PASSIVE DETECTION OF IONOSPHERIC OBJECTS

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PREFACE

When Guglielmo Marconi sent the first radio message across the Atlantic Ocean in 1902, the ionized portions of the atmosphere played a very important part in the communication link. In the dawn of the age of space, ionization in the atmosphere very well may play another important role. The study of microscopic meteors and communication by means of radio wave reflection from meteor trails is already a reality. A system for the detection and tracking of ionospheric objects (satellites, missiles, etc.) by utilization of the radio wave reflection from their ionized trails will be developed in this study.

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Professor Paul A. McCollum provided a large amount of unofficial but helpful discussion and gave cheerfully of his time whenever asked.

Finally I wish to thank my wife, Helen, for typing the rough drafts despite not having typed since our marriage.

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INTRODUCTION

With the advent of man-made satellites traversing the ionosphere and the other types of space vehicles now envisioned by man, a very stark reality presents itself. It becomes practically a necessity to have some means of detecting and tracking ionospheric objects without active radio transmitters.

The lack of radio transmission on the part of ionospheric objects may occur for many reasons. Some of the major reasons are enumerated.

1. Their batteries may have expired.
2. Radio transmitter malfunctions may have occurred.
3. The radio transmitters may be controlled by an unfriendly power, and transmissions may occur only for short periods of time in response to triggered signals. The transmissions, therefore, would be extremely difficult to detect.
4. The objects may be missiles with no transmitting equipment, whatsoever, but only lethal devices installed.

The electronic reconnaissance of other nations' missile and satellite capabilities has become one of the pressing present requirements of national security, and the ability to detect and track hostile missiles has become a vital part of any country's defenses. Both of these require some method to passively detect and track ionospheric objects.

At the present time there are two major methods of detecting and tracking ionospheric objects without radio transmitters. They are the optical method and the radar method. The radar method of detection and tracking of ionospheric objects will be mentioned later as a means of comparison to the proposed system.

It is a well established fact that long distance radio communication is feasible due to specific layers of the ionosphere acting as partial reflectors of radio waves at particular frequencies. Radio waves also have been reflected and have been returned by the ionized trail left by meteors in the ionosphere. Evidence is now accumulating that satellites leave ionized trails in much the same manner as meteors and that missiles also can be expected to produce such trails. The reflection, and/or refraction, of radio waves from these ionized trails appears quite feasible.

By utilizing some of the basic concepts developed in the radio study of meteors in addition to some of the principles of meteor burst communication and some other theories, a system for detecting and tracking ionospheric objects without radio transmitters will be developed.

It should be pointed out that, while all of the principles of the system are quite basic, some of the equipment which may be required for an effective continuous system might demand, in some instances, advanced component engineering and/or further developments in the state of the art.

The principles developed by a system of this type could have truly fantastic future applications in addition to those already spelled out. For example, they could be applied to the air (or space) traffic control of arriving and departing space vehicles. Also, in not quite so futuristic a vein, controlled satellites could be placed into specific orbits, with devices to aid ionization, and in this manner establish communication links far superior to the present meteor-burst type communication links.

The word "passive" as used in this study shall have the same general meaning as given in The Space Encyclopedia (1). It means the observation of any ionospheric objects without assistance from any radiating equipment in the objects.

CHAPTER II

THE FOUNDATIONS FOR THE SYSTEM

There are a number of phenomena and principles which, when considered together, point the way toward a new system of passive detection and tracking of ionospheric objects. The building blocks will be examined one at a time before an attempt is made to fuse them together.

Ionospheric Reflection

Man's present knowledge of the ionosphere is quite meager. Heretofore, the major device for the study of the ionosphere was by means of radio waves which were originated on the earth and whose reflection or lack of reflection by ionospheric layers could be analyzed by suitable radio circuits. Two new major methods of study should cast great amounts of light upon this subject by means of satellites that actually are traversing the ionosphere and transmitting data on conditions encountered back to ground stations. Also, with the expansion of radio astronomy, the ionosphere now may be studied with radio transmissions which are extra-terrestrial rather than terrestrial or earth originated.

