VLF PHASE TRACKING FOR PTTI APPLICATION

by

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1.0 PURPOSE OF PAPER

The purpose of this tutorial paper is to give a short review of some basic facts about VLF propagation for PTTI applications, and to discuss equipment problems and the effects of ionospheric disturbances.

2.0 SOME BASIC FACTS ABOUT VLF PROPAGATION

For the theory of VLF propagation one may consult the books of Budden[1] and Wait[2]. Practical aspects may be found in the VLF Radio Engineering book by Watt[3].

VLF waves propagate in the wave guide provided by the ground and by the ionospheric shell. When close to a transmitter it is convenient to describe observed phenomena by means of ray theory. Beyond the distance of 1,000 kilometers or so, it is advantageous to use mode theory with a mode being one of the solutions of Maxwell's equations for a bounded propagation medium.

Normally, we have to worry only about the first- and second-order modes. These modes differ by three important parameters: (1) their phase velocities (the higher the mode number, the higher the phase velocity);

(2) their attentuation rates (below 25 kilohertz, the higher order modes normally have higher attenuation per megameter); (3) their excitation functions (at a given time of the day one mode is better excited by a transmitter than the other). For many applications, one can use the simple flat-earth model with infinite conductivity on the ground and in the ionosphere. If greater precision is desired, a spherical model should be used, with appropriate approximations for the ionospheric conductivity as a function of height and with inclusion of the geomagnetic field. A very useful approximation for the ionospheric conductivity is given by an exponential function depending on some reference height and a gradient. Pertinent tables have been published by Wait and Spies[4] for determining phase velocity, excitation function in db and loss in db/Mm as functions of reference height and gradient. Normally one assumes for daytime propagation a reference height of 70 Km and a gradient of 0.3 Km^{-1}, and for nighttime a reference height of 90 Km and a gradient of 0.5 Km^{-1}.

For many applications of VLF there are some simple rules of thumb by which one can interpret observed phase and amplitude anomalies.

One rule is that any natural disturbance (except a solar eclipse) lowers the reference height. That means the phase velocity will go up for both the first- and the second-order modes whereas the amplitude for the first-order mode may go up or down depending upon frequency and the amplitude of the second-order mode always goes down. When the gradient increases, which seems to be the usual case in a disturbance, the phase velocity decreases for all modes, and the amplitude increases (the latter is understandable because with a larger gradient the ionosphere is denser and, therefore, has less leakage). From this it can be seen that if a disturbance occurs, there are two phase effects which oppose each other: the height reduction will increase the phase velocity, and the increase of the gradient will decrease the phase velocity. However, the decrease is negligible when compared to the opposing increase so, as a general rule, whenever the ionosphere comes down the phase velocity will increase. Amplitude anomalies, on the other hand, are not so easily predictable. Below about 18 kilohertz, e.g., solar X-ray bursts may either cause signal enhancement, no discernible change or signal loss, depending on signal frequency, path direction and location, and flare spectrum. Above 20 kilohertz it is quite safe to predict signal enhancement for solar X-ray flares, regardless of path geometry.

In the event that there is more than one mode present, it is possible to handle the explanation of many phenomena with a simple vector model.[5] The two mode phasors are computed for the given path, e.g., by using the tables of Wait and Spies.[4] Then the phasor of the second-order mode is added to the phasor of the first-order mode. If there is an ionospheric disturbance, the phasor of the first mode will advance in phase by a certain amount, and the phasor of the second mode will advance by a larger amount. Depending on the original positions of the two phasors with respect to each other, an ionospheric disturbance can cause a large variety of VLF anomalies. There can be an amplitude increase or decrease with practically no phase change, or a phase delay or advance with almost no amplitude change, or any combination of the two.

Another important point is that when a path crosses either a very huge mass of ice or a permafrost area where the electric ground conductivity is low, propagation losses are substantially increased.[5,6] Therefore, one should avoid a path which crosses Greenland or the Antarctic ice.

If one is located as close as 1,000 kilometers or less to a transmitter, one may actually have more trouble in data interpretation than if one is farther away, because the EM field will then consist of a ground wave, an ordinary skywave, and an extraordinary skywave, which is just too much for the ordinary operator to handle. So if it is necessary to pick a VLF signal for PTTI applications, it often is better to select a transmitter which is more than 1,000 kilometers away.

3.0 RECEPTION EQUIPMENT

Figure 1 shows a typical VLF setup. It includes a voltage regulator, an emergency power supply (batteries), a frequency standard (Rubidium standard in this case), two receivers, and a multichannel recorder. The antennas (loop, whip or long-wire) are not shown. There are many potential trouble areas, and most of all there are lots of tempting control knobs. It is a very good idea to follow the principle: keep your hands off, once everything works properly. For example, at Fort Monmouth we have a cesium beam frequency standard which we have not touched since March, 1967, except for retuning the Xtal about every three months. This is probably one important reason why it is still working so well after almost five years of operation.

A problem with loop antennas is that of waterproofing. A loop is supposed to be electrostatically shielded by an aluminum tube around it. This tube has to have one gap otherwise the VLF field could not be picked up. At the same time, the tube must be rain-tight, which is accomplished by a nonmetallic fitting over the gap. Although the manufacturer claims that the loops are rain-tight, in practice they are not. Exposure to sun, cold, rain, snow and ice, makes the joints between aluminum tube and non-metallic gap material and the seal of the tuning box leaky. As a consequence, the tuning box will fill up with water and the signal output will decrease. The solution is to cover all joints with a plastic cover which should be open at the bottom to let condensed water get out.

Whips must be protected from dirt splashings on the base insulator. Also, a good counterpoise (6 radial copper braids) should be maintained to avoid signal variations due to change of ground moisture.

Cables should not be left lying on the floor where people may step on them and either damage connectors or break their outer shields. Cable connectors are, of course, a major trouble source. Their contacts may corrode, their pins may get loose, etc.

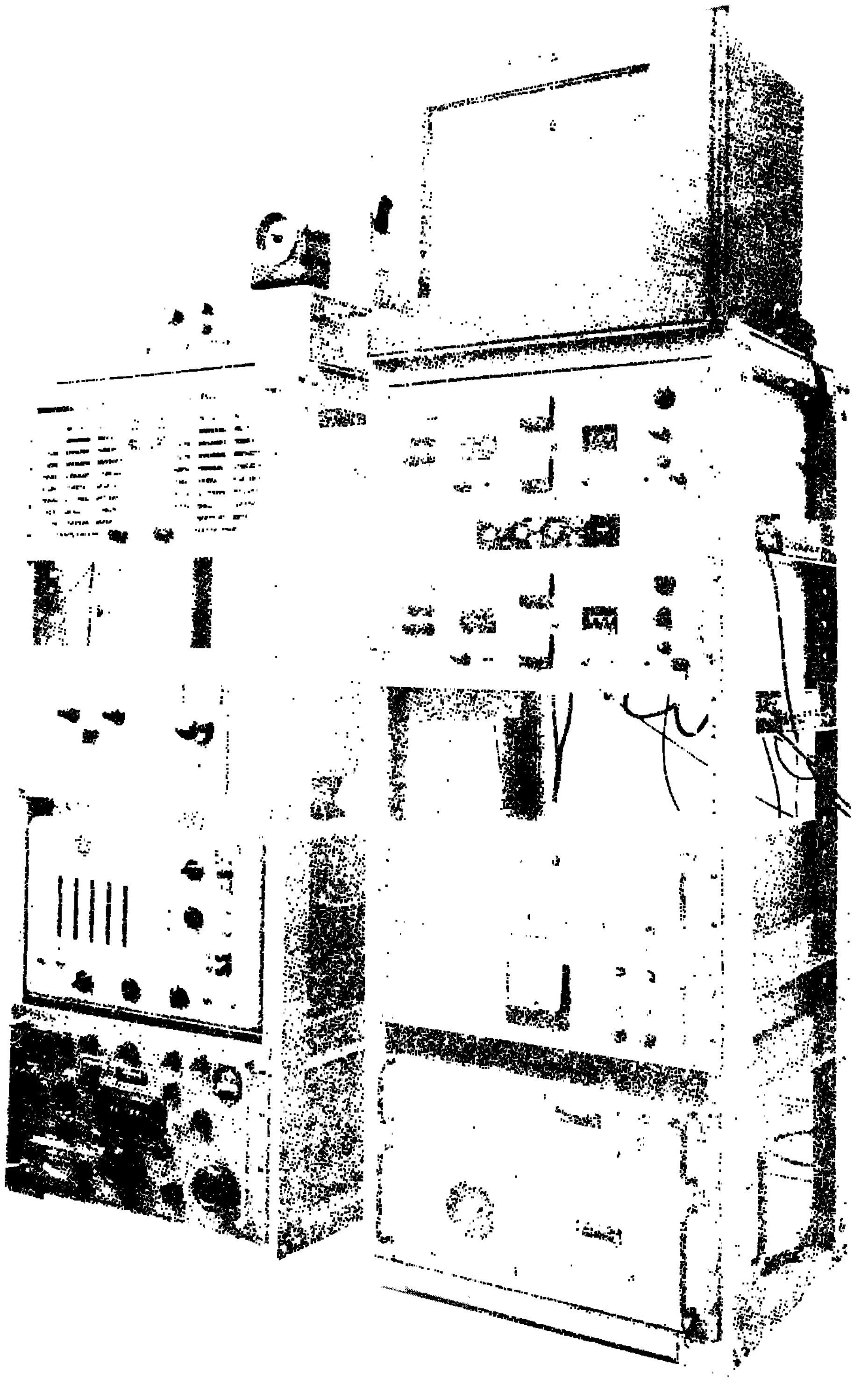

Figure 1. TYPICAL VLF RECEIVER SETUP

One of the most frequent failure sources in a receiver with a modular construction are the plugs between modules and chassis. Therefore, when the receiver fails, the first thing to do is to pull out one by one all the modules and push them right back. In about 80 percent of the cases, this may correct the problem.

