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ACCOUNTING FOR IONOSPHERIC VARIABILITY AND IRREGULARITY IN HIGH FREQUENCY DIRECTION FINDING

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JUNO 2 1982

I. INTRODUCTION

High frequency (HF) radio wave propagation has long been the backbone of many short and long range communication networks. The reasons are straightforward: the technology is well established, the systems are relatively inexpensive and easily fieldable, and the reliability (while not perfect) is high enough to meet a large body of communication needs. In a similar vein, the interception of HF communications is one means of gaining additional intelligence in a military engagement. Taken an additional step, the interception of HF communications can also be used to locate the position of the transmitter, which knowledge may be of strategic or tactical value. HF radio waves propagate in two modes: the ground wave, which can be detected out to distances on the order of 50 km, and the direct wave, which when reflected from the ionosphere, is known as the skywave and can be detected out to very long distances. The radio source location technique for a single station receiver consists of measuring the angle of arrival of the signal of interest in three dimensions. The problem then consists of tracing the signal's path back through the ionosphere to the source, the successful solution of which depends on a knowledge of the state of the ionosphere.

Currently attainable accuracies in HF position location using a single station locator still carry inherent errors of tens of kilometers or worse. These errors arise from three main areas: ionospheric variability and irregularity, locator system size limitations, and problems with data acquisition, processing and interpretation. Of these areas the ionosphere is the single largest source of error and is the principle concern of this paper.

It is now generally agreed that real time information on the state of the ionosphere is required for optimum performance of a single station locator. Most often this is accomplished via a vertical ionospheric sounding made at that station. It then becomes important to quantify the spatial and temporal irregularities of the ionosphere and estimate the spatial and temporal ranges within which ionospheric sounding information gathered at one point can be extrapolated to another point with minimal loss of position location accuracy.

The next section will then outline the general properties of ionospheric irregularities and the order of magnitude of the errors which are introduced into position location accuracies. The spatial and temporal coherence of the ionospheric irregularities will then be estimated. The final section will address the usefulness of a single ionospheric sounding as opposed to multiple and spatially separated soundings.

II. IONOSPHERIC IRREGULARITIES MOST IMPORTANT FOR RADIO SOURCE LOCATION

In principle the location of an HF transmitter can be found by simply measuring the azimuthal and elevation angles of the incoming signal and determining the height of the ionospheric reflecting layer. In practice there are several types of ionospheric irregularities which distort the otherwise straight forward picture of a uniform, concentric, smoothly reflecting ionosphere.

Irregularities can arise from a multitude of causes ranging from plasma instabilities and non-uniform ionization sources, through atmospheric winds and traveling waves, to mass motions of the atmosphere due to tidal and heating effects (see, for example, Kent, 1970; Yeh and Liu, 1974; Fejer and Kelley, 1980; and the references therein). Three phenomena shall be singled out because of their effects on radio source location: sporadic E, ionospheric tilts, and traveling ionospheric disturbances (TID's). Of the above, TID's are the more important.

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Sporadic E is a thin layer of enhanced ionization confined to the E region (principally 100-110 km) and is felt to be a result of an enhanced concentration of ions (principally metallic ions) caused by wind shears in that region. These wind shears may in turn be a result of the propagation of acoustic-gravity waves through the E region, and thus sporadic E may be an E region manifestation of one type of traveling waves which also produce F region irregularities in the form of one class of TID's. The properties of sporadic E are summarized in Table I for the midlatitudes (after Smith, 1957; Peterson, 1980). Sporadic E-like occurrences are also found at low and high latitudes and are associated with the equatorial and polar electrojets; these are not considered further here.

The patchiness of sporadic E is somewhat a function of the radio frequency employed. Higher density patches of a few hundred kilometers extent or less, as discerned by radio frequencies above 7 MHz, may be found embedded in larger, lower density patches as defined by radio frequencies below 3 MHz (Peterson, 1980). Both scales of patches apparently move with similar velocities which suggest similar originating mechanisms.

Sporadic E, because of the thinness of the layers and the sharpness of the vertical gradients, is often an aid in communications and often provides a better reflecting surface than the F region. The principal deleterious effect of sporadic E for radio source location is the creation of multi-mode interference. Signals from the source may suffer reflections from both E and F layers, thus causing additional problems with resolution of modes.

