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MET.O.15 INTERNAL REPORT

No. 74

OMEGA - ITS OPERATION AND APPLICABILITY TO C-130 RENAVIGATION

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FH5B

OMEGA - Its operation and applicability to C-130 renavigation.

Introduction :

The ability to determine position correctly is essential in meteorological experimental flying. Although inertial navigation systems respond quickly and accurately, they tend to build up velocity offsets over a period of time. This is manifested as a slow position drift, causing errors in both position and flight level wind determination. Thus if we have a stream of reference data giving absolute position, we can, *a postiori*, calculate correctional offsets for the INS values.

The traditional method has been to use the DECCA hyperbolic navigation network, but in March 1987 the MRF C-130 was equipped with an OMEGA receiver, the Litton LTN-211.

OMEGA is a radio navigation system operating in the VLF (Very Low Frequency, 10-14 kHz) range. It is being increasingly used by both civil and military ships and aircraft, and since the construction of the eighth transmitting station in 1982, it provides coverage of the entire globe.

Receivers encompass a wide range of technology and price. The most basic are paper tape recorders which must be used in conjunction with hand plotting on hyperbolic charts. At the other end of the scale are extremely sophisticated automatic units, capable of controlling an aircraft autopilot. The latter type is like that fitted to the MRF C-130.

Due to the wide acceptance of OMEGA there have been many tests and assessments carried out, and many documents are available describing the system and its characteristics.

This report will attempt to view OMEGA with its applicability to the activities of the Meteorological Office in mind, and provide an independent check of accuracy for the areas in which the MRF C-130 is likely to operate. Background technical information is limited to that which will enable the reader to appreciate the problems involved, but further reading may be found in the references.

We will begin with a general description of the principles of operation of the OMEGA network, with mention of some of the common problems that affect it.

This will be followed by a more detailed look at the particular receiver installed in the C-130, the features of the program it uses, and the data we extract from it.

Finally we shall compare the published figures of OMEGA accuracy (and predictability of accuracy) with our findings in day-to-day use on experimental flights. Much of this data was collected during the FIRE marine stratocumulus project in San Diego, USA, and this may be compared with similar flights over the UK. The evaluation was carried out alongside the INS and DECCA systems, and conclusions will be drawn considering their relative merits.

OMEGA - General Principles :

(i) Station specifications :

The OMEGA transmission network consists of eight stations distributed around the world (see table 1) and giving global coverage. These stations are run by the governments of the relevant countries, and coordinated through the International OMEGA Association.

Table 1 : Transmitting stations.

Station	Location	Antenna type
A	Bratland, Norway	Valley span
B	Liberia	Grounded tower
C	Haiku, Hawaii	Valley span
D	North Dakota, USA	Insulated tower
E	Reunion Is.,Indian Ocean	Grounded tower
F	Golfo Nuevo, Argentina	Insulated tower
G	Woodside, Australia	Grounded tower
H	Tsushima Is., Japan	Insulated tower

A number of frequencies are used, but all lie in the VLF range. This means that their wavelengths are of the order of 15nm, and thus the range of a particular station is virtually unlimited on the earths surface, at least in terms of signal strength.

Position location is achieved by deriving phase information from the signals received. There are a number of ways of doing this, and the method used by the receiver on the C-130 will be described in the next section.

Notwithstanding, whichever method is used, there must be known phase relationships between the signals from different stations if we are to extract any useful information.

To this end all of the eight stations are kept very carefully synchronized to UTC (Coordinated Universal Time). Comparisons between stations are continually being made, and weekly corrections are applied. This time keeping is of such a high standard that at any time a particular station is likely to be synchronized to UTC to within 2 us. (This corresponds to 2 centicycles at 10.2 kHz).

This balance between precision timing and high power global transmission requires a combination of both very small and very large scale technology. Each station has four Cs frequency standard atomic clocks that feed independent chains of oscillators to produce the required frequencies. Each chain incorporates a phase shifter that may be used to adjust the phase offset occasionally, or may be varied periodically to correct frequency. The signals from the four chains are intercompared and only the most reliable is sent to the transmitter.

Transmission is by means of a 150 kW vacuum tube transmitter which drives a large antenna. Most of the antennae are 1500 foot towers, although the largest is a 3 km valley span in Norway. At the 30 km wavelength used this approximates to an infinitesimal dipole. The tuning and antenna systems must carry currents of about 400 A at voltages of up to 224 kV to generate the nominal 10 kW of radiated power.

During transmission the station also receives its own signal from a local receiver, which it then compares with the pre-transmission signal, and applies corrections if necessary.

(2) Transmission format :

The four basic OMEGA frequencies are : 10.2 kHz
11.05 kHz
11 1/3 kHz
13.6 kHz

The eight stations transmit their various frequencies in a fixed commutation pattern. This is based on a ten second cycle which is unambiguous and coordinated to UTC via the station atomic clocks. Each station transmits eight frquency pulses during the pattern: one of each of the four basic OMEGA frequencies and four on a frequency unique to that station. The sequence of pulse lengths is non-repeating, allowing receiving units to synchronize with the commutation pattern easily.

Once this has been achieved, a signal of a certain frequency can be attributed to the appropriate individual station. The commutation pattern is shown in Fig.1.

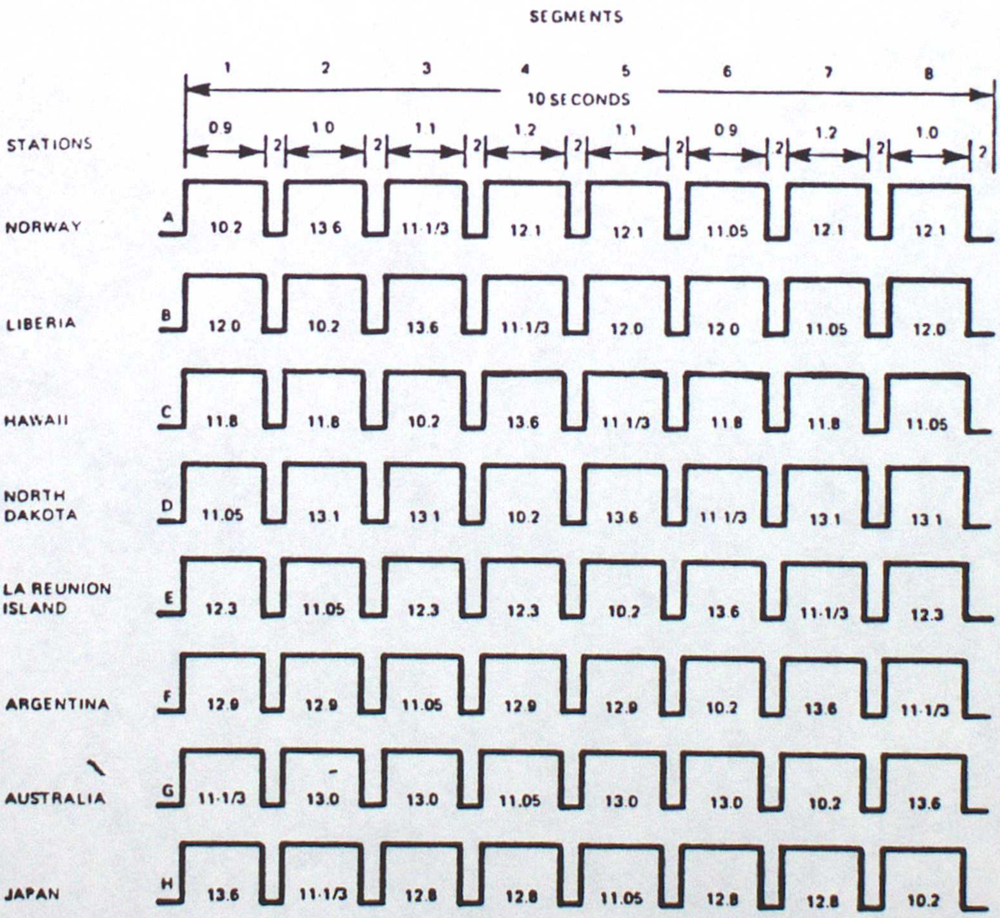


Fig. 1—OMEGA Signal Transmission Format

(3) Position location :

OMEGA may be used to navigate in two ways; the first is hyperbolically :

Signals of the same frequency from different stations are compared to find the phase difference. Lines of constant phase difference (or lanes) between two stations are a set of hyperbolae, separated by a half-wavelength (8 nmi at 10.2 kHz) when measured on a line between the stations.