The ionized layers of the atmosphere are believed to be caused primarily by radiation from the sun with some assistance from meteor ionization trails at certain levels. The layers into which the ionization forms itself are subject to changes due to the seasons, time of day, and sunspot activity.

Ionization is said to have taken place when an electron is removed completely from a molecule or atom leaving a positively charged ion. It, of course, requires energy to accomplish this process. Ionization may take place for any one or combination of the following reasons.

1. Collision of atoms or molecules with:
   a. Electrons
   b. Positive or negative ions of atomic or molecular mass
   c. Excited atoms or molecules
2. Collision of atoms or molecules with photons (photoelectric effect)
3. Cosmis radiation
4. High temperatures in gases or vapors
5. Chemical action

The first reason, collision causing an ionized trail, would be the primary basis upon which a system for passive detection of ionospheric objects would depend.

For normal sky wave propagation, the ionosphere does not reflect waves in the same manner as a metallic conductor. However, for the case of overdense meteor trails, the trail is considered to act as a metal cylinder for a certain period of time until diffusion changes the trail. The maximum frequency which will be reflected from an ionized area is dependent only upon the electron density of the area. Skilling (2) has shown that, for the case of a wave rising vertically, the maximum critical reflection frequency is given by:

$$f = 9.0 \sqrt{N}$$

where

f = frequency in kilocycles per second

N = electrons per cubic centimeter

Ionized layers are present up to heights of 250 miles; therefore, it at least would be reasonable to expect ionization by collision at these altitudes, which, incidentally, are the altitudes at which most missiles operate. Kraus (3, 4) has detected CW reflections from quite small satellites at altitudes as high as 1,000 miles which is quite convincing evidence that some ionization process must take place above the normal ionospheric layers. Further, it has been reported that the U. S. S. R. Satellite Sputnik III found a noticeable quantity of ions at an altitude of 620 miles (5).

A secondary use for the data obtained from a system for passive detection of ionospheric objects presents itself. Data obtained from the system could be compared with known satellite tracking information. Statistical studies of this information should give definite information about the electron content of the ionosphere at different altitudes and, in this manner, should contribute to present information on the physics of the upper atmosphere.

Meteor-Burst Communication

The forward-scatter propagation from ionized meteor trails has been utilized for communication links (6, 7). Communications have been established and maintained beyond the line of sight at frequencies which normally had been used only for line-of-sight communications. The signals are stored on magnetic tape and transmitted at greatly speeded up rates when a meteor trail establishes a link between the two stations. The transmitter sends out a constant unmodulated carrier, and, when a meteor trail causes reception at the receiver, it immediately sends the transmitter a signal to send (or burst) information. The transmitter will continue to burst information as long as it receives the signal which indicates that the information is being received due to a meteor's trail having sufficient ionization to complete the path.

A fairly wide bandwidth can be employed with meteor-burst communication as compared with the narrow bandwidths encountered with ionospheric or tropospheric scatter communications. This wide bandwidth allows the system to transmit either voice, teletype, or facsimile.

The usual height of meteor trails employed is considered to be 100 kilometers. The frequencies employed are usually in the band of 30 to 50 megacycles per second. Distances between transmitters and receivers range from approximately 600 to 1500 miles.

Fairly low power in the order of 400 to 750 watts is utilized. In so far as the system is for point to point communication, directional antennae are employed; however, they are usually not of the extremely high gain type. The most commonly encountered type is the fairly simple yagi array, although a few rhombic type antennae have been employed.

Tests have indicated that two meteor-burst transmitters can both operate at the same frequency without serious interference provided there is a relatively small geographic spacing between the two. It should be pointed out that ionospheric scatter propagation also is present at the meteor burst wavelengths, but its signal strength is much less than that received from meteor bursts. The meteor-burst communication system in use in Canada is known as the Janet system.

It has been found that meteor-burst communication systems are highly impervious to attempts at jamming (7). This is due to three of its inherent characteristics: first, its burst rather than steady type of communication; second, the constant changes in signal path geometry dependent on each meteor's position; and, third, the unpredictable times of actual transmission links.

It is believed that the experience gained and the principles learned from meteor-burst type systems could well be utilized for a more sophisticated system to detect and track ionospheric objects without transmitters. This system would use the forward-scatter propagation from object trails rather than from meteor trails.