Ionospheric tilts refer to generally large scale horizontal gradients in the electron density, such that contours of constant electron density are no longer parallel to the earth's surface. The effects are to cause an error in estimating the angle of arrival, principally the elevation angle, and to misjudge the virtual height of the reflection point. The most regular and predictable ionospheric tilt is that caused by the diurnally varying solar ionization rate in the F region. The effect is most noticeable at sunrise and sunset, and can thus be anticipated and accounted for. In a generic sense, ionospheric tilts can refer to any deviation from the horizontal plane of the contours of constant electron density, whether caused by large-scale phenomena such as solar ionization mentioned above, or due to more transient, localized disturbances discussed next.

Traveling ionospheric disturbances have been noticed since the earliest days of radio wave propagation and were first studied extensively by Munro (1950, 1958). TID's are essentially an ionospheric manifestation of an entire spectrum (not necessarily continuous) of waves propagating through the atmosphere. The spectrum of TID's can be placed in at least two distinct categories: large-scale and medium-scale. According to acoustic-gravity wave theory, large-scale TID's are associated with a discrete spectrum of guided waves whose modes are excited only by upper atmospheric sources and whose horizontal speeds are substantially greater than the (lower atmospheric) speed of sound. Medium-scale TID's are associated with a spectrum of freely propagating internal waves which can be excited by sources at any altitude and whose horizontal speeds are less than the speed of sound. As one might suspect, medium-scale TID's are much more common. (For more information on waves in the atmosphere see Georges, 1967; Yeh and Liu, 1974; Hines, et. al., 1974; and the references therein.) A third category of small-scale TID's exists which is most likely the extension to higher frequencies and smaller size of the medium-scale TID's is generally below the Fresnel-zone size of ionospheric sounders and thus has not been as well documented. Table II summarizes the properties of these different categories (after Georges, 1967; Rao, 1981).

Again the main effects of TID's are to cause errors in the angle of arrival, measured as the azimuthal and elevation angles, and the virtual height of reflection. Table III gives the magnitude of the errors in position location which the ionosphere can cause for selected ranges. A quick "rule of thumb" seems to be 10 km or 10% of range, whichever is worse.

III. SPATIAL AND TEMPORAL COHERENCE OF IONOSPHERIC IRREGULARITIES

The basic question which needs to be answered can be stated as follows, "If the state of the ionosphere can be determined at one point, over what spatial ranges can that information be transferred, and for what time period is it valid?" For the simple case of a single vertically incident ionosonde, the pertinent information would be the height of the reflecting layer and the tilt of the ionosphere. The problems encountered are shown in Figures 1 and 2.

Figure 1 is a plot of the incident angle (plotted as radial distance from the origin) versus the azimuthal angle of arrival (plotted as polar angle) for the return signal of a vertically incident ionosonde. The numbers represent one sounding each minute from 11:49 to 12:39 local standard time (Ernst, et. al., 1974; Rao, 1981). The general pattern of a NW-SE propagation wave is apparent, but so are the patterns of other smaller and differently oriented waves. This is often typical for medium-scale TID's, which are superpositions of several frequency components. Figure 2 shows the constant plasma frequency contours (i.e., variation of reflection heights) as a function of time



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TABLE I
IONOSPHERIC IRREGULARITIES

TYPE OF IRREGULARITY	SPORADIC E	IONOSPHERIC TILT
Structure	Patches of enhanced electron and ion density often hundreds of kilometers in horizontal extent. Vertical thickness generally 1-2 km at an altitude of 100-110 km. Patches of higher density often embedded in larger, lower density patches.	Horizontal gradient in electron density over distances on the order of 1000 km. Found at F region altitudes (>140 km).
Origin	Wind shears, probably from propagating acoustic-gravity waves.	Daily variation of solar ionizing radiation.
Motion	Patches (not plasma) generally move 50-100 m/s, no preferred direction.	Pattern shifts with sun's diurnal motion.
Duration	Several minutes to several hours.	Over the order of 1-2 hours.
Occurrence	More frequent during day, with peak occurrence before noon, and in some locations a secondary peak near sunset likely in summer. More frequent off the east coast of Asia and Indonesia. Frequency of occurrence (i.e., detection) more likely for lower radio frequencies.	Daily near sunrise and sunset.

for the passage of a large-scale TID. This large-scale wave can cause ionospheric tilts of up to 3° - 4° for short periods of time, with tilts on the order of 1° being common for an hour or more (after Rao, 1975).