The recorder shown in Figure 1 has excellent reliability and precision, but its 10-millivolt full-scale-sensitivity requires great care to avoid ground loops. It is our experience that such ground loops are particularly difficult to avoid if the receivers are connected to standby battery supplies (which is a must to avoid phase jumps during power failures). One indication of such a problem is nonlinearity of the recorder scale. Another indication is that the scale does not go to zero because of the presence of a stray voltage. To avoid this trouble, it is advisable to fasten all equipment needed for the recording tightly into one metal rack. Sometimes it helps to connect appropriate ground terminals of the DC supplies, receivers and the frequency standard by a reasonably heavy copper braid (but too many ground connections may be self-defeating).

A last remark on reception equipment: always use an RF filter in the front-end of the receiver, because the signal you tracketh may not be what thou thinketh. (Can be mirror signal of something else.)

4.0 TRANSMITTER PROBLEMS

Figure 2 shows an example of transmitter phase jumps which we have had in the past (NAA, NPG, NPM and GBR trackings). The distinct jumps occurred when the transmitters switched between FSK and CW, because one mode of operation required an extra filter. The example marked NPM-Fairbanks is taken from a 1964 recording of NPM at Fairbanks. We were, at first, extremely happy because it happened to be that the period of this oscillation was about four minutes, and this period was thought to be a typical period for electron precipitation. Fortunately, we took a look at records of NPM

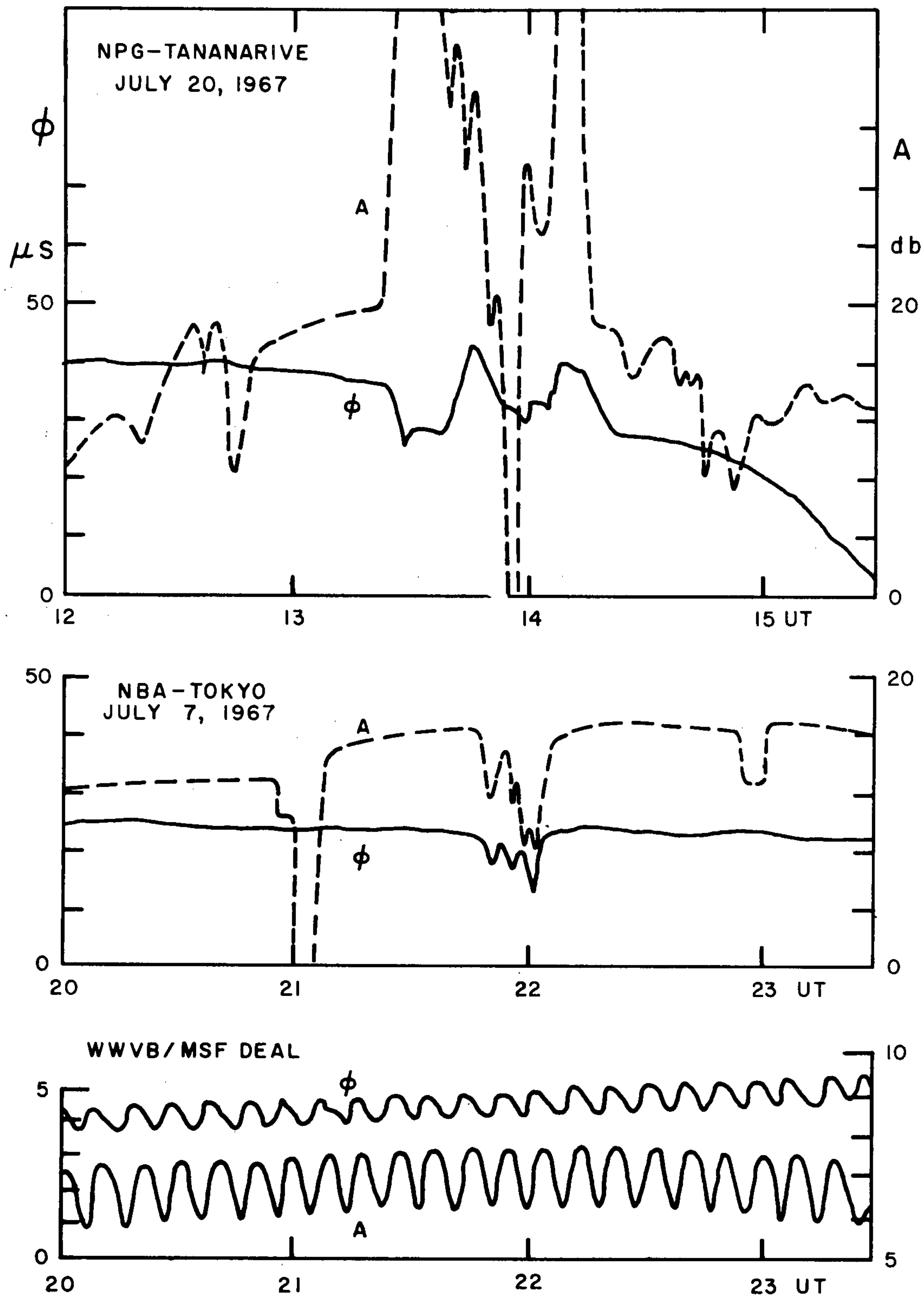

Figure 3. EXAMPLES OF VLF SIGNAL INTERFERENCE

Figure 4 illustrates some typical diurnal phase patterns. More or less sharply defined phase changes occur during sunset and sunrise at the path terminals. The dashed curves pertain to the standard deviations with respect to 14-day averages. The plot, NPM to Deal (summer) shows during the morning hours (0800-1600) mode interference effects typical for VLF frequencies above 18-20 kilohertz. The second-order mode which is excited near the transmitter gets converted at the solar terminator into a first-order mode which interferes with the first-order mode passing through the terminator. As the terminator moves, the two first-order mode phasors observed at the receiver site rotate with respect to each other, causing a series of amplitude minima and phase steps.[7]

In order to understand these diurnal phase patterns, it helps very much to have available sunlight-twilight-night charts[8,9] plotted for two week

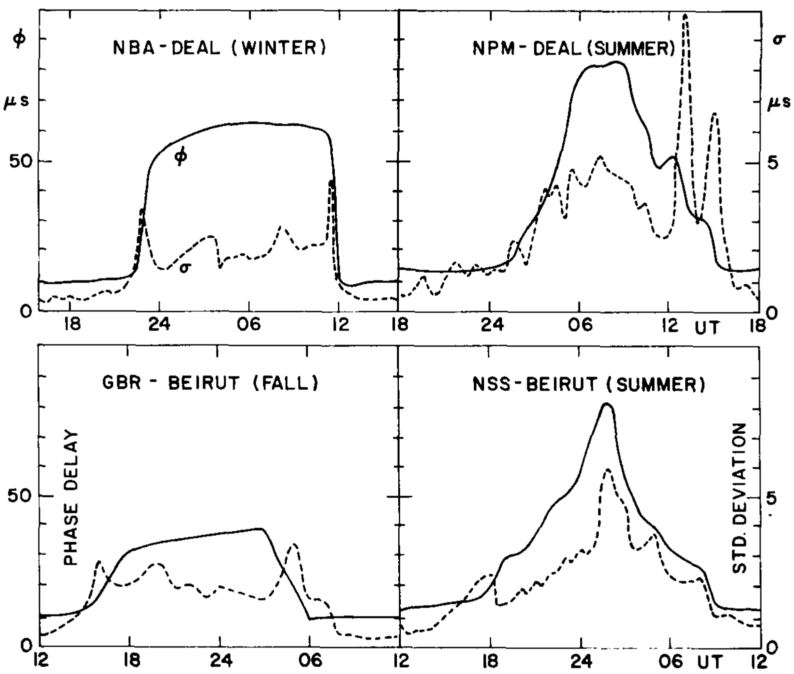

Figure 4. SOME TYPICAL DIURNAL PHASE PATTERNS AND STANDARD DEVIATIONS

intervals with a map overlay (Figure 5). To find out at what times the sun will rise on a particular path, one plots the path on the map overlay -- for intance, NPM to Sao Paulo -- picks the terminator chart for the right date, lays the map over the chart and turns it until one of the path terminals passes through the terminator. Then the time the sun will rise or set will be indicated by the angular position of the map overlay with respect to the terminator chart (time scale along circumference of chart is not shown in Figure 5).

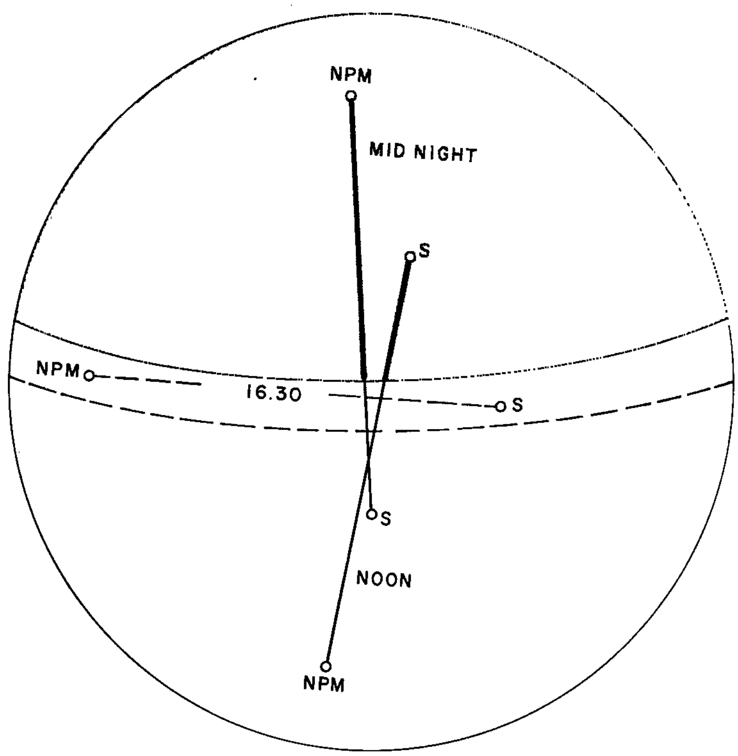

Figure 5. EXAMPLE OF A VLF PATH LOCATION WITH RESPECT TO SOLAR TERMINATOR (S Stands for Stockholm)

Figure 6 proves that these mode interference effects can also be present in the evening.