The half-wavelength ambiguity should not cause problems, as the beat frequency between two of the OMEGA frequencies can be used for more approximate location due to its longer wavelength. Another way of looking at this is that the ambiguities in the hyperbolic lines-of-position from the 10.2 kHz will only coincide with those from, say, the 13.6 kHz every 24 nmi.

So position determination accurate to within a few centicycles of the 10.2 kHz lanes can be performed if the first-guess position is within a half-wavelength of the lowest beat signal between the various OMEGA frequencies. Using all four this coorresponds to a distance of 288 nmi.

Comparing a frequency from three stations is enough to give a unique point of intersection of the three hyperbolae. Although the stations do not transmit simultaneously, phase differences are obtained by comparing each signal, as it occurs, with an internal oscillator, and storing the result. The fact that this oscillator is not synchronized to UTC is unimportant using the hyperbolic method, as only phase differences and not absolute phase are required.

The second method of navigation is to process the data using the range-range or 'rho-rho' system. This is the method employed by the LTN-211 :

The phases of the transmissions from a single station are measured to determine the range from that particular station. Using the three frequencies 10.2, 11 1/3, 13.6, we can form several beat frequncies, the lowest of which has a period of 15/17 microseconds. (See Fig.2) This corresponds to a repeat distance of 144 nmi. The phase of the 144 nmi 'wide lane' signal can be found by subtracting the 10.2 kHz phase from the 11 1/3 kHz phase.

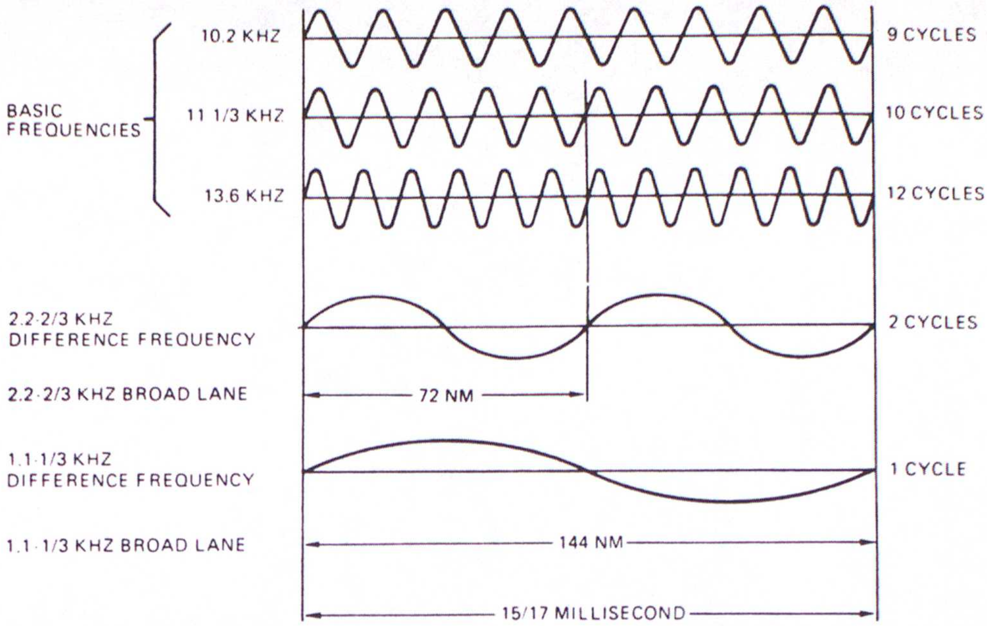


Figure 2. OMEGA Frequency Relationships

We can use the broad lane phase to find our range from the station within a 144 nmi lane. Then within this we can use progressively higher beat frequencies to place the range more accurately until we have located our position within a 10.2 kHz lane.

Performing this in three stations will give us three ranges, and the intersection of the three circles formed by their loci will give us a unique point.

However, with this method the offset of the internal clock relative to the station atomic clock must be known, in order to determine the absolute phase of the signals. If the unit is receiving three stations there is enough information to deduce both position and clock offset. This is because we are solving three independent equations to find three unknowns : latitude, longitude and clock offset.

(4) Sources of error and coverage prediction :

Determining the reliability of the signal received is by no means a simple matter.

In terms of signal/noise ratio (SNR) the maximum useful distance from a station is about 8000 nmi. Due to geomagnetic field effects, coverage is better easterly than westerly, and is moderate north/south.

However, even if signal to noise levels are very good this does not guarantee good position determination, because what we are using is phase information.

The OMEGA signals propagate globally by using the gap between the earth and the ionosphere as a concentric spherical waveguide. The properties of a waveguide depend crucially on its width and on the conductivity of its boundaries. As the ionosphere is a dynamic and changeable region of the atmosphere any alteration in its structure may have a significant effect on the propagation characteristics in the VLF range.

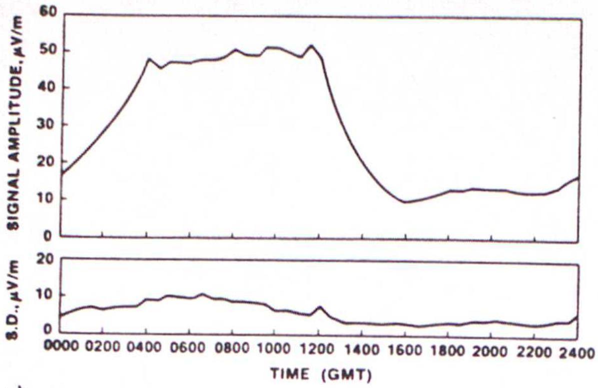
Many of these changes are predictable, varying diurnally or seasonally, or being peculiar to some geographical location.

The diurnal variation is caused by ionospheric changes in the sun-lit portion of the propagation path. Solar UV radiation alters the equilibrium of dissociated molecules, thus affecting the conductivity. Thus is manifested in signal strengths being greater at night, but signal variability also increasing.

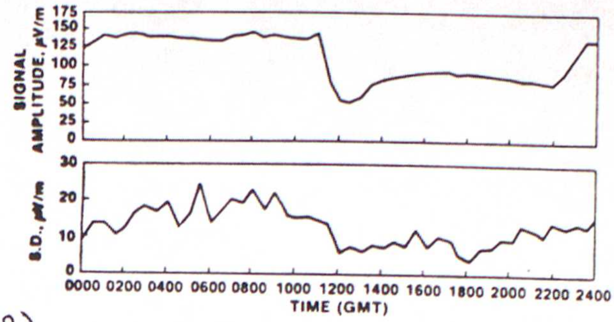
Phase difference shows a well-behaved variation of up to 80 centicycles (cc). (See Figs.3(a,b,c)) However, during the transition between lit and unlit conditions the phase offset changes quite rapidly (20 cc/hour) and any small error in phase offset estimation will have a relatively large effect on position determination.

The overall effect is of poorer position location at night, particularly around the day/night transitions. Expected location accuracies (all other conditions being nominal) are +/- 1 nmi by day and +/- 2 nmi by night.

The effects of ground conductivity are also well understood, and comprehensive maps exist which may be used to calculate phase corrections.

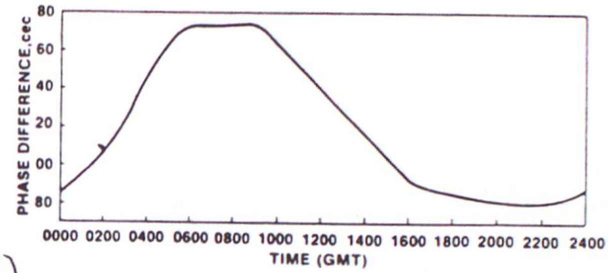


(A) Average field strength and corresponding standard deviation for 10.2-kHz signal received at Rome, NY, from Haiku, Hawaii, Oct. 24–Nov. 10, 1962.



(B) Average field strength and corresponding standard deviation for 10.2-kHz signal received at Farfan, C.Z., from Forestport, NY, Nov. 27–Dec. 21, 1962.

Figs.3 Diurnal effects on propagation.



(C) Average 10.2-kHz phase of Omega Hawaii received at Forestport, NY, May 17–24, 1966. Standard deviation approximately 2 centicycles.

As may be expected with a spherical waveguide, signals propagate in all directions around the globe and reinforce at the antipodal point. This leads to unpredictable phases and renders the station useless in that region.

A similar problem linked to OMEGA's long range, is that in some conditions, the signal that has travelled the long-path round the earth is received with greater strength than the short-path signal.

