right to overfly the NDB and immediately get on the heading to test the crab angle. Leveling off at 8500 ft, OAT was 15 Degrees C, so the E6B computes the IAS to be 122 Knots for a ground speed of 150 Knots. Now, for 5 hours there is very little to do but monitor the airspeed, keep adjusting the heading to maintain the true bearing in the face of changing magnetic variation, and resetting the gyro to match the compass. 4X is used to speed up the process.

We take the first step in determining a position fix by measuring the first LOP, at 1306 GMT. In the "not to scale" sketch below, the solid line represents the sun LOP through our preflight assumed position. The average of 10 octant readings around 1306 yielded a sun elevation angle of 100 minutes of arc less than the sun's elevation of 68 degrees 36 minutes for the assumed position. So the line of position is moved away from the direction of the sun by a distance representing 100 NM, and is shown as the dotted line labeled LOP-1 on the chart below. This adjusted line of position, since it is nearly perpendicular to our line of flight, gives us a good clue as to our ground speed. We have traveled 100 NM further in the prescribed time than we planned, so our Ground Speed has been 157 Knots.

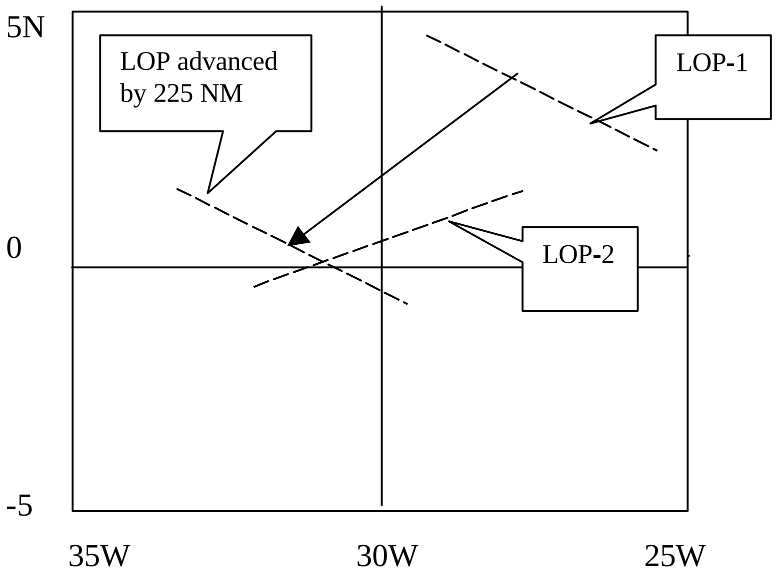


[Until we get a “real” octant gauge, we must cheat a bit and peek at the HUD display of lat and long, and use that peek ONLY to set the amount of adjustment of the assumed LOP toward or away from the sun. This is done again for the second octant reading in 90 minutes.]

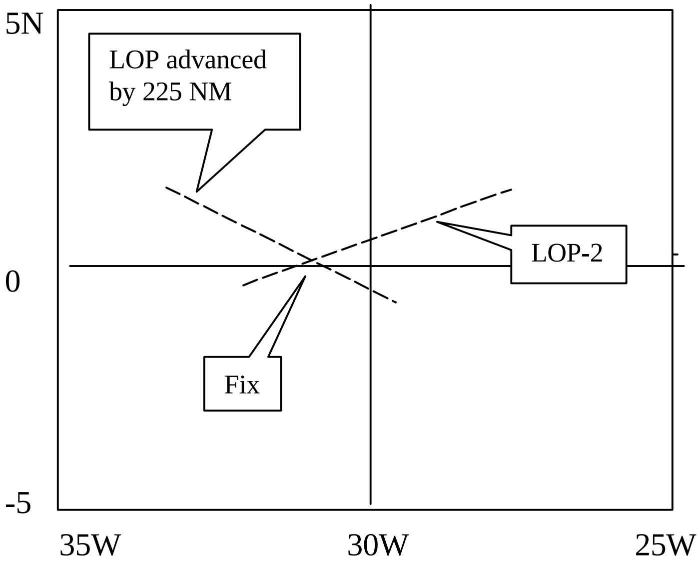
At 1436 GMT, we will get the second LOP. Note carefully that the cockpit clock jumps “back” one hour when the plane crosses the W30 degree meridian (approximately). So you need to be watching the clock and a “real” clock or timer to know GMT. On the sketch below, we have moved the LOP-1 dotted line down from the assumed to the correct position, and the preflight assumed LOP-2 is the solid line. The angle of elevation to the sun from the assumed position is 65 degrees 36 minutes. The measured angle of elevation to the sun was 66 degrees 31 minutes, so the angle being greater than the angle from the assumed position, the line was moved 55 minutes of arc (55 NM) toward the sun. The dotted line below labeled LOP-2 is the corrected LOP.



Finish this up by advancing LOP-1 by 225 NM (the distance traveled between the first and second measurement) in the direction of the line of travel, 220 degrees true. We now have an intersection of two lines of position which is the fix. We advanced the LOP-1 maintaining the same true angle of 117 degrees, in the true direction of travel, 220 degrees. See the sketch below:



The sketch below is the finished running LOP sunline fix. It is at North 0 degrees 30 minutes, and West 31 degrees 45 minutes. The LOP-2 is accurate to 15 NM, and the advanced LOP-1 is accurate to 15+23=38 NM, because it was advanced 225 NM.



Using this fix and the VE6B, the true bearing to SBNT is computed to be 435 NM at 208 degrees true. The forecast winds at 9000 ft are East at 16 Knots, so the VE6B says our heading should be left 6 degrees, or 202 degrees true, 220 degrees Magnetic. The TAS should be 143 Knots to maintain 150 Knots ground speed. This course is assumed as soon as possible after the fix, and in the old days (before VE6B), a chart and protractor would probably have been used to determine the course and distance. The OAT is showing 12 degrees C, so the E6B says the IAS should be 120 Knots. At a ground speed of 150 Knots, and distance of 435 NM, the elapsed time to Natal is 2H 54M, so the ETA is now projected to be 1730 (15 minutes early). We should start our descent at 300 ft/min about 25 minutes before arrival, at 1705 GMT, or 1505 Cockpit Clock time. Tuning in the NDB at 400 KHz, we hear it first at 1700, about 5 degrees left of our nose, so we correct course. Contacting Natal tower for landing instructions, we are cleared to left base for landing on runway 16. We learn the wind is SE at 5 Knots. We touch down at 1730. 398 gallons remain in the tanks, which contained 1150 gallons at take-off.