A very undesirable consequence of mode interference is shown in the lower part of Figure 7. In the evening the pattern develops apparently in a normal way (indicating a phase delay). At nighttime the phase becomes usually a little more disturbed. Then in the morning, instead of returning

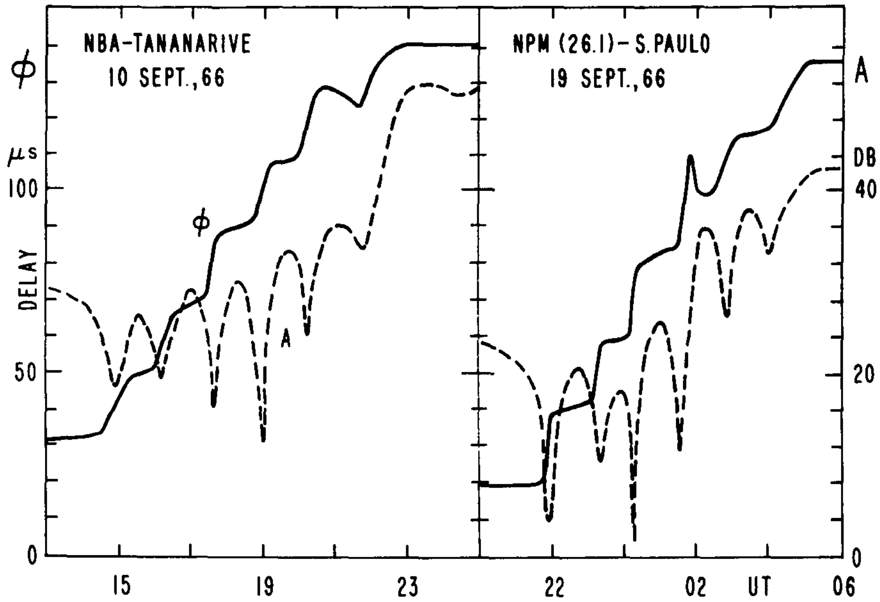

Figure 6. MODE INTERFERENCE DURING EVENING SHIFT

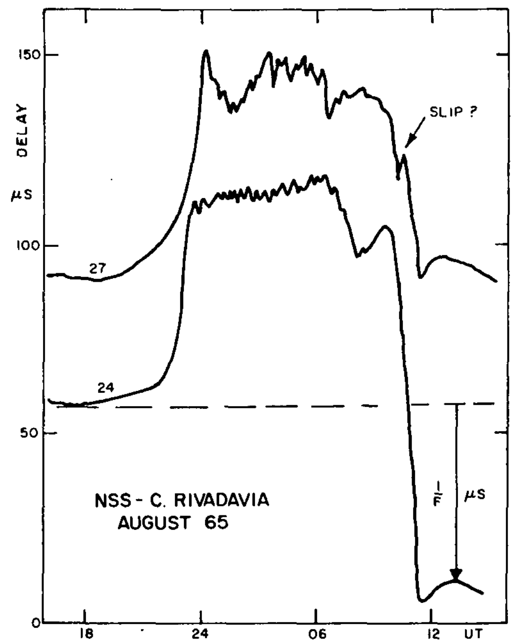

Figure 7. EXAMPLE FOR PARTICULAR MODE INTERFERENCE OBSERVED ON NSS-C (Rivadavia)

to the level of the previous day as one would expect, the phase undergoes an additional cycle advance before settling down for the daytime. Such a cycle advance due to mode interference is not much of a problem if one has a good reference standard, but otherwise it can be a lot of trouble. The only consolation is that it is known that the correction has to be exactly one cycle.[5]

Figure 8 depicts a case of mode interference observed on NAA-Deal (Fort Monmouth), a path of medium length (1,000 kilometers). Depending on the ionospheric activity and depending on the season, almost any pattern can be observed: phase advance in morning and delay in evening (#4, normal), advance in morning and evening (#13), delay in morning and evening (#5), and delay in morning, advance in evening (#10, reversed pattern).

Another undesirable feature occurs on some transmissions crossing the magnetic equator. For instance, Figure 9 shows the diurnal phase pattern of Haiku (12.2 kilohertz) to Brisbane, Australia in comparison with the normal diurnal patterns observed at Tokyo and Deal.[5] The diurnal shift observed at Brisbane is much smaller than expected. Of course, one thinks immediately cycle slips occurred at about 0700 and 1800 and ought to be corrected . But if one corrects the night portion by 1 cycle the diurnal pattern will be too high. So one has a choice of whether one wants the pattern to be too low or too high.

Figure 10 gives an example of a path which is just so long that the first-order and the second-order modes are almost equal in amplitude and nearly out of phase with each other during the night. One observes then two phasors at the receiver site which almost cancel each other. Then the slightest ionospheric disturbance can cause relatively big phase changes. As a result, nighttime phase may either show a "cave-in" or a "blow-out" (not shown in figure), with the phase difference being again exactly 1 cycle.