Finally there are uncertainties caused by higher transmission modes. To say that the phase is a predictable function of distance we must assume that only the lowest mode is dominant, but adverse ionospheric and ground conditions can conspire to produce multi-modal interference. This is particularly a problem with equatorial stations like Liberia and Argentina, and is more pronounced at 13.6 kHz than at 10.2. Signal are also assumed to be severely modal within 500 km of the transmitting station, the unusable region tending to extend equatorwards and westwards.

From our observation and understanding of the ionosphere, all of the above effects can be forecast and corrected for to some degree. The Omega Navigation System Centre (ONSCEN, previously

ONSOD) has a computer model which runs a global full wave analysis to assess propagation for the signal from each station. An example of the type of result produced is shown in Fig.4. Symbols printed on the map are coded as 1,2,3 for signal/noise ratio (in decreasing order), A for antipodal effects, L or - for a competing long-path signal, and M for multi-mode interference.

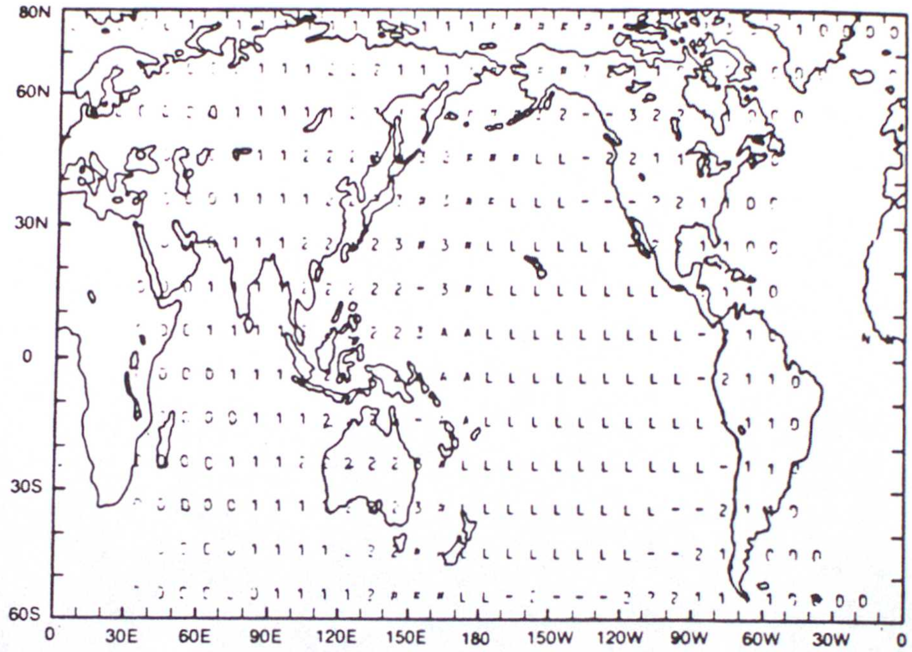


Fig. 4. Coverage of Omega Liberia at 10.2 kHz during idealized day conditions.

The results of this type of analysis for each station can then be combined to produce station coverage prediction maps (Fig.5, letters refer to stations in table 1) and estimated fix accuracy maps (Fig.6, numbers are c.e.p, circular error probable).

Hence, despite all these sources of variability, our knowledge of these phenomena enables us to select our stations wisely and to apply phase corrections when appropriate.

There are however, more sporadic ionospheric disturbances that are not only unpredictable, but whose effects may be far greater in magnitude than those discussed above.

These are mostly caused by solar flares sending out streams of x-rays and charged particles :

(1) Sudden phase anomalies (SPA) - These arise from Sudden Ionospheric disturbances (SID's). The increased x-ray flux falling on the sunlit path reduces the width of the waveguide by increasing the conductivity of the lower regions of the

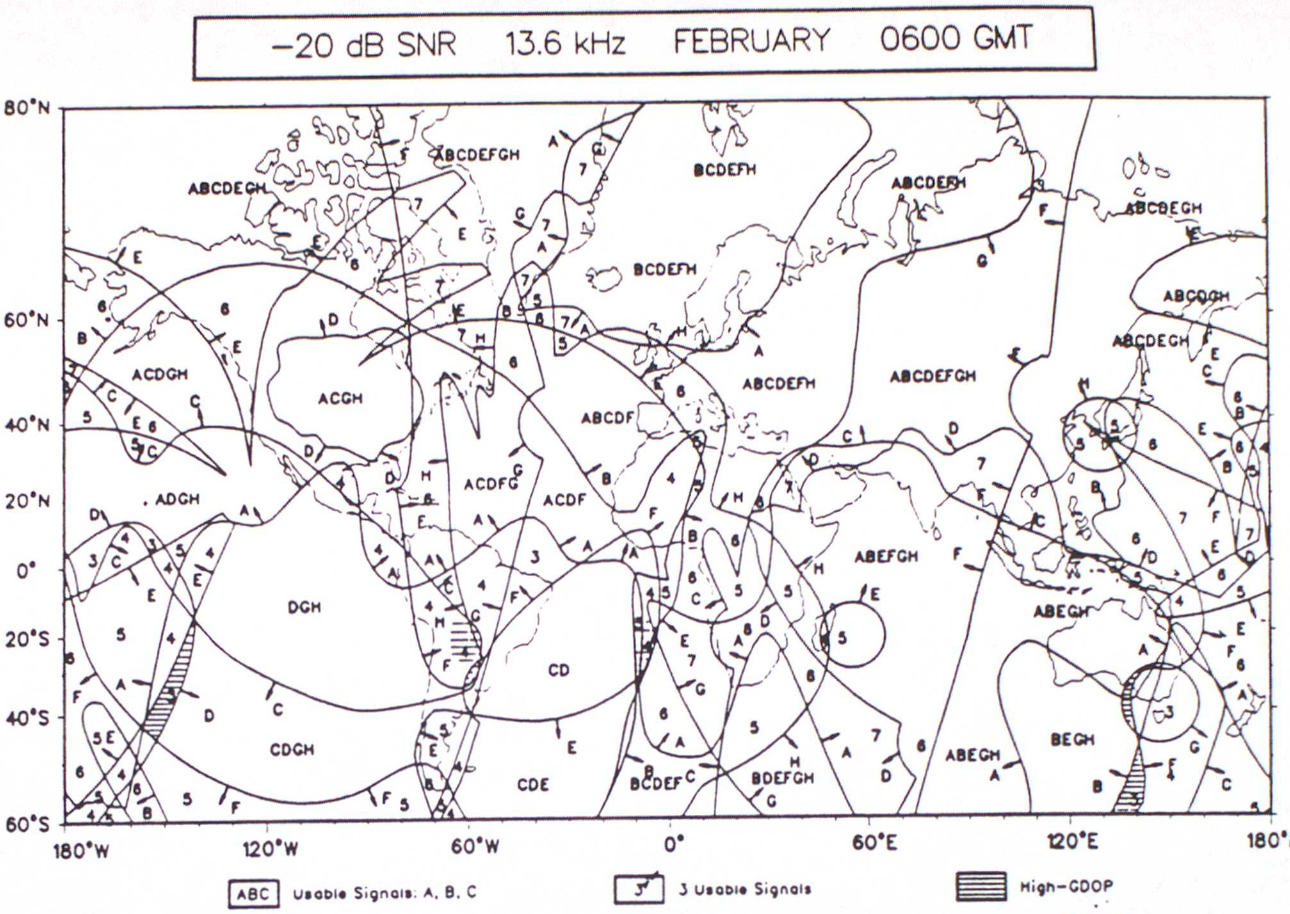


Fig. 5 Composite Signal Coverage Prediction Diagrams: 13.6 kHz, February, 0600 GMT[18]

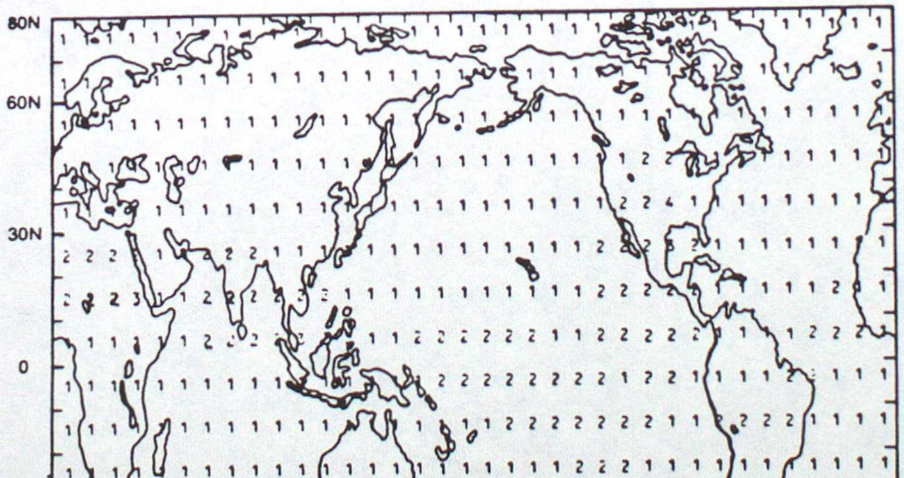


Fig. 6. Fix accuracy of Omega during idealized night conditions using only 10.2-kHz transmissions (c.e.p., nmi).

ionosphere. The average duration is 45 minutes to 3 hours. Due to this short timescale no warnings are issued. Position errors are of the order of 4 nmi.