The relevance of ionospheric data taken at one point when extrapolated out to successively larger distances may be estimated from the following example. The positions of known transmitters are estimated from received signals, and the fixing errors between calculated and known ranges are determined. This is done two ways: first, by assuming the ionosphere is uniformly flat, and second by assuming the ionosphere is tilted, based on the ionosonde data at the receiver. The scatter plots of the fixing errors are shown in Figure 3 for three transmitters at successively greater distances (Rao, 1981). The 45° line in each plot corresponds to the condition of equal errors from the two models. Thus, points above the line correspond to smaller "tilted ionosphere" fixing errors, while points below the 45° line correspond to smaller "untilted" fixing errors. For the case where the actual range is 30 km, using the tilted ionosphere model (i.e., "extrapolating" the ionosonde data out to a point 15 km away) produces noticeably smaller fixing errors. The same is true when the range is extended to 70 km (i.e., ionosonde data are extrapolated to a point 35 km

TABLE II
TRAVELING IONOSPHERIC DISTURBANCES

TYPE OF DISTURBANCE	WAVELENGTH AND STRUCTURE	MOTION	PERIOD	FREQUENCY OF OCCURRENCE	SOURCE
Large-scale	>1000 km horizontal wavelength.	>300 m/s north to south.	30 min - 3 hr usually 1-3 cycles.	Infrequent, less than daily.	Events in the auroral zone.
	Wave front width on order of 1000 km.				Strong correlation with magnetic activity.
	Phase fronts tilted nearly horizontal.				
	Retains shapes over thousands of kilometers.				
Medium-scale	10's-100's km horizontal wavelength.	100-250 m/s variable directions, with seasonal trends.	10-100 min several cycles to trains.	Daily, more common in daytime.	Tropospheric phenomena.
	Wavefront width 100's to over 1000 km.				Upper atmospheric and polar winter sources.
	Phase fronts tilted 30° - 60° from vertical.				
	Do not retain shapes well over distances >100 km; energy does propagate globally.				
Small-scale	<10 km horizontal wavelength. Structure not well resolved.	100-250 m/s (est) variable directions.	<10 min long trains to families as wavelength decreases.	Daily	Probably tropospheric; not well established.

TABLE III

MAGNITUDE OF ERRORS IN POSITION LOCATION
ACCURACY DUE TO ERRORS IN ANGLE OF ARRIVAL
FOR E AND F REGION LAYERS

RANGE (ACTUAL) HEIGHT OF REFLECTING LAYER	200 km		300 km	
	105 km	250 km	105 km	250 km
Range Error (km) for:				
1° elevation angle uncertainty	6.9	9.8	10.9	11.5
3° elevation angle uncertainty	20.6	29.3	32.7	34.4
Cross-Range Error (km) for:				
1° azimuthal angle uncertainty	3.5	3.5	5.2	5.2
3° azimuthal angle uncertainty	10.5	10.5	15.6	15.6
Range Error (km) for:				
10 km height uncertainty	19.4	7.7	27.6	11.5

away), although to a somewhat lesser extent. However, when the range is extended to 170 km (ionosonde data must be extrapolated 85 km), there is no advantage to using the tilted ionosphere model over the untilted one. Thus, in this example, extending ionospheric data from one point to another for distances of more than 50-100 km does not seem to be of any advantage.

Similar conclusions have been reached by measuring the angles of arrival of HF signals from a series of geographically spaced transmitters. Assuming a one-hop propagation path some useful results were obtained by cross-correlating the angle of arrival deviations of the signals from pairs of transmitters (Ernst, et. al., 1975; Hoover, 1976; Rao, 1981). A maximum in the cross-correlation function means that the variations in the angle of arrival at one location are reproduced at the second location some time T later. The results indicate significant decorrelation of a persistent ionospheric pattern over distances of 50 to 100 km. This does not mean that a single frequency component of the composite disturbance necessarily decorrelates over distance on the order of 100 km, but rather that interference between waves from different sources, or from the same source traveling different paths, can result in the observed decorrelation.