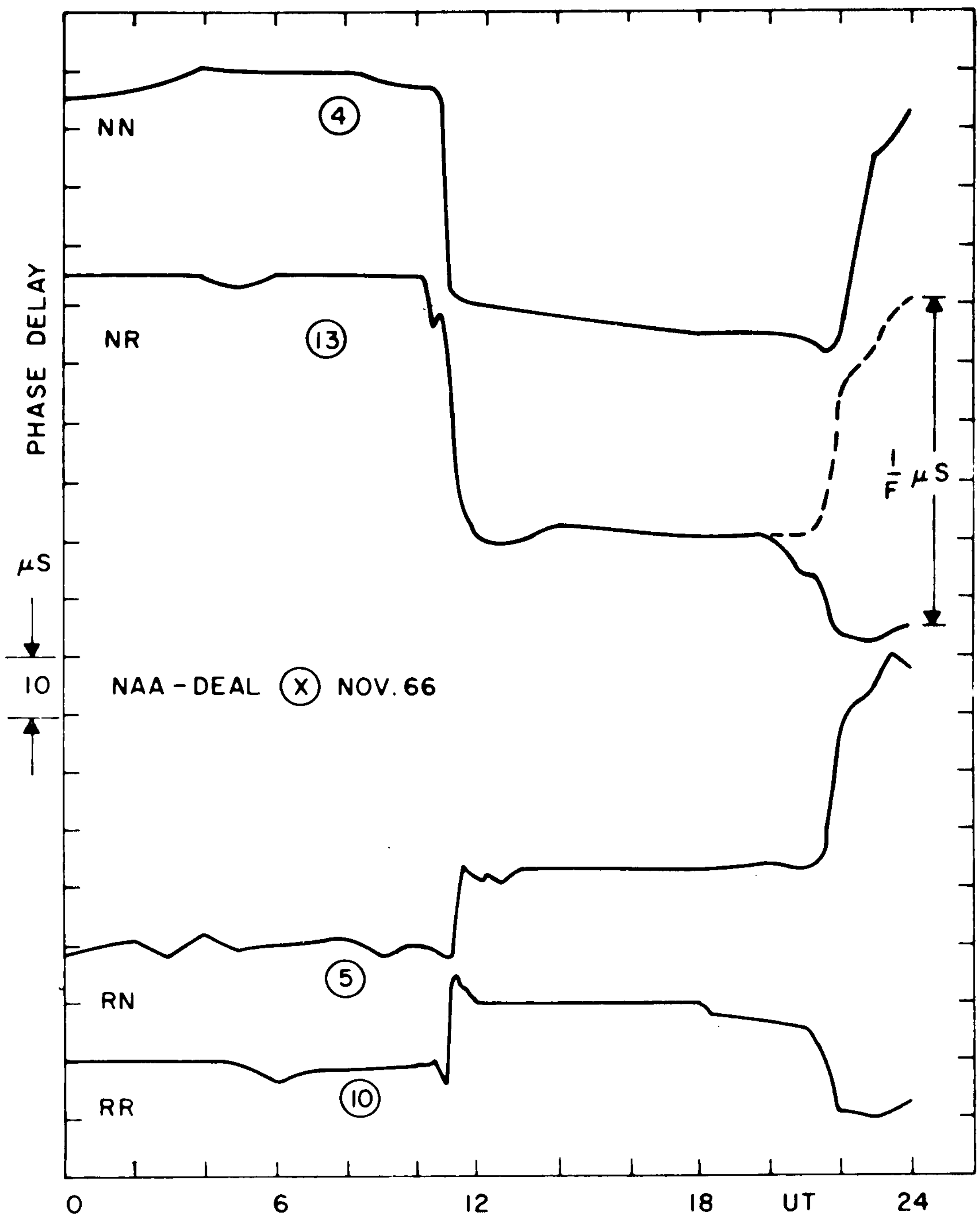

Figure 8. VARIETY OF DIURNAL PHASE PATTERNS ON NAA-DEAL

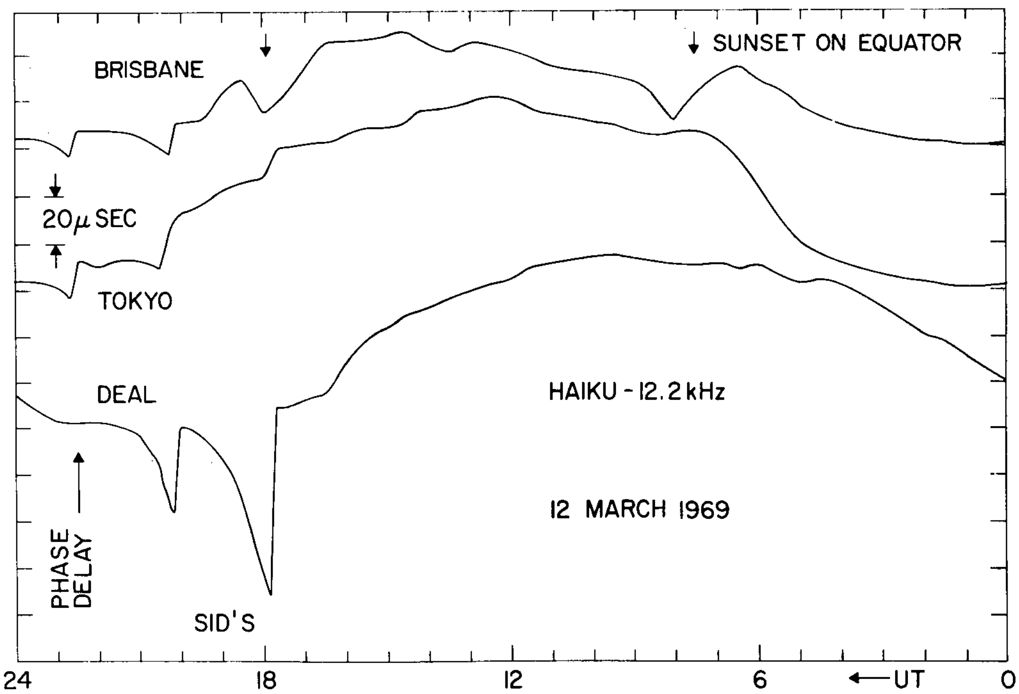

Figure 9. PECULIAR DIURNAL PHASE PATTERN OF NPM-BRISBANE AS COMPARED WITH THOSE OF NPM-TOKYO AND NPM-DEAL

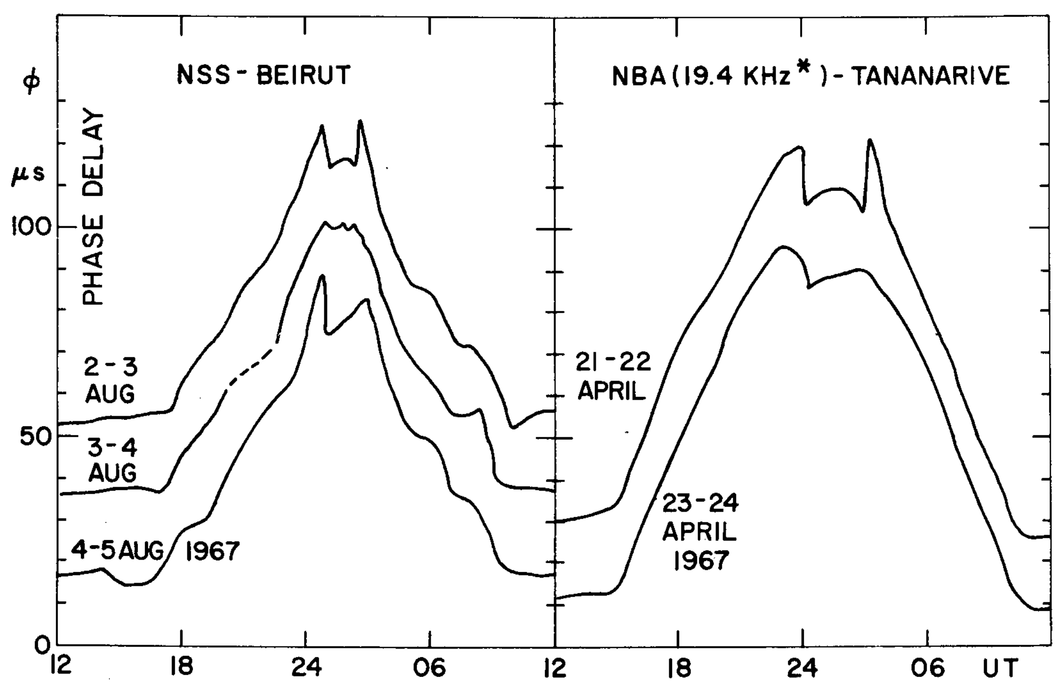

Figure 10. EXAMPLES FOR MODE INTERFERENCE DURING NIGHTTIME ON PATHS FOR WHICH FIRST- AND SECOND-ORDER MODES ARE ALMOST EQUAL IN STRENGTH AND OUT OF PHASE WITH EACH OTHER

An example of the so-called "morning layer"[10] is shown in Figure 11. If one has a signal path which passes through the morning terminator almost simultaneously along its entire length, one observes a temporary additional phase advance which will typically last for about 90 minutes, before the phase will reach its regular daylight value. The advance, for instance, of GBR to Cordoba, Argentina, is of the order of 10 microseconds. On the path from NBA to Fort Monmouth, it is of the order of a maximum of 5 microseconds. The anomaly is caused by a temporary excess of electrons in the lower ionosphere and will be the larger the longer the path is and the faster the entire path crosses the terminator.

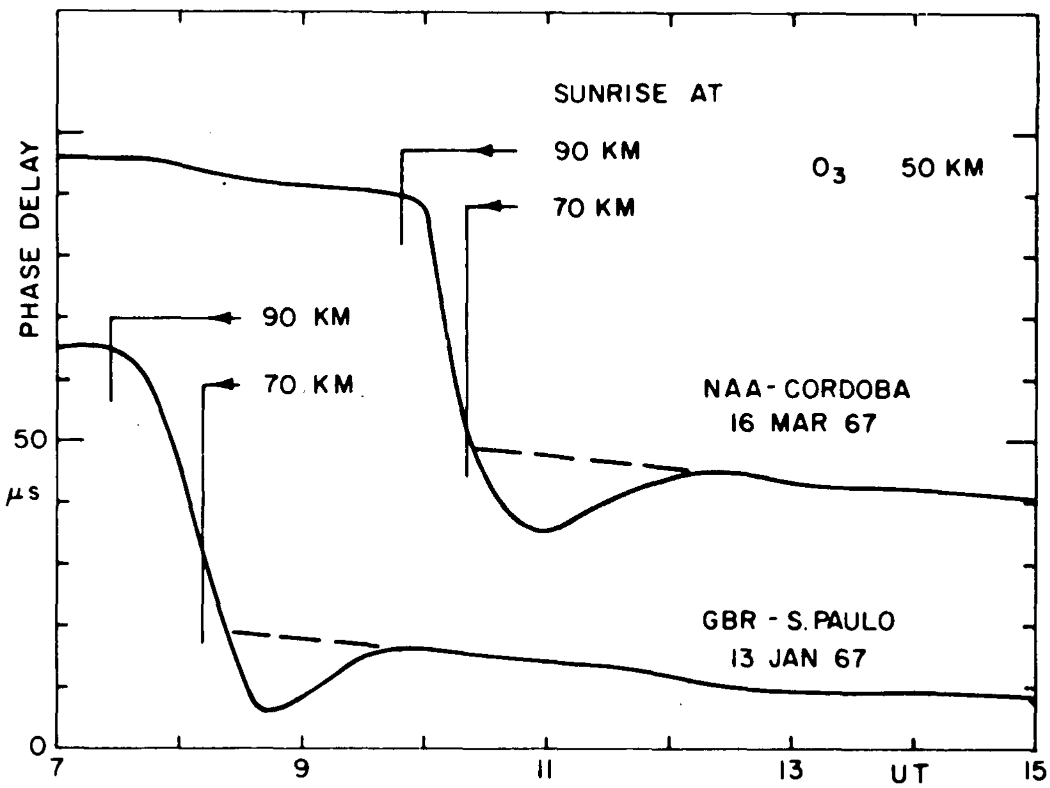

Figure 11. EFFECT OF SUNRISE LAYER ON VLF PHASE

Figure 12 gives an example of antipodal interference. The short path runs across Greenland; the long path runs across the Antarctic ice cap. In