(2) Polar Cap Absorptions (PCA) - Quantities of charged particles (mostly protons) released following flare activity are funnelled down the lines of the earth's magnetic field onto the poles. This severely reduces the width of the waveguide and drastically reduces the propagation efficiency over the pole. A PCA begins within a few days of a proton flare, and last for 2 to 5 days. Warnings are disseminated to user agencies. Position errors can be up to 8 nmi.

PCA effects are more localized as the only transpolar paths are affected. These paths are often difficult anyway, due to the properties of the ice sheets.

Measurements have shown that 0.2% of the time the nominal position error is exceeded due to SPA's and PCA's. (See Fig.7) Although the probability of this occurring is low, the position deviation may be high (>5 nmi).

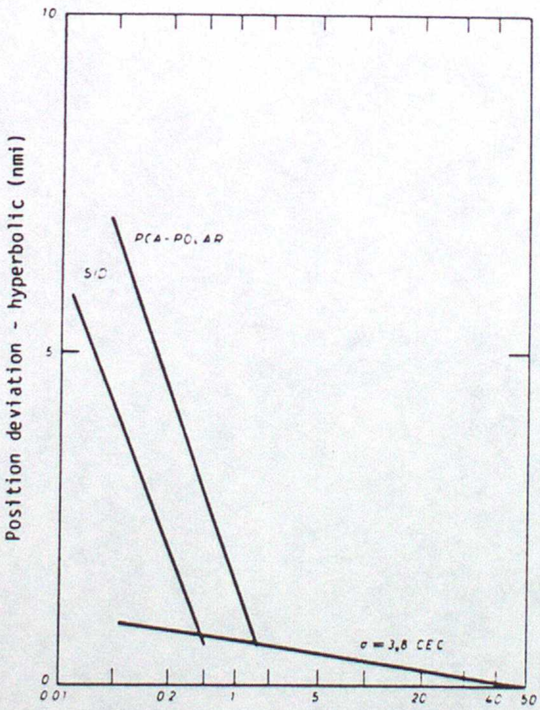


Fig.7 Probability of a propagation induced error in position fix.

Finally, position accuracy depends on the more prosaic phenomenon of transmitter malfunction or 'outage'. This is, in general, not a significant problem, as each station has two vacuum tube transmitters, keeping one as a backup. During 1985 individual stations were on air an average of 97.1% of the time.

Routine maintenance, however, does require station shutdown from time to time, and this is coordinated between the various operating countries to try and ensure that simultaneous outages of two stations do not occur. Measurements in 1980 showed that simultaneous outage occurred just 0.1% of the time, and that the median time for which it occurred was only six minutes.

Even in this extreme condition, there are still likely to be stations available, as the useful range is about 8000 nmi. Fix accuracy tests using only the 10.2 kHz frequency have shown that in typical conditions, we can expect an a c.e.p of 1.5 nmi using the best stations, and 3.2 nmi if the most desirable station is missing.

The LTN-211 Receiver :

We will now look at the characteristics of the OMEGA system mounted on the MRF C-130.

The LTN-211 is one of the most sophisticated types of receiver available, and uses the 'rho-rho' method of position location. Operation of the unit is almost completely automatic, requiring the navigator only to enter date, time and an approximate position on run-up.

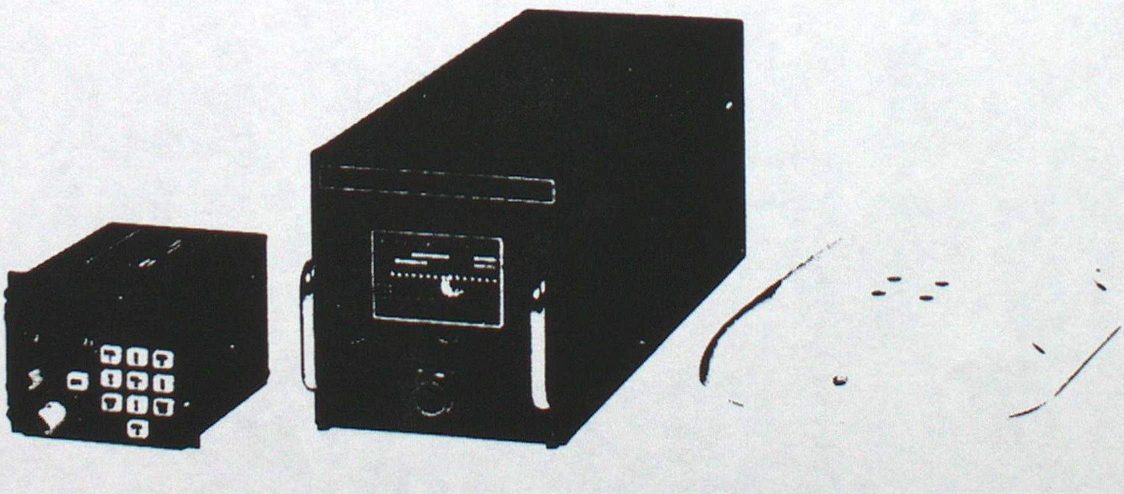


Figure 8. The LTN-211 OMEGA naviagation system.

Most of the processing is done using the three frequencies 10.2, 11 1/3, 13.6 kHz which give a lowest beat frequency of 1.13 kHz, and hence an ambiguity distance of 144 nmi.

Physically the receiver consists of three parts: the Receiver Processor Unit, the Control Display Unit (CDU), and the Antenna Coupler Unit. (See Fig.8) The system is controlled via the CDU which is located at the Navigators position on the flight deck. The antenna is housed in the tail.

Used to its full capacity, the LTN-211 will compute best paths between preset waypoints, and navigate the aircraft on this course via an interface with the autopilot.

However, in its passive navigational mode we may divide the operation of the unit into five stages :

(1) Synchronization : When first turned on the receiver samples ten seconds of incoming signal to try and determine the start of the transmission sequence. This is done by dividing the ten seconds into a hundred 0.1 second slots and comparing the pulse lengths at various frequencies to the known commutation pattern. If the attempt is unsuccessful another ten second sample is taken until the unit can lock-in. It can then identify which stations are sending the signals it receives.

(2) Phase tracking : The phases of the incoming signals are found by comparison with those generated from an internal oscillator. These are sampled 120 times per second and stored for further use. At this stage we are not finding absolute phase, but phase relative to the internal clock. Hence we still need to calculate the offset of the clock from the stations atomic clocks. This is performed in step 4.

(3) Station selection : The following criteria are applied when deciding which stations are to be utilized :

(i) Stations which have been manually deselected by the navigator are eliminated.

(ii) Stations further than 8000 nmi are eliminated.

(iii) Stations known to cause modal interference along the propagation path are deselected.

(iv) Only stations whose signals exceed a certain SNR are acceptable.

(v) Stations are deselected if the difference between measured phase and computed phase (based on estimated distance) is above a certain limit.
When the RAF Hercules fleet navigation systems update began in 1982, the Australian station was not yet on air. So even though the MRF C-130 did not get its receiver until 1987, the software does not account for the Australian transmitter. For this reason, *station G must always be manually deselected.* This has no great effect on position determination around the British Isles, but may be important in other areas, particularly in the southern hemisphere.