The approximate ranges of the quasi-periodic variations of several ionospheric irregularities have been listed in Table II. While there have been numerous studies pertaining to the statistics of occurrence of characteristic periods or frequencies, the subject of temporal coherence seems to have received less attention. The temporal coherence of the ionospheric waves (particularly the medium-scale TID's) observed at a given location depends on the sources of the waves and the sources' duration. In practice, many waves due to several sources or multi-path propagation from a single source are probably present at any given instant of time. One can assign a decorrelation time to a group of waves which would essentially represent the time it takes the group to change form due to interference of the several components. This approach was taken by Walton (1971) who found a predominant decorrelation time of approximately 5 minutes. The approximate range in speeds for medium-scale TID's is 100-250 m/s. Using the decorrelation time of 5 minutes, this would yield a "decorrelation distance" in the range of 30-75 km, in good agreement with the previous estimates of spatial coherence.

Therefore, the spatial and temporal coherences of ionospheric sounding information appear to be on the order of 50-100 km and 5 minutes, unless sophisticated techniques of spectral analysis are employed to extract individual waves which remain coherent over much longer distances and time periods.

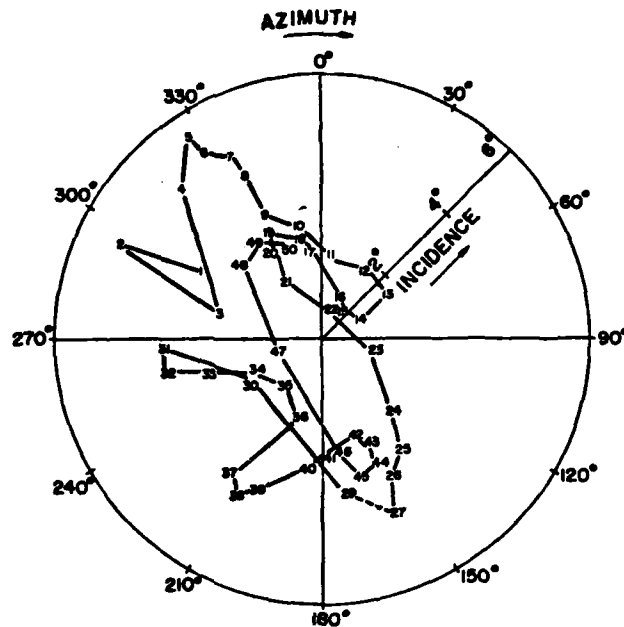


Figure 1: Incident angle, plotted as radial distance from the origin, versus azimuthal angle, plotted as the polar angle, for the return signal of a vertically incident ionosonde over a 50 minute interval.