Meteor Astronomy

Closely related to the meteor-burst communication systems is meteor astronomy (8, 9). Meteor astronomy usually is considered as a branch of radio astronomy. It concerns itself with the study of ionized meteor trails by radar-type methods. The information gained from this study has both geophysical and astronomical applications.

When a meteor evaporates in the upper atmosphere at a height range of 80 to 120 kilometers, it leaves an ionized trail containing electrons. This trail occasionally may be visible; however, it also is responsible for the scattering of radio waves. Back-scatter (or radar-type reflection) normally is employed for meteor astronomy while forward-scatter is used exclusively in meteor-burst communications systems. Frequencies employed in meteor astronomy normally are in the range of 30 to 80 megacycles per second.

The ability to determine almost instantaneously the velocity of meteors is one of the salient features of meteor astronomy (9). Since the determination of the velocity of hitherto unknown ionospheric objects would be valuable information, the methods as applied to meteor astronomy will be outlined.

The method utilizes one station and radar-type equipment. In actuality, what is done is observation and measurement of the Fresnel diffraction pattern as the ionized column is formed across the antenna beam. The patterns are observed as amplitude variations of the returned signals presented on cathode-ray oscilloscopes.

Either pulse modulation or continuous wave may be used. The perpendicular range to the meteor trail is measured by usual radar methods and is designated as R. The oscilloscope display has the general appearance shown in Figure 1.

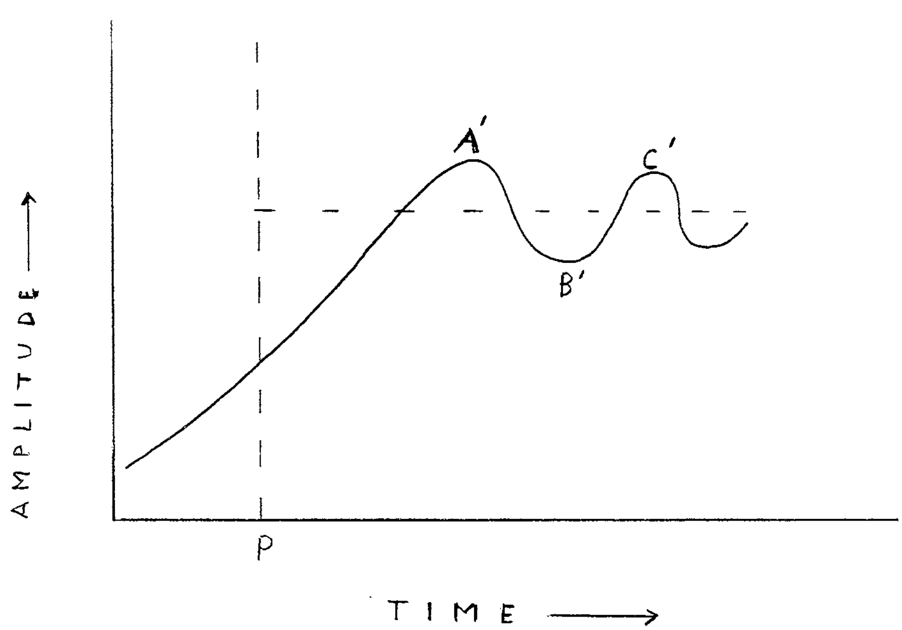

Figure 1. Fresnel diffraction pattern of a meteor trail as displayed by an oscilloscope.

The meteor trail through space has the features illustrated in Figure 2 with A , B , etc., being corresponding points in both figures.