By setting the main selector switch on the CDU to STA, the navigator may display an eight digit status word which tells him which stations are in use. (See Fig.9)

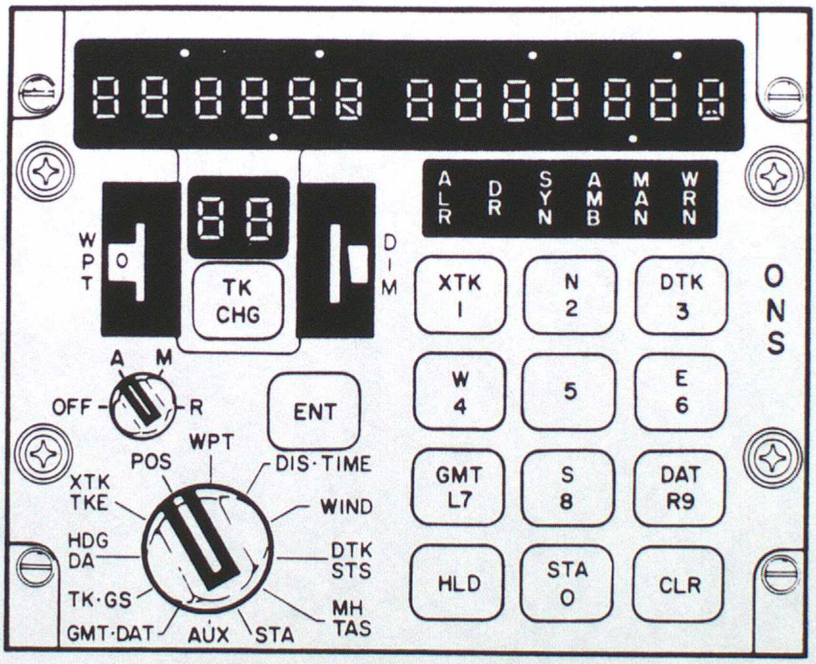


Figure 9. Control Display Unit front panel.

A solid digit indicates that the station is presently being used for navigation. Flashing digits show stations available but not currently in use. Solid zeros are stations deselected by the OMEGA computer, and flashing zeros show manually deselected stations.

Station selection criteria are checked every ten seconds.

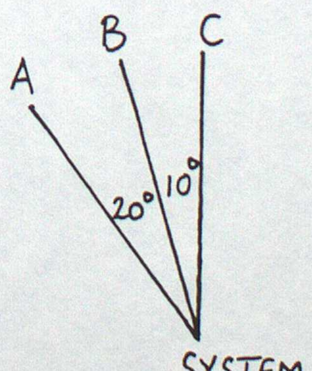
(4) Position determination : Before any accurate position can be found the system computes the approximate paths to the transmitting stations in use, to calculate the propagation characteristics. The LTN-211 possesses a propagation model which is a simplified version of that used by ONSCEN. A ground conductivity map of the world (on a 4 by 4 degree grid) is internally stored, and use is made of this, together with consideration of day/night and antipodal effects, to produce a phase correction for a given path.
(This is achieved by a 1 degree step length integration along the short-path great circle. Global oblateness is accounted for.)

Using the corrected phase measurements of the signals from three stations the OMEGA computer uses a 'least squares' type fitting process to calculate corrections on the estimated values of latitude, longitude and clock offset. (We need three stations because we are solving for three unknowns.)

Once the receiver has warmed up and the clock drift rate has become constant we no longer need to keep correcting the clock offset, and hence only two stations are necessary to solve for latitude and longitude. However, the system will use as many stations as are available.

In certain circumstances (see Fig.10) the geometric arrangement of the aircraft and transmitters is such that the least squares estimator cannot distinguish between clock offset error and position error. In this case clock offset is held constant and the equations are solved only for latitude and longitude.

Figure 10. Geometric arrangement of stations and OMEGA receiver likely to cause ambiguity between position and clock offset error detection. Can occur if less than 45° between stations.



The minimum requirement for OMEGA to initially achieve navigational mode is to receive all three frequencies from three stations for one minute.

During flight, should there be no available stations for a time, dead reckoning is used to update position, calculated from inputs of TAS and magnetic heading.

Given the TAS and magnetic heading inputs, and using its own derivation of ground speed, the receiver calculates windspeed and direction, and aircraft drift angle.

(5) Data output : In addition to the lat/long display on the CDU, the LTN-211 gives output in both digital and analog form. As the DRS uses the digital data streams, we shall restrict ourselves to these, but full information on all outputs and their format can be found in the LTN-211 technical description (See refs).

Input to the DRS is in terms of 12 bit numbers, recorded at 1s intervals. Due to different word sizes, some of the OMEGA output parameters are split into coarse and fine for recording purposes. The total list of OMEGA parameters taken by the DRS is shown in Table 2 below :

Table 2 : OMEGA parameters used by the DRS.

Quantity	Abbreviation	DRS par.No.
Latitude, Coarse	LATC	160
Latitude, fine	LATF	60
Longitude, coarse	LONC	161
Longitude, fine	LONF	61
OMEGA groundspeed, coarse	OGSC	162
OMEGA groundspeed, fine	OGSF	62
OMEGA heading	OHDG	64
OMEGA windspeed	OWS	65
OMEGA wind angle	OWA	66
OMEGA drift angle	ODRA	56

details of the DRS data conventions for the above can be found in Loose Minute D\MET O(MRF)\9\2\6 dated 30/3/87.

OMEGA also produces other digital data streams which are not utilized. These are :

Track angle,
Distance to waypoint,
Time to go to waypoint,
Cross track distance,
Track angle error,
Desired track.

The system also gives an analog system status annunciation. This should not be confused with the OMEGA station status described in step 3 of this section (displayed by turning the CDU main selector switch to STA). The System Status Annunciation relates to the mode the unit is in at present.

The navigators log is filled in directly from the CDU lat/long readout. This is the only in-flight visual lat/long output : there is no slave display in the van.

Results :

In this section we shall be examining OMEGA data collected by the MRF C-130 in day-to-day experimental flying. Although OMEGA has been recorded for all flights since March 1987, we have restricted ourselves in this investigation to a database consisting of :

13 flights from the FIRE marine stratocumulus experiment off San Diego, held in June/July 1987. (H801-H813)

6 standard flights over the British Isles (ie. North Sea, S.W.Approaches, Scotland etc.)

It is not the aim of this section to explain the causes of all of the phenomena observed, but to make the potential OMEGA user aware of their existence, so that he is better able to make an objective judgement concerning the quality of renavigation data.

The first question that presents itself is that of the absolute accuracy of the OMEGA fixes. The only concrete comparison points we have are at those times when the aircraft is stationary at a known ground position. In one case we also have a coast crossing, which can be positively identified, recorded by the downward facing camera (DFC).

Figure 11 shows the distribution of OMEGA positions when stationary at the start and end of flights for San Diego North Island airbase, in terms of km deviation from the known map position. Figure 12 shows the same thing for the British flights, in this case relative to Farnborough pan map position. Fixes taken before the beginning of each flight are shown as dots, and those after the flight as crosses.

To assess accuracy we will look at 3 statistics :

The offset of the centroid of the fixes relative to the true map position;

The standard deviation of the points about the centroid;

The average distance of the points from the true position. This may differ from the centroid offset distance because we are in this case looking at

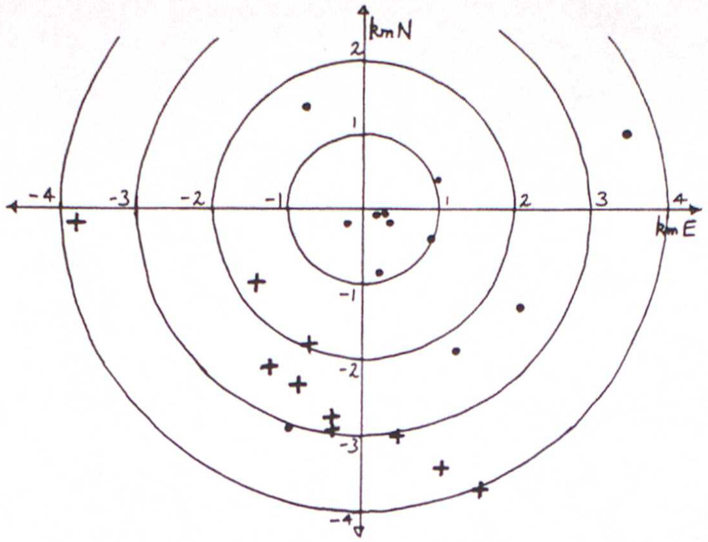
$$\sqrt{\overline{x^2 + y^2}} \quad \text{rather than} \quad \sqrt{\bar{x}^2 + \bar{y}^2}$$

The former will be affected by any correlation between x and y.

Taking all the fixes together we find that in the FIRE cases their centroid is offset from the true position by 1.3 kmN, 0.0 kmE, with a standard deviation of 1.4 km in both N and E components. Hence the true position lies within 1 s.d. of the centroid, and 1.3 km is well within the 2nm (3.7 km) nominal accuracy. The average distance from the true position is 2.1 km.