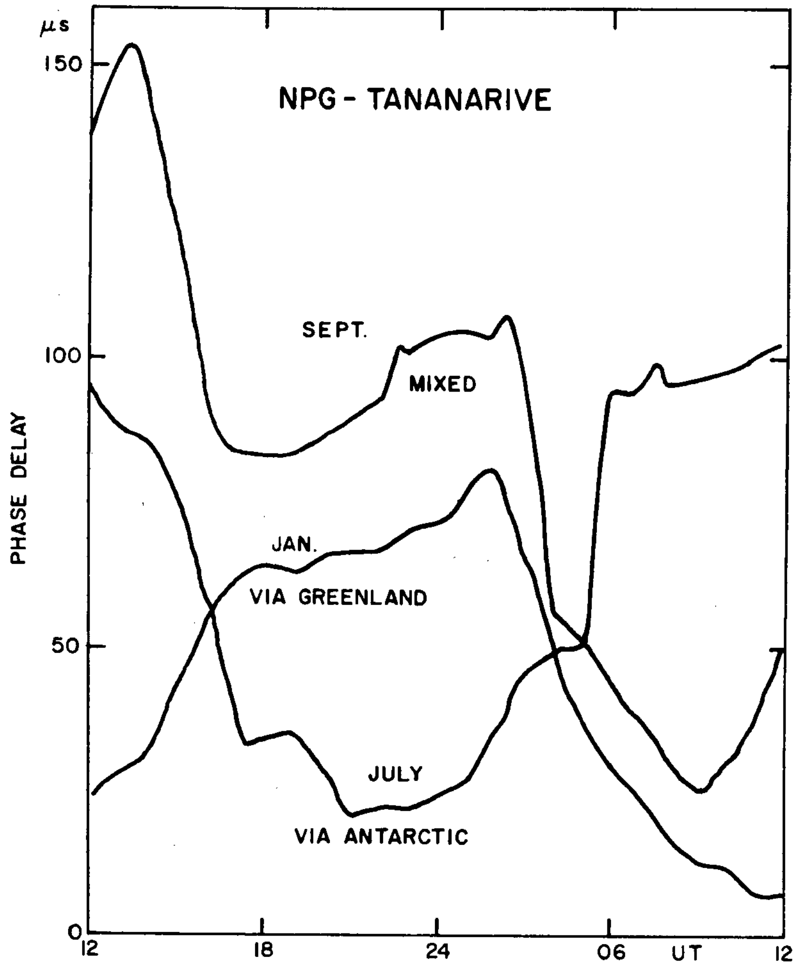

Figure 12. ANTIPODAL INTERFERENCE ON NPG-TANANARIVE

summer when Greenland is in sunlight, the attenuation over Greenland is extremely strong -- approximately 20 to 30 db. This signal is then cut off and the signal to Madagascar comes from NLK via the Antarctic which is in night, and therefore, the losses are not so high. In winter it is just the other way around: Greenland is in night and so it affects the signal only slightly, while the Antarctic is in daylight and cuts off the long-path signal. During spring and fall both signals are present at Tananarive. Reading from the top of Figure 12 down, the first curve pertains to September (mixed); the second curve to January (signal from Greenland only); and the third curve to July when the signal comes only via the Antarctic. Consequently, the January and July patterns are out of phase with each other. We see that the huge ice masses act as season-triggered filters.

7.0 DISTURBANCES

The upper left part of Figure 13 depicts some typical phase and amplitude anomalies caused by sudden ionospheric disturbances (SID's) due to solar X-ray flares.[11] As expected for single-mode signals which are free of antipodal interference, the phase always advances. In this example, the amplitudes increased. However, as mentioned before, amplitude will definitely be enhanced only at frequencies above 18-20 kilohertz. E.g., the signal GBR-Tananarive usually (but not always) indicates an amplitude decrease during an SID.

The upper right-hand part of Figure 13 demonstrates frequency dependence of VLF phase anomalies due to SID's: the lower the frequency, the larger the anomaly. For instance, on 29 December 1968, Haiku 10.2 to Deal deviated by almost 80 microseconds, Haiku 13.6 to Deal by about 50 microseconds, whereas the NPM 23.4 kilohertz to Deal anomaly was only 20 microseconds. All three paths are of equal lengths. The NLK 18.6 kilohertz-Deal anomaly was smaller again because this path is considerably shorter.

The lower part of Figure 13 illustrates what can happen to long-path signals on a day of very high solar activity. SID's followed one another all day long and the phase of Aldra 12.3 kilohertz -- Tananarive was advanced by an average of 20 microseconds during the time 0500Z to 1200Z.

If at all possible, one should never record phase alone, but always phase and amplitude. How advisable this is for proper interpretation of VLF phase anomalies is illustrated by Figure 14. On 2 September 1967, the SID at about 2040Z is clearly indicated by a phase advance and amplitude increase with distinct peaks and typical recovery. The phase advance commencing shortly after 2200 hints at another SID but the lack of any amplitude

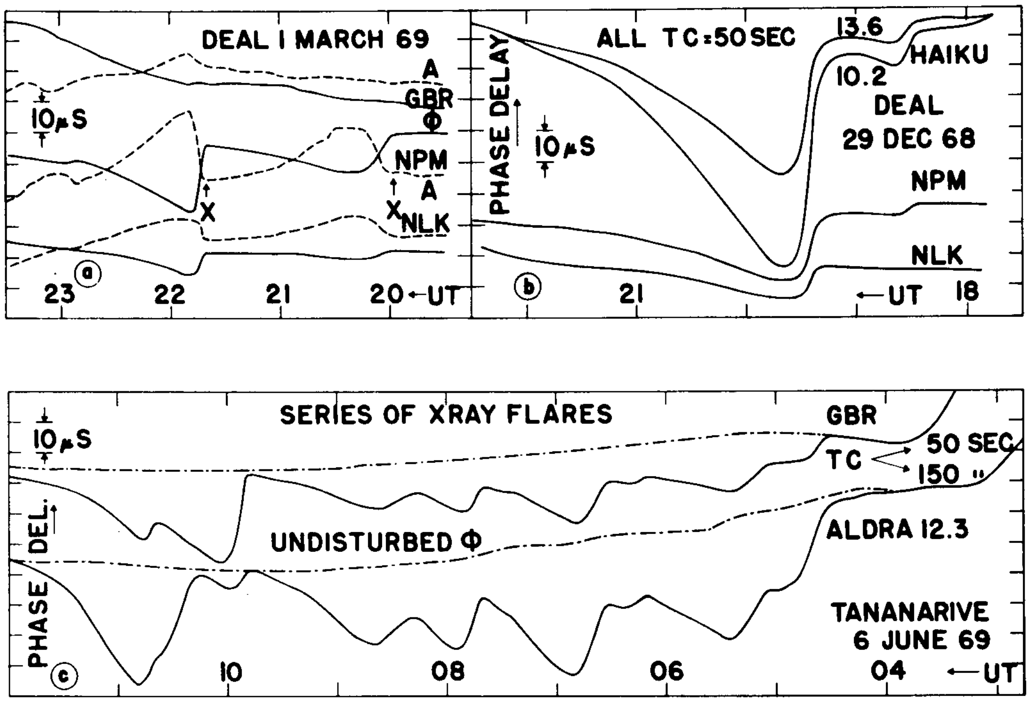

Figure 13. SOLAR X-RAY EFFECTS ON VLF SIGNALS

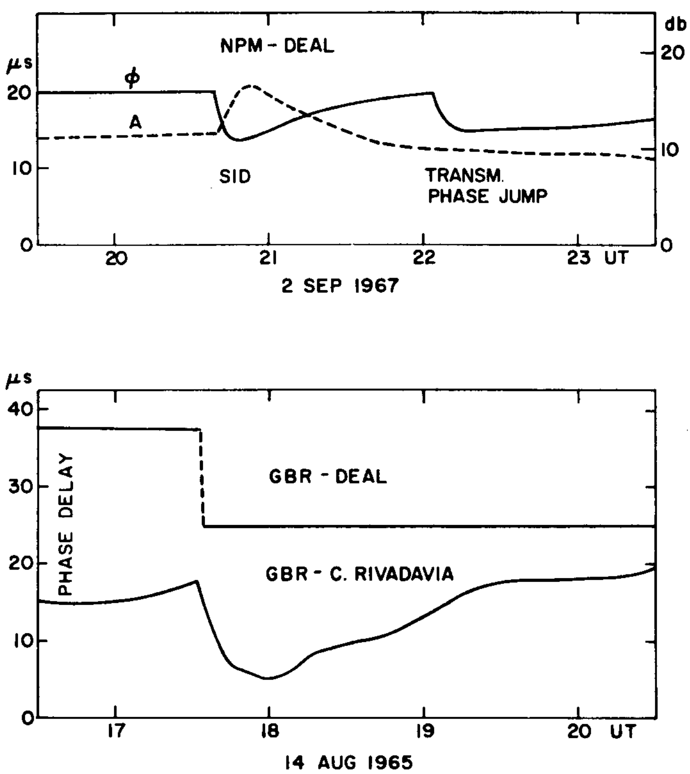

Figure 14. EXAMPLES FOR PHASE JUMPS CAUSED BY EQUIPMENT FAILURES BUT LOOKING LIKE SID'S

anomaly points to a transmitter phase jump. The GBR-C. Rivadavia (Argentina) phase anomaly on 14 August also has all the appearance of an SID, but the GBR-Deal recording clearly indicates a GBR phase jump. The onset is too sudden for an SID, there is no phase recovery and the amplitude shows no enhancement (typical for that path). Why does the GBR-C. Rivadavia anomaly look like an SID? Poor signal-to-noise ratio on this long path required use of an extra-long time-constant (150 sec), which rounded off the lower portion of the phase recording and the diurnal evening shift commencing slowly at 1700 and accelerating around 1800 provided a decieving simulation of the recovery of an SID. Had a reliable amplitude recording been taken at C. Rivadavia, it would have been obvious immediately that no SID occurred between 1700 and 1800 on 14 August 1965.

A short path, like Forestport 13.6 kilohertz-Deal (350 kilometers) can result in reversed SID's. Figure 15 is an example: GBR to Sao Paulo and Trinidad to Deal are paths longer than 3,000 Km and their SID's are normal (phase advance), while the SID's observed on Forestport-13.6 kilohertz-Deal are reversed (phase delay). This behavior can be explained by a phasor model using two modes as discussed before.

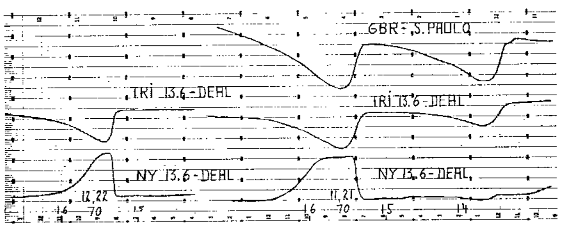

Figure 15. REVERSED SID PHASE ANOMALY ON FORESTPORT 13.6 KILOHERTZ-DEAL

Figure 16 shows some examples of electron precipitation effects. The electrons come directly from the sun or from the radiation belts and have been detected both at high and middle-latitudes. What is typical about them? Let us first take the path from NBA to Deal on 28/29 March 1966. At about 1908Z an SID occurred and it recovered within about 2.5 hours without discernible after effects. On the other hand, on GBZ and NPG to Deal we see the X-ray SID effects followed by new anomalies lasting to beyond 0300 on 29 March. Typically, electron effects last for several hours (two to eight and more). Another example for electrons is shown for 26/27 December 1966.