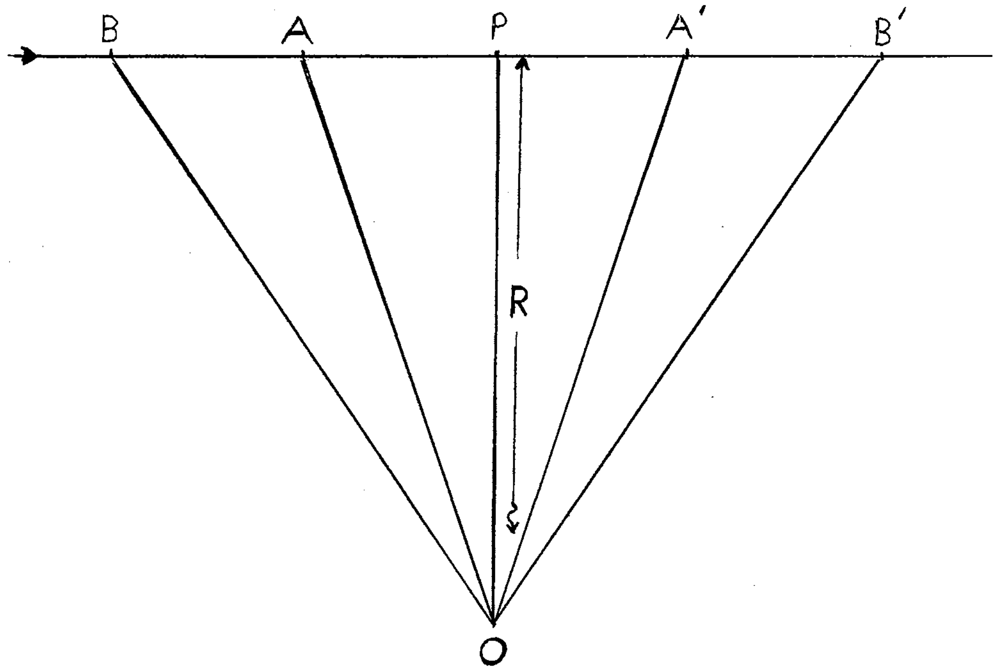

Figure 2. Geometrical construction of the Fresnel zones of a meteor trail.

In Figure 2:

$$OA' = OA = R + \frac{\lambda}{4}$$

$$OB' = OB = R + \frac{\lambda}{2}$$

from geometry:

$$(PA')^2 = (OA')^2 = R^2$$

$$(PA')^2 = (R + \frac{\lambda}{4})^2 - R^2$$

$$PA = \sqrt{\frac{R\lambda}{2}}$$

The terms from $(\frac{\lambda}{4})^2$ are neglected since they are of little consequence.

Similarly

$PB' = \sqrt{R\lambda}$

The distance from A' to B' is equal to $PB' - PA'$.

A' to $B' = \sqrt{R\lambda} - \sqrt{R\frac{\lambda}{2}}$

A' to $B' = \sqrt{R\lambda}\left(1 - \frac{1}{\sqrt{2}}\right) = .3\sqrt{R\lambda}$

Since the time t from A' to B' may be measured on a properly calibrated oscilloscope, the velocity V of the meteor trail may be determined from the following equation:

$$V = \frac{\text{distance}}{\text{time}} = \frac{.3\sqrt{R\lambda}}{t}$$

Another feature of meteor astronomy which may have future implications is the ability to determine the radiant or path of the meteor through space.

Three transmitters are situated so that their beams intersect at a point equidistant from the three stations at a height of 100 kilometers. Since a meteor trail gives a back-scatter return only when it is at right angles to the axis of the radar beam, the three stations will receive maximum returns at different times. The time separation of the three patterns can be used to calculate the radiant of the meteor.

Satellite Detection by CW Reflection

Dr. J. D. Kraus (3, 4) of Ohio State University has reported the detection of satellites by CW reflection. The satellites detected by this method include Sputniks I and II and also Explorers I and III.

The satellites were detected at altitudes of from 100 to 1,000 miles using signals which were transmitted originally by station WWV in Washington, D. C. The receiving station was located at Columbus, Ohio, a distance of 330 miles from the transmitter. Detection was accomplished at frequencies of both 20 and 25 megacycles per second. The time duration and amplitude of the received signals quite exceeded those normally reflected from meteor bursts on the same frequencies.

Dr. Kraus (10) applied the equations of radar reflection to the received signals, and the effective reflection area calculated was approximately 600 square meters. This is much larger than any satellite area and, therefore, suggests ionization as the reason for the large returned signal rather than a pure radar effect.

It is of interest to note that Explorers I and III, which are quite small satellites, were detected at a height of 1,000 miles using 25 megacycle WWV signals. The 25 megacycle signals of WWV are transmitted at a power of 100 watts compared to 1,000 wats for the 20 megacycle signals.