Looking at the data from the British flights in the same way we find a centroid offset of -0.2 kmN, -0.8 kmE with a s.d. of 1.2 km about this point. This appears at first sight to imply a better overall accuracy for the British data, the average distance from true of just 1.0 km reinforcing this impression.

However, when we examine those fixes taken at the starts of the flights separately from those taken at the ends, we find a more complicated picture emerging.



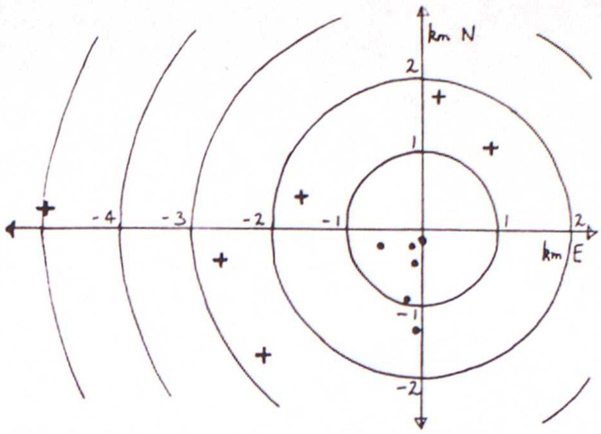


Fig.11 (left) Distribution of OMEGA position fixes from FIRE;
Fig.12 (Right) Distribution of OMEGA position fixes over the U.K.
Dots are pre-flight fixes, crosses are post-flight fixes.

Consider first the FIRE cases : It is clear from figure 11 that the end positions are on average displaced from the start positions by some 1.6 kmS and 1.2 kmW. So although the average initial fix position is offset from true by only -0.5 kmN, 0.5 kmE, the final average position is offset by -2.3 kmN, -0.7 kmE. The s.d of both of these sets of points is about 1.2 km which is larger than the 2.3 km final position offset. These statistics are summarized in Table 3.

The reasons for this southwesterly drift are not clear. An attempt was made to link the position of each fix to the GMT at which it was recorded, and also to correlate the degree of drift with the time of flight. Both of these showed no significant result.

Therefore either the drift is a warm-up effect occurring near the beginning of the flight, or an hysteresis effect due to the path followed during the flight. The OMEGA software carries no memory of conditions more than a few seconds past, and so the fact that the system has been stationary prior to take-off should not affect position determination once in flight. Before further speculation let us consider the British cases in Figure 12.

Here we find that the spread of the fixes as well as the offset of the centroid for the end of flight fixes increases relative to the pre-flight data. In this case the drift is 1.3 km west and slightly north, the spread being small for the pre-flight data but increasing for the post-flight data to a value comparable to that found on the FIRE flights.

These differences point to the fact that as the system warms up the effect on fix accuracy will differ for different parts of the world. It is nevertheless a puzzling fact that in both cases fix accuracy decreases rather than increases.

As the final positions are the more general case we will quote their average distance from true as representative of the two operational areas :

San Diego	2.8 km c.e.p
British Coastal Waters	2.6 km c.e.p

A further encouraging result was obtained by comparing DFC pictures at two coast crossings near Aberdeen and Ottringham with the OMEGA position recorded at that time. This proved to be accurate to within 1 km.

Table 3 : OMEGA accuracy statistics :

	Dist.of centroid from true. (km)		S.D about centroid (km)		Mean dist. from true (km)
	Lat	long	Lat	long	
British initial	-0.4	-0.2	0.4	0.3	0.7
British final	0.2	-1.5	1.2	1.7	2.6
All British	-0.2	-0.8	1.0	1.4	1.7
FIRE initial	-0.5	0.5	1.1	1.3	1.5
FIRE final	-2.3	-0.7	1.1	1.4	2.8
All FIRE	1.3	0.0	1.4	1.4	2.1

To asses the second-to-second variability of the fix, we will define the "spread index" : The OMEGA positions north and east are compared with their previous value (one second ago) and sorted into bins accordinly. Bin 1 covers the range 0.000 to 0.001 degrees, bin 2 covers 0.001 to 0.002 and so on. So we form a histogram of first differences between consecutive positions north and east. The "spread index" is the ratio of the third bin to the total number of points. This is a fairly arbitrary quantity as the speed of the aircraft in each direction is not constant, but as most of the fight is spent in L-patterns, the mean speeds north and east should be about equal.

As the aircraft experimental speed is 100 m/s all of the points should fall into bins 1 and 2 assuming perfect OMEGA positioning. Anything in bin 3 implies a distance of greater than 0.002 degrees (about 200m northerly) traversed in 1 second. Hence in an ideal case we would have a spread index of zero. Figures 13(a),(b) show typical histograms for FIRE and British flights respectively.

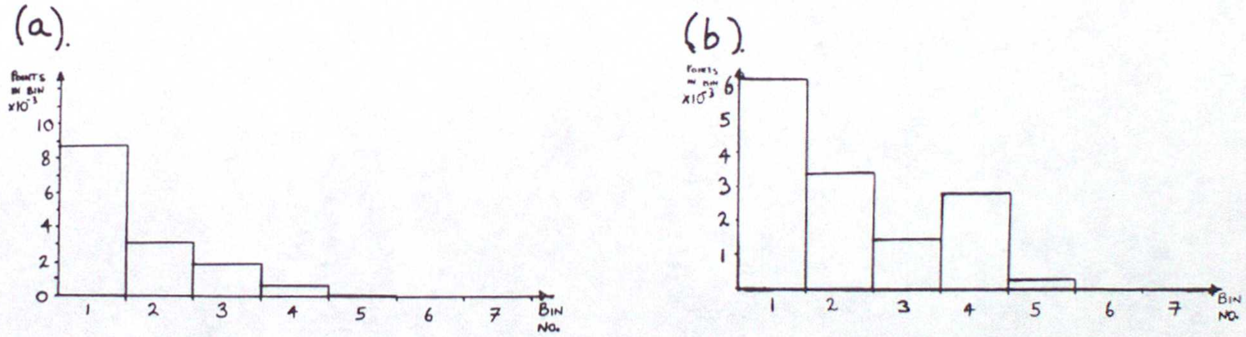


Fig.13 Fix interval histograms from (a) FIRE, (b) British flights.

General characteristics are that easterly spread is always greater than northerly spread (as expected due to differences in lengths of degrees) and the bimodal nature of the British histograms.

This second feature is not easily explained, although a look at the original data shows that the same position may be recorded for several seconds, followed by a jump of perhaps 0.004 degrees. The FIRE data gives a smoother variation and thus a monomodal distribution.

The average spread index is 0.76% N, 2.8% E. There appears to be no correlation between high spread index and high position error, and little difference between the spread index of FIRE and British flights.

Statistics were also collected of the percentage of points rejected as completely erroneous (ie. wrong by several degrees). This as similar for most flights and averaged at 0.08%, a thoroughly acceptable figure. Again, no correlation between percent flagged and high position error was observed, and the constancy of the result in both FIRE and British flights leads us to believe that these errors are an effect of the recording or data transmission rather than intrinsic to the OMEGA system.

The next point we shall consider is the effect of solar activity on OMEGA reception. Daily sunspot, flare and magnetic anomaly data were examined for the whole of June and July 1987 which encompasses all the FIRE flights.

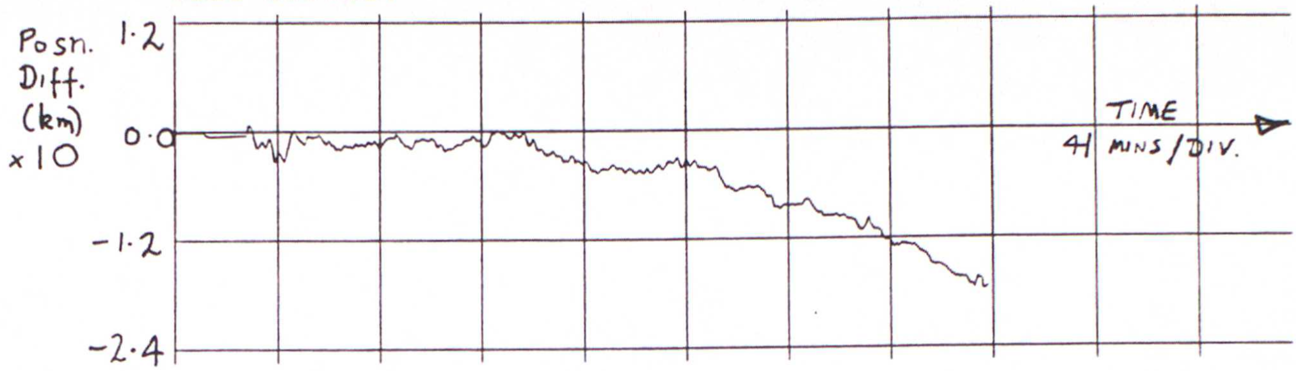
To use solar activity as a predictor for the usefulness of OMEGA on a particular day, we must first define what we mean by a "bad" OMEGA flight. This is a flight in which the OMEGA position varies from true in such a way that it is of little use for correcting INS velocities. The traces in figure 14 illustrate this. They show OMEGA position minus INS position (integrated velocities) in km as a time series for two different flights.