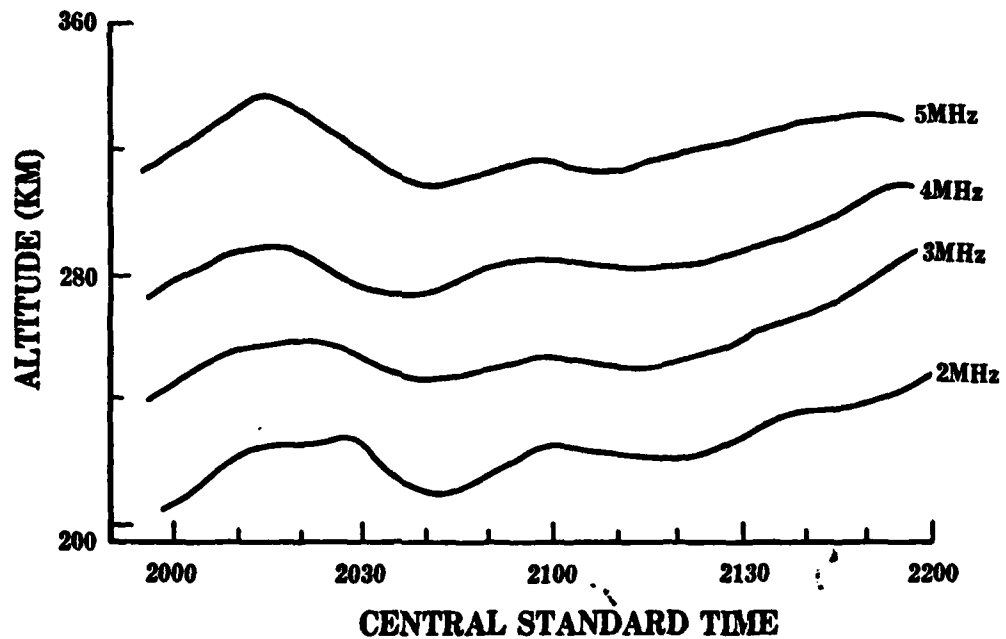


Figure 2: The altitude of the constant plasma frequency contour (i.e., signal reflection heights) versus time for a large-scale TID.

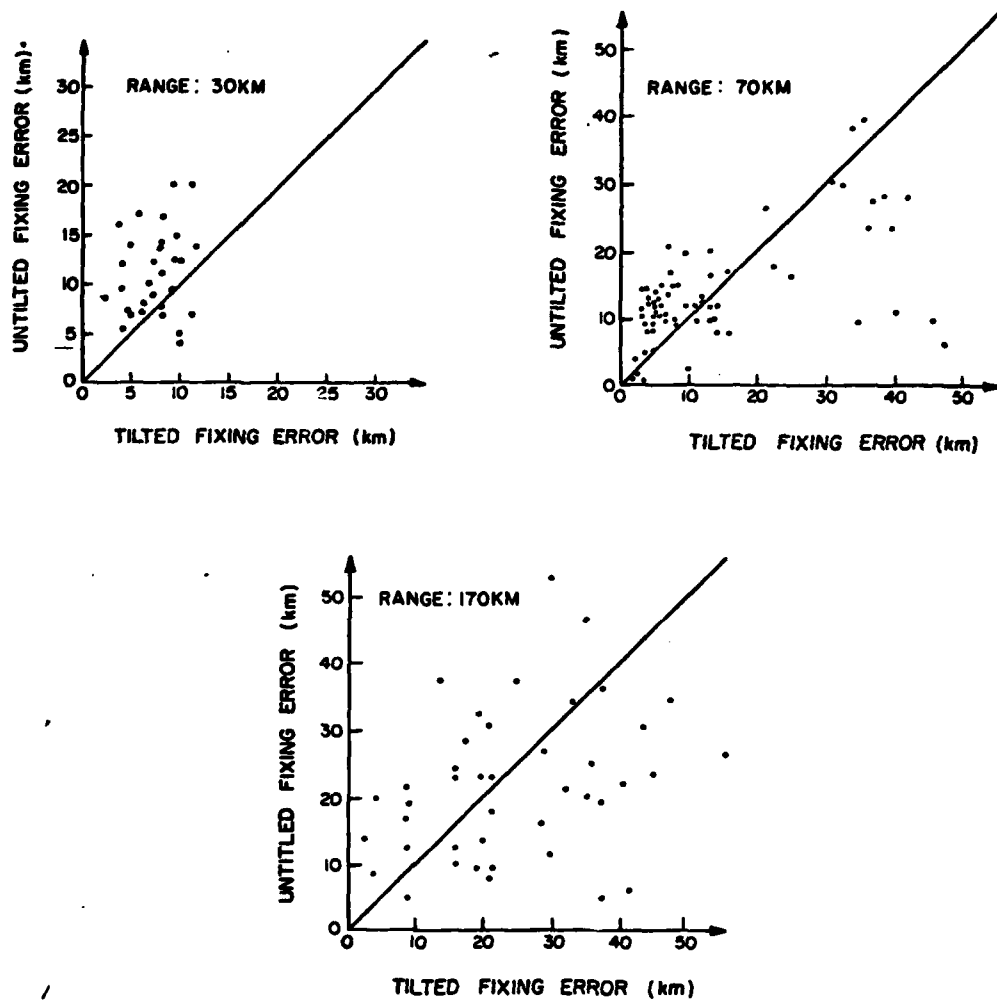


Figure 3: The scatter plots of the radio source location errors using two ionospheric models for three transmitters at successively greater distances.