Dr Kraus (10) used this method of detection to show that the disintegration of Sputnik I was actually a gradual process lasting a number of days with the main satellite first breaking into separate pieces followed by each of the individual pieces further being broken up into smaller pieces. It is significant that the investigation could be carried on only at night, as the normal daytime ionospheric reflection at the frequencies used provided a continuous strong signal which prevented burst detection.

The reason why the signals were investigated originally was because when Sputnik I was initially transmitting on 20 megacycles its signal had a very marked transition from a rough to smooth character at approximately the same point of its travel on each pass. This transition has been attributed tentatively to an ionized cone which precedes the satellite on its travel. This cone is formed when the satellite bounces gas molecules it has encountered ahead of it, and the resulting collision forms an ionized cone.

The transmitting antennae utilized were omidirectional vertical dipoles while the receiving antennae were a pair of horizontal half waves dipoles separated by 350 feet on an east-west base line and hooked up as an interferometer. However, useful reflections were received using only one antenna of the interferometer pair.

Attempts were made to detect the satellites using a local CW transmitter on 21 megacycles. The reflections from aircraft were too strong and numerous, and the attempt was discarded after a three day trial.

The times of maximum signal reflection coincided quite closely with the times when the satellites were expected to cross a hypothetical line from the transmitter to the receiver.

Forward-scatter Principles

In contemplating a system for passive detection of ionospheric objects, two distinct methods of detection are at once apparent. Either the back-scatter propagation or the forward-scatter propagation may be used. Indeed, it may be necessary for a completely integrated system to employ both types; however, the forward-scatter technique will be used predominately for the following reasons.

1. The duration and amplitude of a meteoric signal observed in forward-scatter may be appreciably larger than the back-scatter case.
2. With sufficient separation between stations, forward-scatter techniques should be disturbed slightly by aircraft which would be a major detriment to back-scatter techniques.
3. A return is evidenced only in the case of back-scatter when the axis of the trail is at right angles to the antenna beam.

4. There may be instances where transmitters designed and operated for entirely different purposes may be used for detection by means of forward-scatter techniques merely by the installation of suitable receiving sites.

Equations have been developed for the forward-scatter of radio waves from overdense meteor trails by Hines and Forsyth (11). Since the forward-scatter technique is to be primarily employed, the parameters of the equations for meteor trails probably will be closely analogous to those for forward-scatter from ionospheric objects. With this in mind, the equations will be examined.

Meteor trails are classified as either underdense or overdense. An overdense trail is defined as one having 10^{14} or more electrons per meter for the length of the trail. An overdense column will behave in a manner roughly analogous to a metallic reflector. The amplitude and time duration of the signals recorded from satellite reflection by Kraus would establish object trails as belonging to the overdense category.

In the equations for forward-scatter, three angles are encountered. Consider the illustrated transmission path in Figure 3.