In (a) the OMEGA is well behaved, the slow smooth variation observed being entirely due to INS velocity drift and Schuler oscillations. However in (b), the variation is rapid and more irregular. This is indicative of poor OMEGA data.

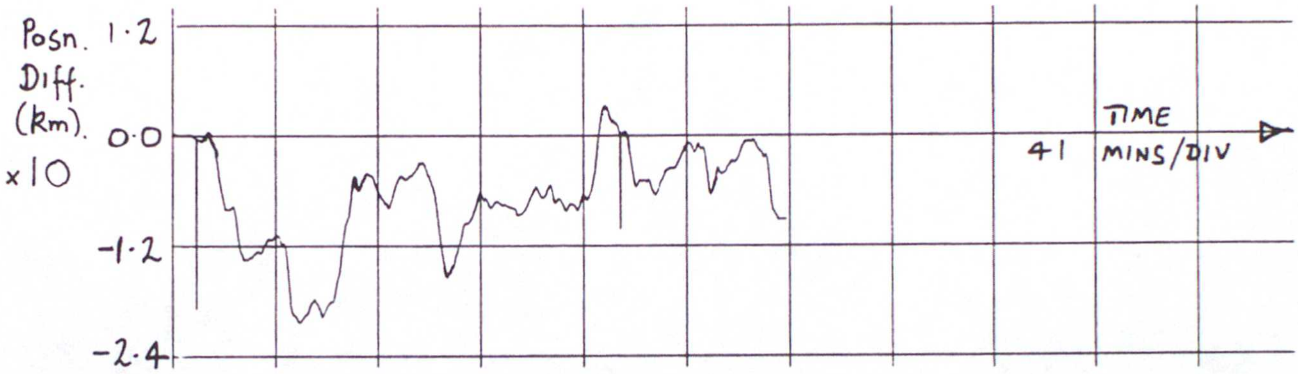
Unfortunately it is difficult to find any quantitative statistic that acts as a pointer to these bad flights. It seems to have no correlation with the number of points flagged or the spread index. The end-of-flight position error is often high in these cases , but may just as often be within the nominal accuracy, seeming to stabilize after the aircraft becomes stationary.

So deciding on the quality of the data is still a fairly qualitative process. Of the OMEGA data from the FIRE flights, H812 is useless, with large and rapid variations of up to 10 km; H801 is poor, though of some use due to long sections of constancy between the bad patches. H806 and H809 also show some variability although this does not impair their usefulness. (See figures 14).

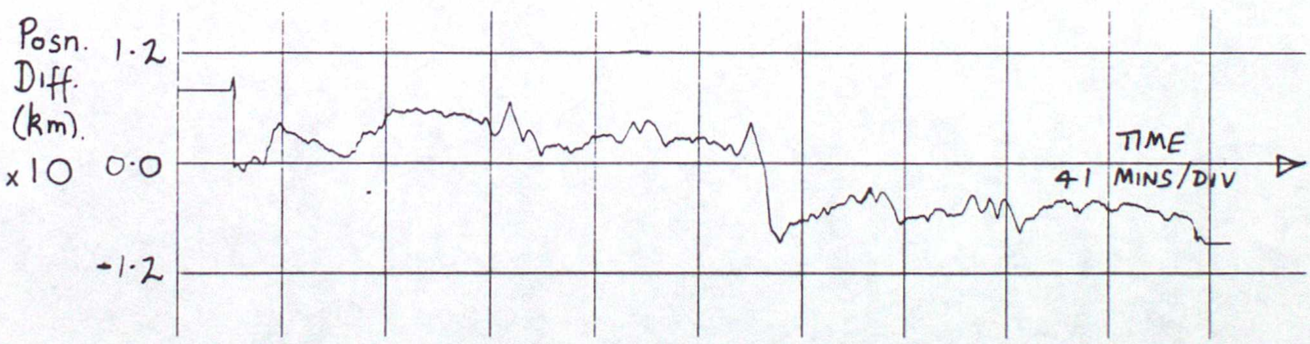
Figure 14. Examples of OMEGA fix minus INS (uncorrected) position time series.



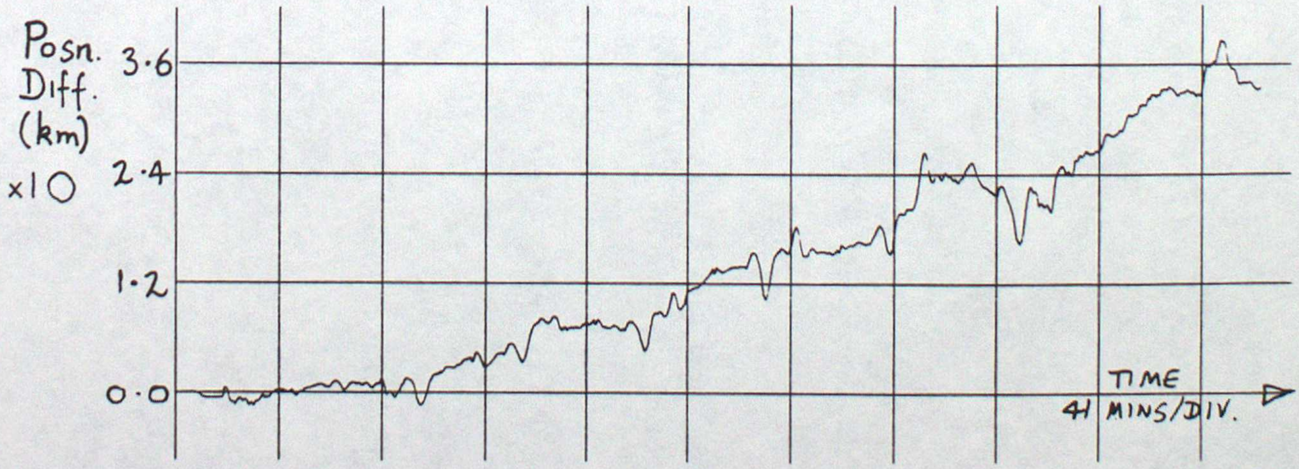
(a) Good OMEGA behaviour. (H804 North)



(b) Very poor OMEGA behaviour. Data unuseable (H812 North)



(c) Large OMEGA jumps, but stable sections between. (H801 East)



(d) Some irregularity but usefulness not impaired. (H806 North)

For comparison with the solar data, time series of three measures of solar activity were plotted, and the days of the flights marked. The three quantities used were Ri, the daily sunspot number; Ak, the geomagnetic index (amp.fluc. in 2nT); and the Wolf number. Of these the best correlated to OMEGA quality was Wolf number (see Figure 15). This is an index whose value is related to both the number of regions of activity on the sun, and the number of sunspots in each area. Although empirically defined, Wolf number is found to relate to the overall solar activity.

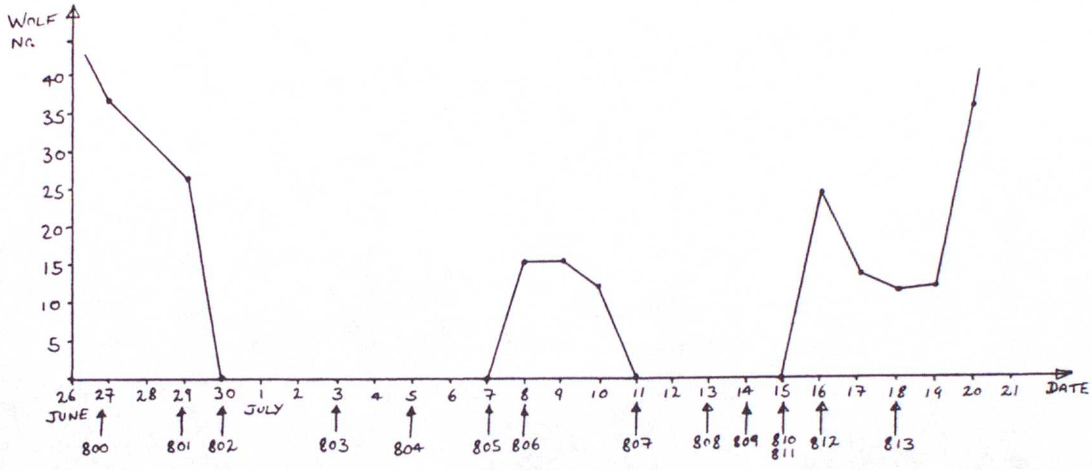


Fig.15 Time series of Wolf number during FIRE period. Flight numbers are marked.