IV. DISCUSSION AND CONCLUSION

The previous sections have outlined the types of ionospheric phenomena which are most likely to affect radio source location. Estimates of the magnitude of some of the induced errors in position location accuracies have been given, and estimates of the spatial and temporal coherence of medium-scale TID's have been made.

Most of the ionospheric irregularities considered here can be thought of as wave-like phenomena which propagate through the neutral atmosphere, with corresponding effects on the ionized component of the atmosphere. The possible exception, at least in behavior, is sporadic E, although the wind shears thought to be responsible for sporadic E may be due to gravity waves. The main effect of sporadic E is to introduce uncertainty as to which ionospheric layer, E region or F region, the signal is returning from and to provide additional opportunities for multimode reflection of signals. The concepts of spatial and temporal coherence, or decorrelation, are applicable to sporadic E only in the sense that the physical size of the patch and its motion will give some estimate of how long the phenomenon is expected to persist at any one given point.

Ionospheric tilts and traveling ionospheric disturbances produce the major problems in radio source location by introducing error in the angle of arrival and uncertainties in the height of the reflecting layer. Multiple reflections from wave-like or corrugated layers also producing multimode interference. The ionosphere tilts due to solar influence and the large-scale TID's show good spatial and temporal coherence, maintaining their shapes over long distances and for times on the order of an hour or more. Superimposed on these more regular waves are the spectrum of medium-scale TID's. The medium-scale TID's are the most frequently occurring ionospheric irregularities and the ones showing the least spatial and temporal coherence. While single frequency components of medium-scale TID's may persist for longer distances and periods of time, the composite TID seems to decorrelate over distances of 50-100 km and times of 5 minutes. Table IV provides a summary of this group of properties for ionospheric irregularities.

The emphasis of this paper has been implicitly directed toward the concept of a single station locator using a single, vertically incident ionospheric sounder. One basic constraint in radio source location is that the reflection point of the intercepted HF signal is some distance from the receiving site. For a spatially and temporally uniform, or at least slowly varying, ionosphere this would present no problem. In reality, however, ionospheric irregularities reduce the usefulness of information gathered at one point when transferred to another point. Medium-scale TID's seem to place the severest limitations on extrapolation of state-of-the-ionosphere information. The basic space and time decorrelation parameters have been listed above.

If the concept of the single station locator is retained, then the inherent problem of errors due to the ionospheric propagation path may be approached by either living within the constraints of a single point sounding, or expanding the ionosonde network. Four options will be explored: (1) Limit the use of the system to live within the current constraint of a single, overhead sounding; (2) Place the ionosonde at the anticipated mid-point of the propagation path; (3) Resolve the various frequency components of the ionospheric disturbance, and (4) Employ an integrated network of ionosondes.

The first option recognizes the basic constraints of the available ionospheric data and limits the use of a single station locator to within these constraints. This implies that the system would be of essentially strategic use, but has the advantage that it is essentially self-contained and could be fielded well behind the forward battle area.

The second option attempts to gather ionospheric data where it would be most useful, near the anticipated ionospheric reflection point. This implies a preselection of range and direction over which radio source location will be attempted so that the system and the sounder can be optimally positioned. Thus additional constraints on system use have been imposed, not the least of which is the transfer of data from the ionosonde to the receiving station. Once the step of moving the ionosonde has been taken, it is a natural extension to consider using several ionosondes.

A basically analytic approach to the problem of decorrelation of ionospheric data would be to resolve the various frequency components of the medium-scale TID. It is felt that the individual components maintain their coherence and propagate over distances and times longer than 50-100 km and 5 minutes. While this approach is conceptually straightforward, it is not clear how much ionospheric data would be needed as input. It would appear, however, that data from several ionosondes would be needed. The additional data correlation and analysis effort would place very large requirements on any fielded computer system.