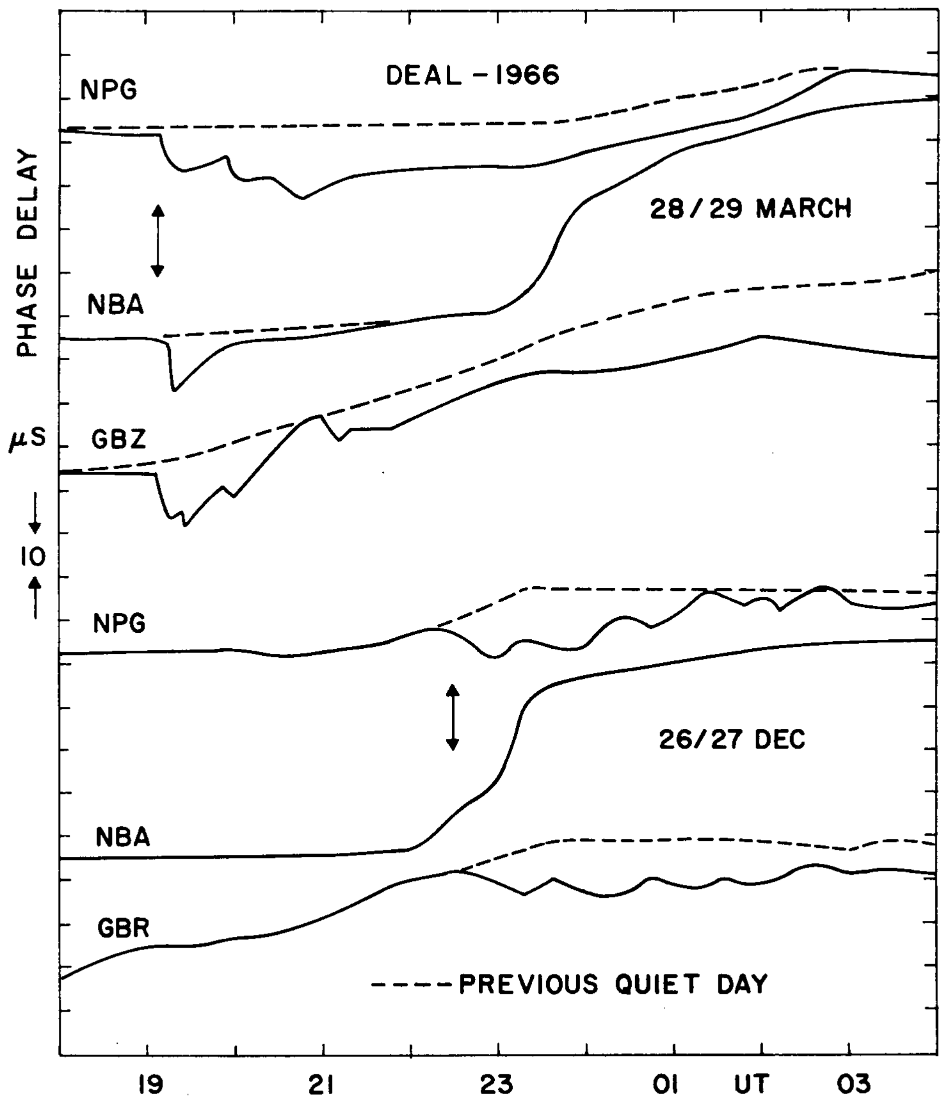

Figure 16. EXAMPLES OF ELECTRON PRECIPITATION EFFECTS

For PTTI purposes, one should avoid a polar path, because polar paths may be affected strongly by protons from the sun and these effects may last up to 10 days. Events of proton precipitation often lead to blackout of HF communication through the polar cap. Therefore, a proton precipitation event is called Polar Cap Absorption (PCA). Figure 17 shows some paths which are susceptible to protons. The ellipse represents approximately 62° geomagnetic latitude. Inside this so-called polar cap a VLF path will be disturbed by protons. If proton precipitation is accompanied by a magnetic storm, the ionospheric disturbances may spill over to lower latitudes and become noticeable on such paths as GBR-Deal, NSS-Beirut, etc.[6]

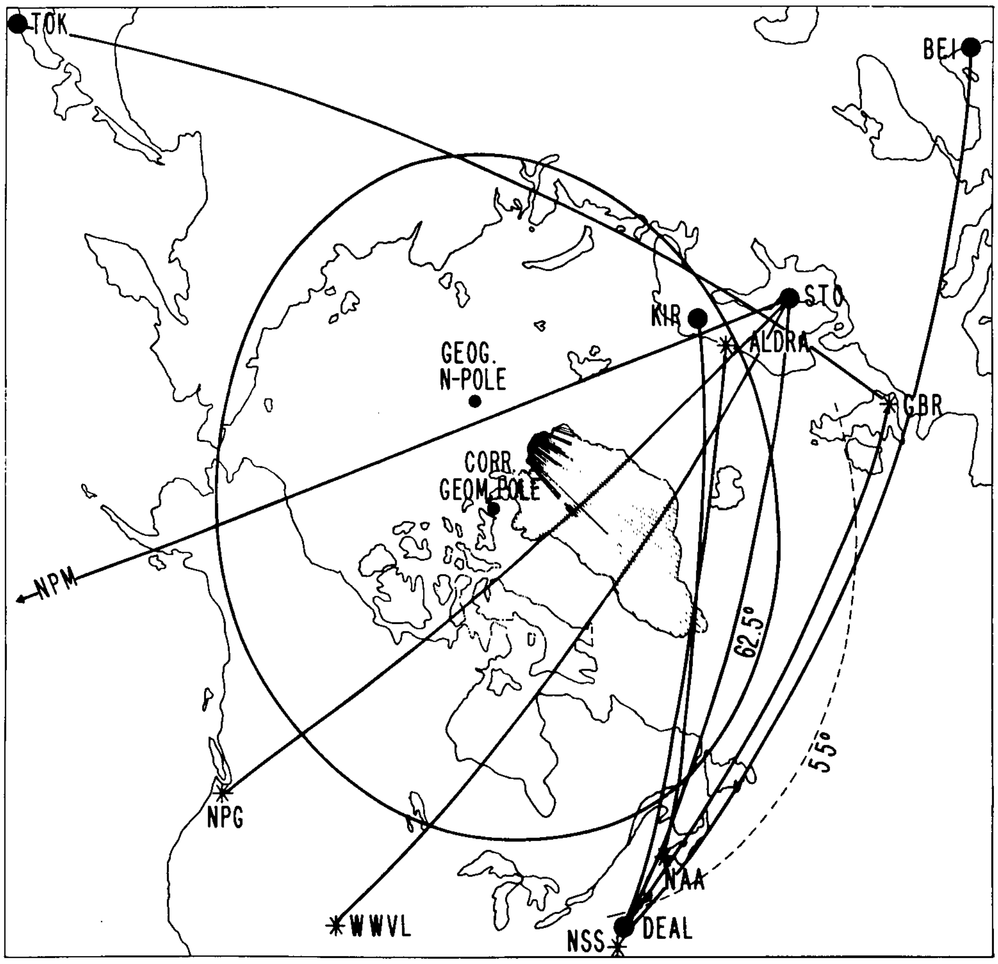

Figure 17. VLF PATHS THROUGH THE NORTHERN POLAR CAP

Figure 18 illustrates the dependence of PCA effects on path distance from the geomagnetic pole (center of polar cap). NSS to Stockholm has a large distance and one sees only a relatively small effect. NPM to Kiruna lies closer to the center of the polar cap and a more pronounced effect is evident. The WWVL to Stockholm path, shows a strong effect and NPG to Stockholm is the most disturbed. First of all, NPG-Stockholm passes close to the geomagnetic pole, and secondly, it runs across Greenland. Any ground with low electric conductivity will increase this type of anomaly. Figure 19 depicts the PCA effect of 18 November 1968 on the Omega signal Aldra 13.6 kilohertz to Deal. The onset was unusually abrupt -- peak phase deviation of 70 microseconds (100 microseconds on 10.2 kilohertz) was reached within 45 minutes -- and recovery took about six days.