For comparison purposes it is unfortunate that the data all fell in a wide solar activity trough, and so we have not been able to look at the effect of very high Wolf number. Data were unavailable for all but two of the British cases.

However, the very good flights correspond to Wolf number zero, and both H801 and H812 are relatively high. If this is a true relationship the effect at higher activity levels could be very serious. Plots of Ri, Ak and Wolf against % flagged, spread index and mean final deviation show no significant correlation.

So while this is by no means a full test of the effect of solar activity, we may say that the results do seem to indicate that it is a major factor in causing large and fluctuating position errors. The World Data Centre at the Rutherford Appleton Laboratory dispenses free solar data by telephone or mail, and solar activity forecasts are also available.

We will now briefly look at two other types of anomaly which have been observed in the flights sampled.

(1) The first of these is poor OMEGA performance in the early part of several of the FIRE flights. This seems to start just after take-off, even when the OMEGA ground position is stable, and lasts for up to about half an hour (or about 120km out of San Diego). Characteristics are a wandering OMEGA track, with deviations from true of up to 5 km. (See figures 16(a),(b))

This may be a warm up effect, although it is not observed on every FIRE flight and, so far, never on a British flight.

Alternatively it could be due to poor propagation near the coast of Southern California, but the main argument against this is that the effect is seldom seen on the return journey.

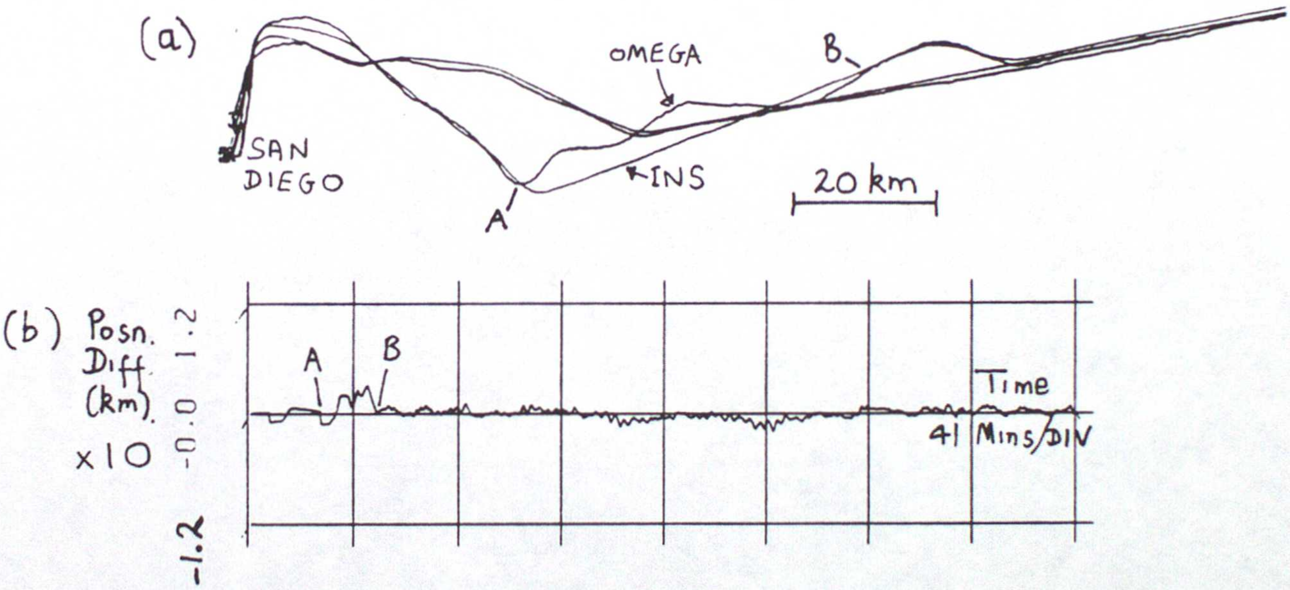


Fig.16 Poor OMEGA fixes early in flight for H804. (a) Trackplot, (b) Time series of OMEGA minus corrected INS (East compt).

(2) The second type of anomaly is the sudden jump. This has only been observed on one flight out of our sample (a British flight). A jump of about 10 km occurred from one point to the next. A few minutes later the jump was reversed. An obvious explanation would be lane slippage, although the LTN-211 software should prevent this sort of sudden alteration. Because station status is not recorded we have no way of telling if any of these problems coincide with station outages or poor propagation.

Comparison with DECCA :

Two flights featured an intercomparison of DECCA and OMEGA. As DECCA only extends around Northern Europe they are both British flights.

H790 followed a northerly track to the North Sea and then turned west to St.Kilda, returning along the same route. Near Farnborough the agreement between OMEGA and DECCA is good to within about 1.5 km. However, as we move further away from the centre of the chain, the DECCA becomes more spiky and irregular. The middle section of the flight is done on an inappropriate DECCA chain, and no DECCA data at all is useable.

The other comparison flight, H836, follows a route to the South West Approaches. DECCA and OMEGA remain within 1.5 km of each other throughout, although the DECCA trace is quite 'spiky' at times.

Thus in the regions where the appropriate DECCA chain was used, OMEGA was accurate to within 1.5 km, which, considering that the quoted DECCA accuracy is 1.8 km near a chain centre, is perfectly acceptable and quite adequate for most purposes. Furthermore, due to the attention required in-flight to keep the DECCA calibrated and locked on to the correct chain, the potential for human error is much greater.

Although OMEGA is more susceptible to atmospheric disturbance, it needs no attention during flight, thus leaving the crew free for other duties and reducing the risk of mistakes. Similarly, during post-flight processing the use of DECCA is a time-consuming and tedious business, whereas OMEGA processing can be made almost completely automatic, and covers the entire globe.

Summary And Conclusions :

1. Considering all points, both the FIRE and the British cases have the centroid of their positions within 1 standard deviation of the true position, and are both well within the quoted OMEGA accuracy of 2 nm (3.7 km).

2. When start-of-flight positions are looked at separately from end-of-flight positions we find :

(i) In the FIRE cases the spread of the points stays the same but during the flight there is a mean southwesterly drift of about 1.5 km.

(ii) In the British cases the start-of-flight spread is small but the end-of-flight spread increases to that of the FIRE data, together with a 1.2 km westerly drift of the centroid.

3. The mean distance from true for the two areas was found to be :

San Diego	2.8 km c.e.p
Britain	2.6 km c.e.p

We may compare this with the figure found by investigators at RAE in 12,000 hours of flying between known datum points over the U.K.. 50% of OMEGA positions were within 2.2 km, and 95% were within 4.4 km.

4. The number of points rejected was fairly constant at 0.08 % and is thought to be independent of location or local conditions.

5. Although by no means conclusive, the data seems to support the assertion that high solar activity may result in OMEGA data being degraded, and in some cases, made unuseable.

6. Temporary deviations lasting no more than 20 minutes and occurring within a few minutes of take-off have been observed west of San Diego, but do not necessarily imply poor data quality later in the flight.

7. Sudden jumps of 10 km have been observed on one flight, the probable cause being lane slippage due to poor reception.

8. When compared with the DECCA system, OMEGA remained within 1.5

km in the flights examined. This is acceptable for most meteorological purposes. OMEGA requires less attention than DECCA both during the flight and in processing afterwards, and presents no opportunity for human error. OMEGA also has the advantage of having global coverage.

DECCA on the other hand, is not as susceptible to atmospheric disturbance as OMEGA, and is more or less guaranteed to give good results over the U.K.

I would therefore recommend that OMEGA position is used as the standard tool for post flight position fixing, but that facilities for using DECCA data are maintained as a back up.

To this end it would be helpful if the Omega Station Status was recorded on the navigator's log at the beginning and end of each flight, together with the positions indicated. Thus if the initial station status indicated a poor selection, special attention could be given to taking DECCA fixes in case of degraded OMEGA quality.

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10/12/86 D\MET O(MRF)\9\2\6 Recording OMEGA navigation system data on the MRF Hercules.
22/1/88 D\MET O(MRF)\9\2\2 OMEGA navigation system.