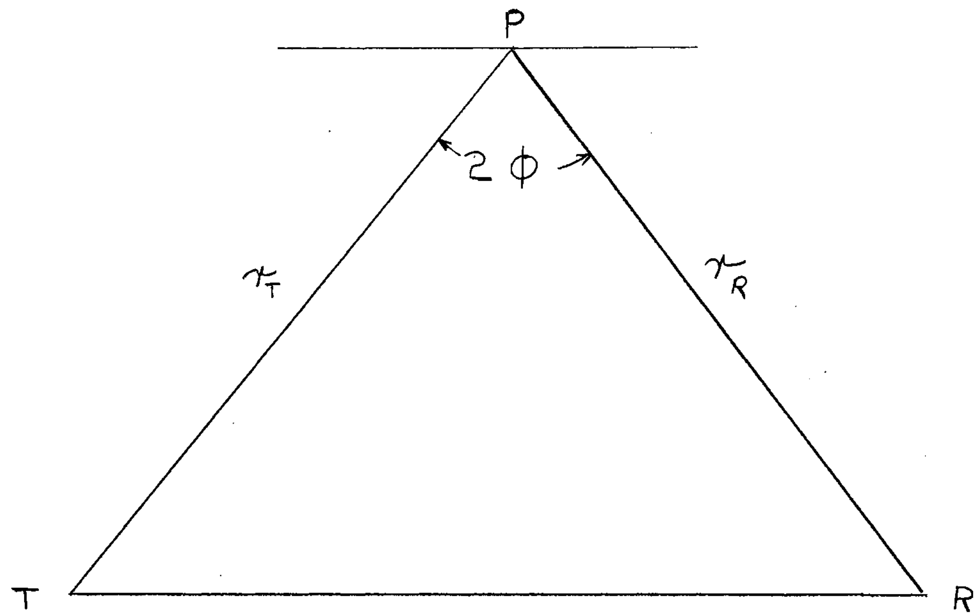

Figure 3. The angle ϕ as developed in forward-scatter geometry.

where

P = point of reflection

T = transmitter

R = receiver

r_T = distance from transmitter to point of reflection

r_R = distance from point of reflection to receiver

2ϕ = angle illustrated T P R

Also consider a top view of the same process, as shown in Figure 4.

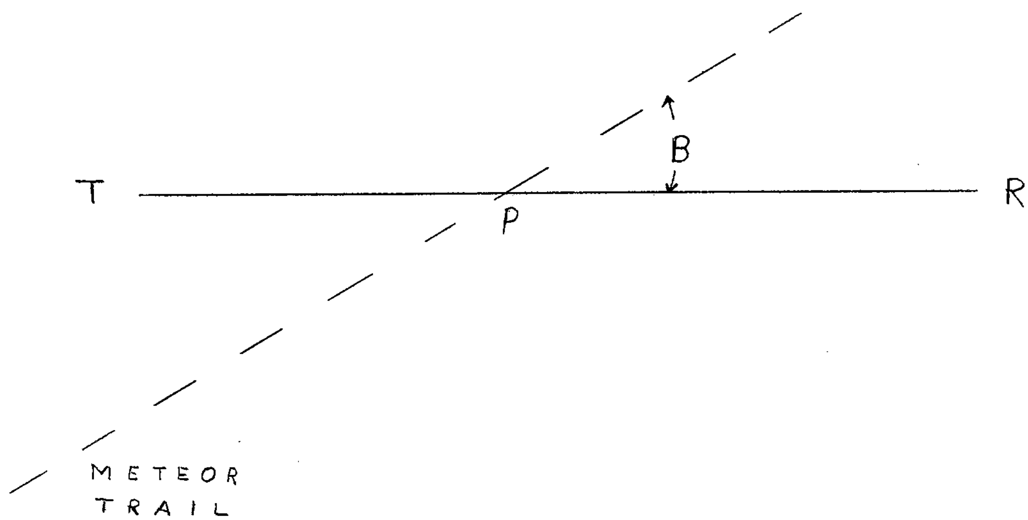

Figure 4. The angle B as developed in forward-scatter geometry.

where

B = the angle between the axis of the meteor trail and the plane of the transmission T P R.

Finally, the angle a is defined as the angle between the incident electric vector and the direction P R of the scattered wave. For the case of horizontal polarization, the angle is illustrated in Figure 5.

Similarly, the case of vertical polarization is demonstrated in Figure 6.