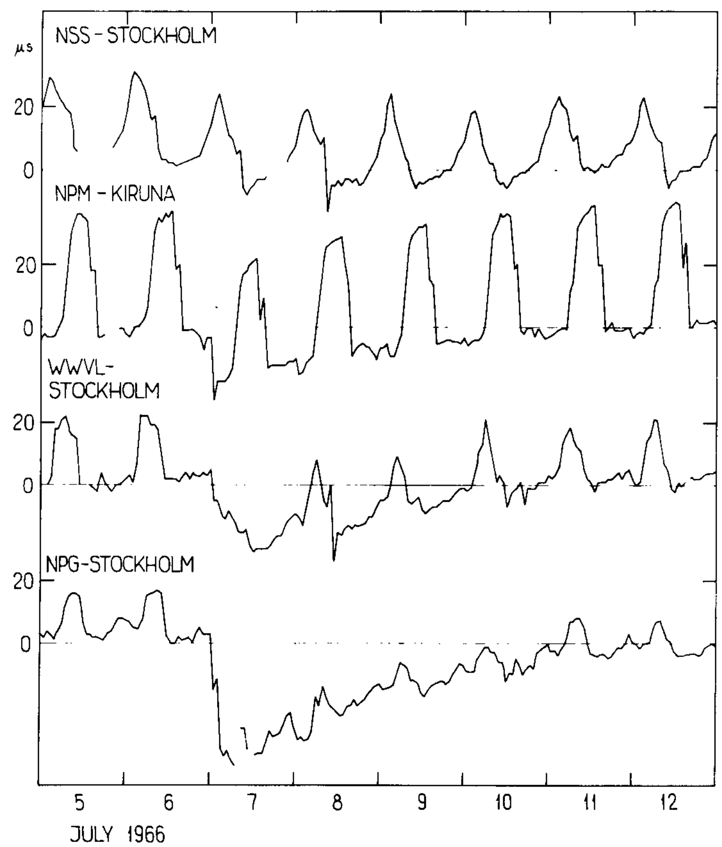

Figure 18. DEPENDENCE OF PCA EFFECTS ON PATH DISTANCE FROM GEOMAGNETIC POLE

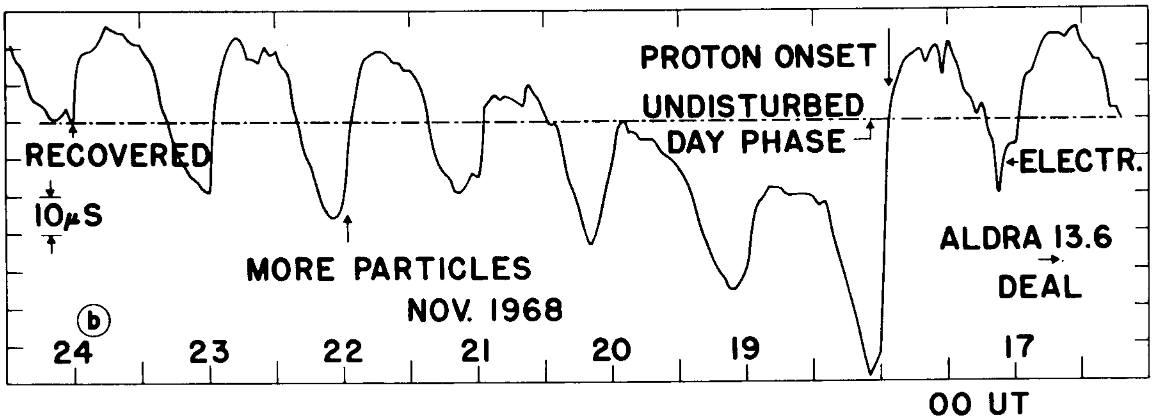

Figure 19. PCA OF 18 NOVEMBER 1968 AS OBSERVED ON ALDRA 13.6 KILOHERTZ-DEAL

8.0 LONG-TERM (SEASONAL) PHASE VARIATIONS

The excellent accuracy of Cs standards controlling VLF transmitters and receivers and the long-term behavior of the lower ionosphere are illustrated by the plots of Figures 20 through 23 which reproduce daily VLF phase values read at the moments of noon at the path centers. The plots are marked; e.g., by Deal-NLK instead of the more customary NLK-Deal in order to avoid errors in data interpretation. Deal-NLK means that the plot will have a positive slope if the frequency of the local standard controlling the receiver is higher than the frequency of the standard controlling the transmitter.

All plots reflect the strong ionospheric disturbances caused by the PCA's of 1968 (marked by arrows along the abscissas).

The Washington-NLK/NPG curves of Figure 20 point to an apparent seasonal lowering of the daytime VLF reference height during the period August-October. The total phase accumulation between the Cs standards controlling the Washington (US Nav Obs) and Deal receivers was only about 35 microseconds between 1 June 1967 and 31 January 1969, which is equivalent to an average frequency offset of the Deal standard of only -7×10^{-13}. (Note that our Cs beam standard was originally set up and adjusted as prescribed by the manual in spring 1967. No controls were touched since,

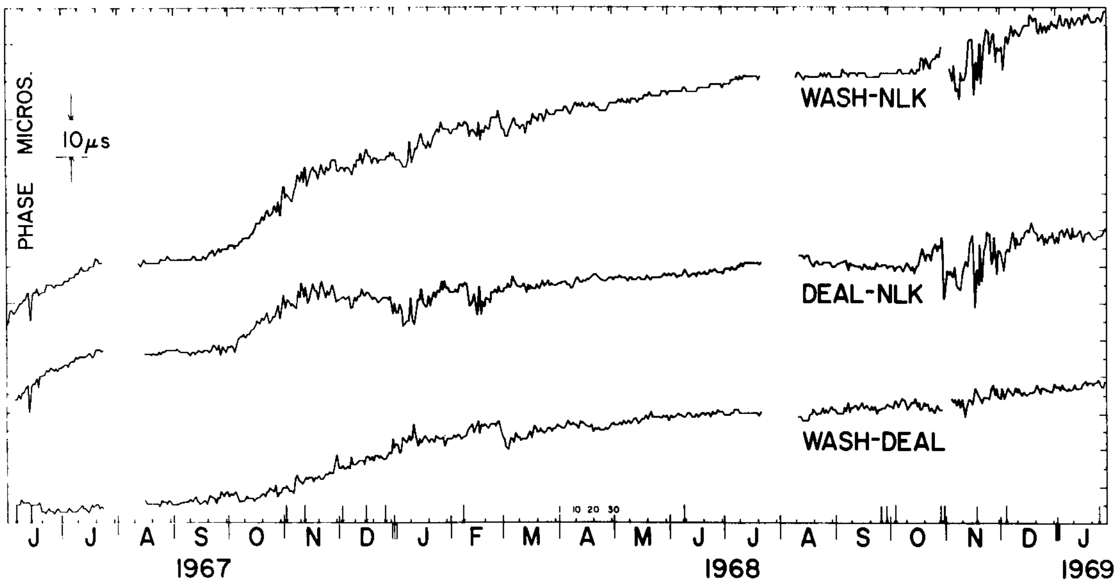

Figure 20. SEASONAL PHASE VARIATIONS OF NLK AT DEAL AND WASHINGTON

except that the driving Xtal oscillator was retuned about every 3 months without opening the servo loop).

Figure 21 shows NPM before and after cesium control was introduced. To the left of the line over 9 April 1968 the vertical scale is 20 microseconds, to the right it is 10 microseconds per major division. The improvement after the change-over to Cs control is obvious. As expected, the PCA effects on the polar signal STO-NPM are much larger than those on the mid-latitude signals Deal-NPM and Wash-NPM. Also, the seasonal variation of the STO-NPM signal phase is very pronounced because the polar region changes from continuous daylight in summer to continuous night in winter.

The seasonal plots of GBR (Figure 22) are included here to give an example for the case of an exceptionally strong PCA effect (40 microseconds) on the non-polar path GBR to Deal on 31 October 1968 (no reading of GBR was taken in Washington). The reason was the coincidence of the PCA with a strong magnetic disturbance which pushed the northern cutoff latitude of the protons far to the south.