TABLE IV

TYPE	SPATIAL DECORRELATION	TEMPORAL DECORRELATION	MAJOR EFFECTS
Sporadic E	~100's km, depending on the size of the patch.	Minutes to hours, depending on relative location of patch and its drift velocity.	Uncertainty in height of reflecting layer. Multimode propagation.
Ionospheric Tilt (solar effect)	100's-1000's km	Hour or longer	Uncertainty in angle of arrival and height of reflecting layer.
Large-scale TID	1000's km	30 minutes to several hours.	Uncertainty in angle of arrival and height of reflecting layer. Multimode propagation.
Medium-scale	50-100 km	~5 minutes	Uncertainty in angle of arrival and height of reflecting layer. Multimode propagation.

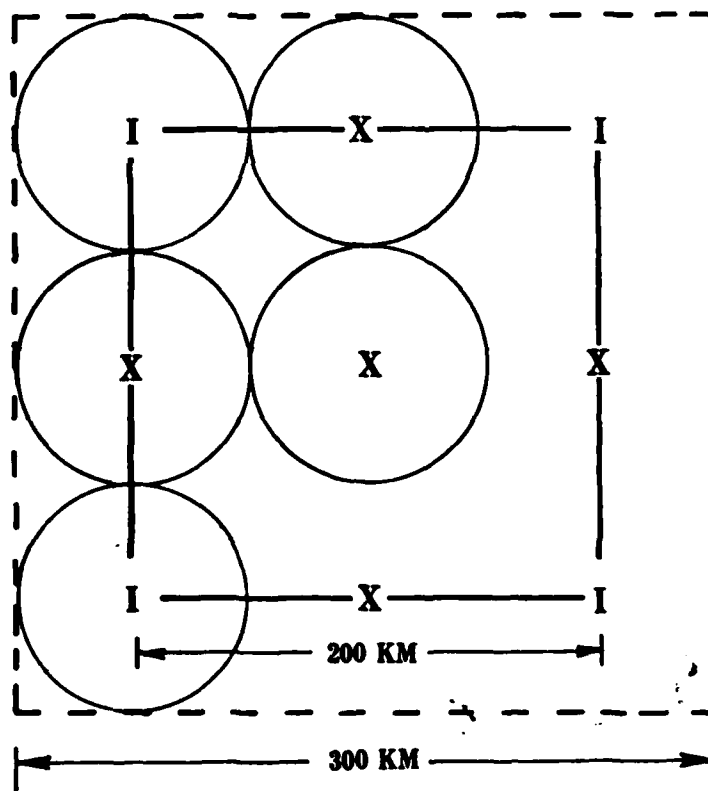


Figure 4: Schematic of how to locate four ionosondes such that maximum ionospheric data over a large area can be gathered from both vertical and oblique soundings.

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The tendency toward the use of more than one ionosonde is apparent. An integrated network of ionosondes could be used effectively to gather sufficient ionospheric data over a large area. As an illustration, place four ionosondes on the corners of a square 200 km on a side. By using vertical soundings at each ionosonde, and oblique soundings between ionosondes, the state of the ionosphere could be determined at nine points along the perimeter and at the center of this square. Thus 78.5% of all the points within a slightly larger, superimposed square, 300 km on a side, would be within 50 km of a sounding point and nominally within the "decorrelation distance". No point in the square would be more than 71 km from a sounding point; see Figure 4. Therefore a relatively large area can be covered by as few as four ionosondes, provided they are integrated into a network using both vertical and oblique soundings. Nominally enough data can be gathered to adequately define the state of the ionosphere for any reflection point within the larger area, and potentially enough data are available for more complicated analysis approaches. The trade-off is that the complexity of a fieldable system has been greatly increased.

In summary, the effects of ionospheric irregularities on radio source locations have been investigated. It was found that ionospheric data (tilt and virtual height of reflection) taken at one point lose their validity when extrapolated over distances of 50-100 km or times of more than 5 minutes. Thus ionospheric soundings should be made more frequently than 5 minute intervals. A single ionosonde is usually not sufficient to adequately represent a large enough area of the ionosphere. An integrated network of ionosondes, using both vertical and oblique soundings is recommended.

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