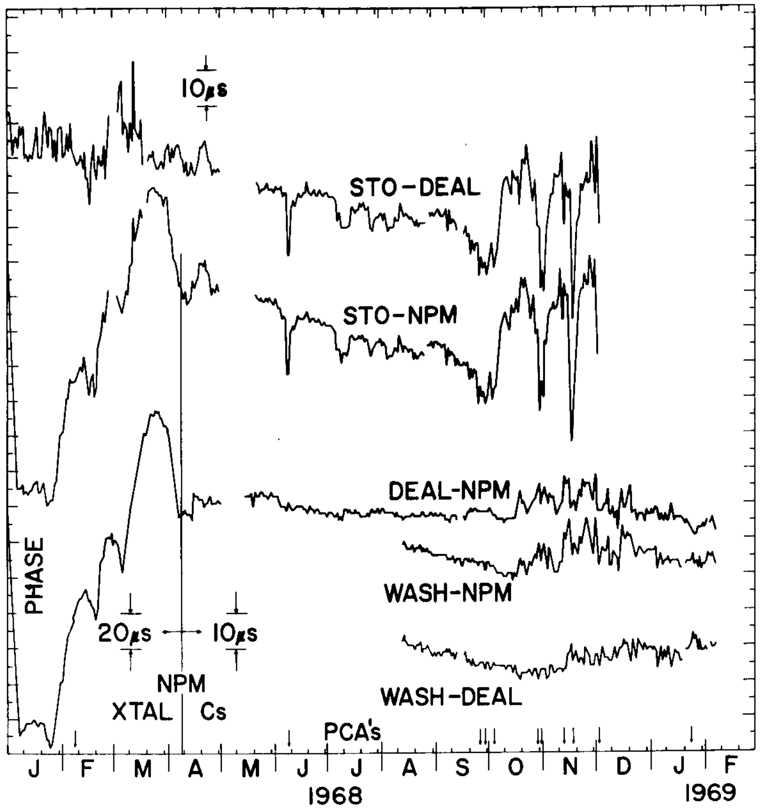

Figure 21. SEASONAL PHASE VARIATIONS OF NPM AT STOCKHOLM, DEAL, AND WASHINGTON

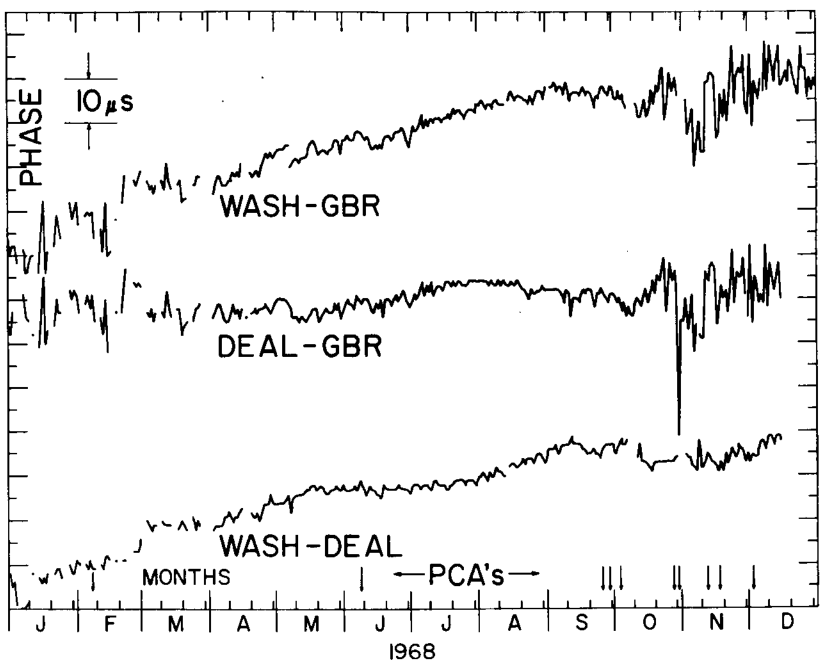

Figure 22. SEASONAL PHASE VARIATIONS OF GBR AT DEAL AND WASHINGTON

Figure 23 depicts midday phase values of Aldra 10.2 and 13.6 kilohertz as measured at Deal during 1967 and 1968. The signals at Deal were quite weak, but the seasonal variation caused mainly by the Arctic summer and winter in the transmitter area, and the strong PCA and electron effects are clearly detectable. The plot marked 3.4 (= 13.6-10.2) gives just the difference between the 13.6 and 10.2 phase readings. The plot marked "COMPOS" gives the phase of Pierce's composite wave[12] computed for his frequency parameter m = 2.25 from the 13.6 and 10.2 kilohertz phase readings. A comparison of the 2 lower plots indicates that this composite wave based on a very simple flat-earth model gives hardly an improvement over the difference (3.4) signal. However, it is expected that a more sophisticated[13] composite wave based on propagation data by Wait and Spies[4] will give considerable improvement in phase stability during ionospheric disturbances.

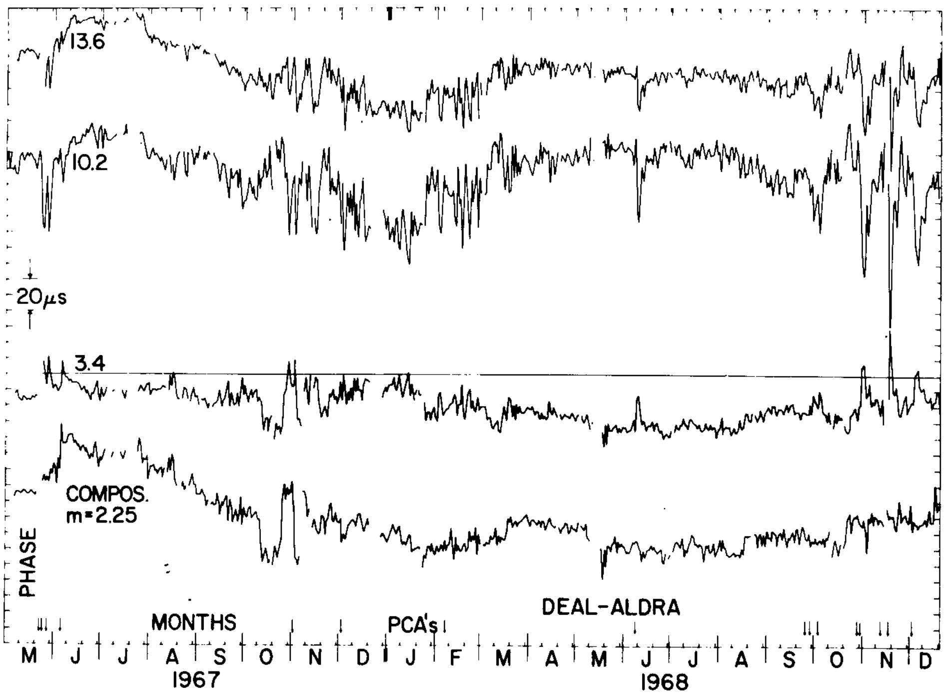

Figure 23. SEASONAL PHASE VARIATIONS OF ALDRA AT DEAL (10.2, 13.6, 3.4 Kilohertz and Composite Signal)

9.0 SUMMARY

What does one have to consider for the selection of the most suitable VLF signal for PTTI applications?

(1) Signal frequency: If one chooses a low VLF frequency (below 18 kilohertz), solar flare effects will be large, but one will in general not be plagued by cycle slips during morning and/or evening hours. If one chooses a high VLF frequency (above 18-20 kilohertz), solar flare anomalies will reduce in size but cycle slips become a real problem. So GBR-16.0, NAA-17.8, and NPG-18.6 kilohertz (> 1000 km) are good choices.

(2) Path length: Short paths have in general almost no or only small and abnormally-shaped diurnal effects, but phase stability is often inferior and anomalies may be more difficult to interpret because of ray or mode interference. On the other hand, very long paths ($> 10{,}000$ km) are associated with long periods of diurnal phase shift. Therefore, a path length between 3,000 and 8,000 km is desirable.

(3) Path orientation: N→S paths give shorter periods of diurnal shift than E→W paths, so the former ones are preferable. The possibility does exist of cycle jumps during those periods in a year when a N→S path passes through the terminator (morning or evening) simultaneously along its entire length (reason: diurnal shift occurs so rapidly that receiver cannot follow), but the critical periods last only a few days. If no N→S paths are available preference should be given to W→E paths since E→W paths give higher propagation losses due to the effect of the earth magnetic field on the ionosphere.

(4) Path location: The auroral zones and the polar caps, as well as areas covered by huge masses of ice or subject to permafrost conditions should be avoided.

As far as equipment is concerned, I would prefer:

(1) selection of equipment predominantly from the point of proven reliability;

(2) location of equipment in an unfrequented room (beware of knob twisters) which is temperature controlled to between 60°-75°F;

(3) heavy emphasis on reliability of electric power (standby batteries, connected to all elements controlling signal phase is a must);

(4) multi-channel recorders with a paper width of more than 6 inches and recording of phase and amplitude on same paper;

(5) tuned loop antennas, properly protected from rain, snow, and ice;

(6) use of a separate loop for each receiver (there are exceptions);

(7) not to use preamplifiers (if I can avoid it) because they add complexity and may cause oscillations in antenna input circuit; and

(8) Cs standards over Rb standards and those over Xtal standards (who would not?). However, for those who cannot afford an atomic standard there is a consolation. If one's main concern is to retain an already synchronized (by portable clock, satellite, etc.) clock to within 50 microseconds throughout day and night or to within 10 microseconds during daytimes, one can drive the receiver with a moderately-priced Xtal standard and use the coherent (with VLF signal) 100 kilohertz output to drive the clock. The Xtal standard has then only to be near the transmitter frequency within the specified receiver tracking bandwidth. Offsets of 10^{-8} can easily be accommodated.

In conclusion I would like to say that during quiet ionospheric conditions the precision of long-distance standard-frequency transfer by means of VLF phase tracking is presently still limited by the precision of our equipment (including transmitter circuits) and not by the ionosphere. At least for daytime and the oblique incidence pertaining to long-distance VLF propagation, one can truly say that the quiet lower ionosphere is of an incredible stability from one day to the next.

10.0 REFERENCES

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11.0 ACKNOWLEDGMENT

Figures 2, 3, 4, 6, 7, 8, 10, 11, 12, 14, and 16 are from Reference (5); Figures 9, 13, 19, 20, 21, 22, and 23 are from Reference (11).

Figures 17 and 18 are from Reference (6); Figure 5 is from Reference (9).

DISCUSSION

DR. WINKLER: I would like to make one more comment or, actually, put up a question, to see corroboration for some of the recommendations which have been made many times before. In spite of the apparent complication of tracking VLF for the purpose of maintaining time lock or frequency lock, it is still a very useful system and relatively inexpensive. But it appears to me that there are only two solutions. One is to have operators available at the station who know what they are doing and who must have a minimum amount of training, or to go to an entirely automatic system, as envisioned in the Omega Timing Procedures indicated this morning by Mr. Chi. I do not see how one can utilize VLF phase-tracking without either one of these, without trained operators -- well-trained operators, consciencious operators -- or fully automated equipment.

DR. REDER: Yes, I agree with that. There is one hope, however, and that is the possibility of reducing these anomalies and the diurnal shift by an improved Composite Wave Technique. The composite wave was originally introduced by Prof. J.A. Pierce of Harvard University. It consists of synthesizing the phase of a new signal (composite wave) from the measured phase values of two signals of different frequencies (e.g., 10.2 and 13.6 kilohertz) emitted by one transmitter in a time-sharing fashion. The synthesis is carried out in such a way that anomalies due to ionospheric changes are minimized. Pierce's original model used plane-wave propagation within a plane earth-ionosphere waveguide with infinitely conducting walls. This model was too simple to accommodate in a satisfactory manner both diurnal shifts and solar flare anomalies with one parameter setting. However, Dr. W. Papousek from the Institute of Technology, Graz, Austria (on invitational travel orders to our laboratory) recently showed that -- at least on paper -- the composite wave technique can be much improved by using the more realistic propagation data of Wait and Spies (exponential ionosphere).

DR. WINKLER: Could an improvement of the composite wave technique be accomplished by using three frequencies?

DR. REDER: Dr. Papousek has found that the realizeable phase measurement precision at least for the relatively low-power Omega signals makes the usefulness of adding a third frequency very questionable. The key to the method is dispersion. That is to say, the known change of phase velocity with frequency is utilized to compensate the anomaly observed at one frequency by the appropriately adjusted anomaly measured along the same path at another frequency. Since dispersion is not very large, the second frequency cannot be too close to the first else measurement errors will degrade too much the precision of the phase differences which are needed for computing composite-wave phase. If the frequencies differ too much, single-mode propagation cannot be maintained. Therefore, adding a third frequency makes either the frequency spacing too small and measurement precision too critical; or it requires consideration of propagation in at least two modes which introduces the need of taking mode amplitudes into account and that clearly becomes impractical.