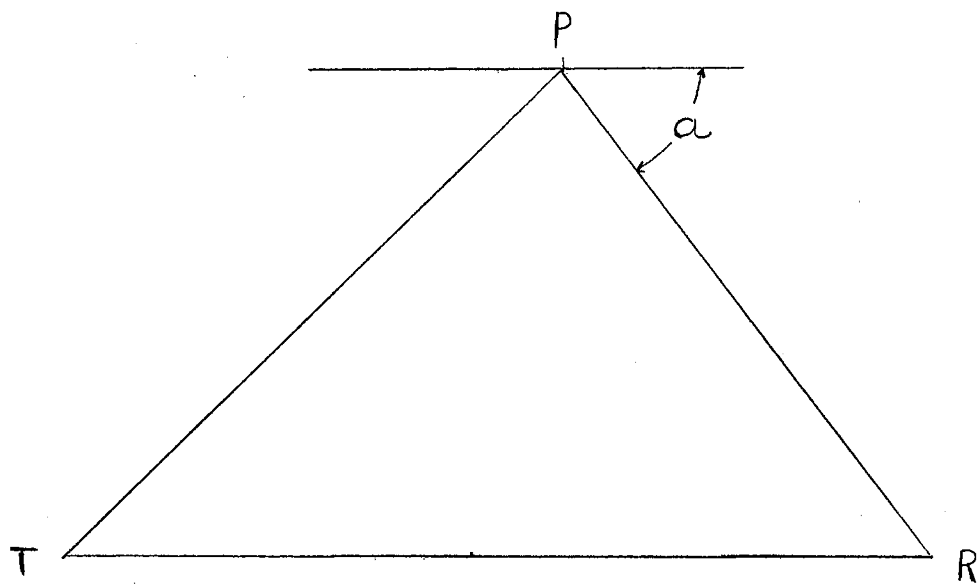

Figure 5. The angle a as developed in forward-scatter geometry for horizontal polarization.

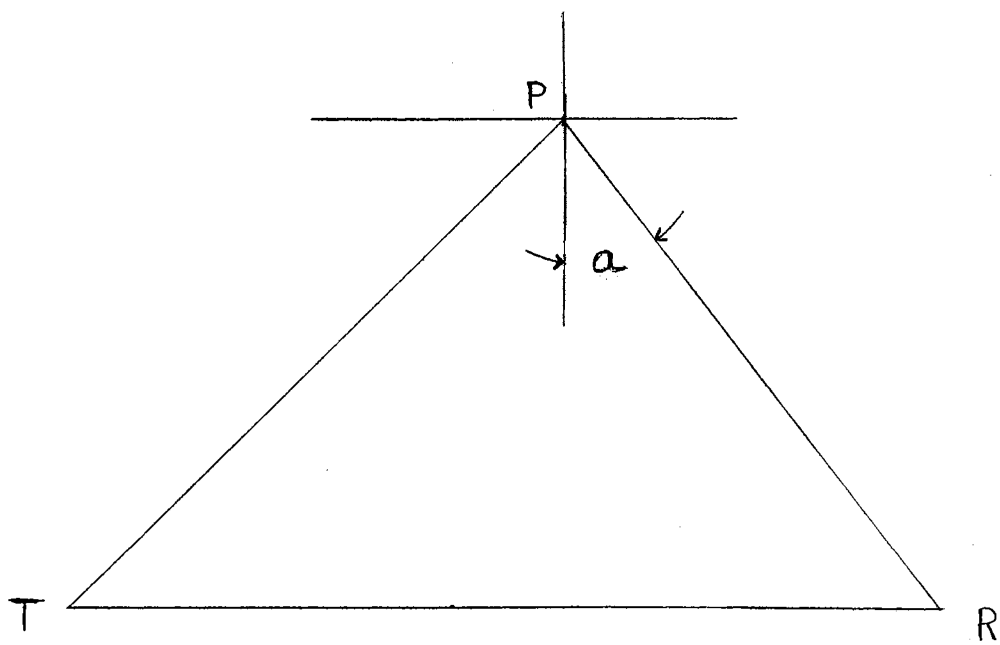

Figure 6. The angle a as developed in forward-scatter geometry for vertical polarization.

The formula for the average received power is given as:

$$P'_R\ (t) = P_T \left[\frac{G_T\ G_R\ \lambda^2\ \sin^2 a}{32\pi^2\ r_T\ r_R\ (r_T + r_R)\ (1 - \cos^2 B\ \sin^2 \phi)} \times \frac{4\ D\ t}{\sec^2 \phi}\ \mathrm{Ln} \left(\frac{\mu_o\ e^2\ g\ \lambda^2\ \sec^2 \phi}{4m\ 4\ \pi^3\ D\ t} \right) \right]^{\frac{1}{2}}$$

where

P_T = transmitted power

g = line density of electrons

G_T and G_R = transmitting and receiving antenna gains, respectively (relative to isotropic radiations)

m = electron mass

e = electron charge

μ_o = permeability of free space

t = time

D = diffusion coefficient

The time duration of the signal is represented by the following equation:

$$\tau' = \frac{\mu_o\ e^2\ g\ \lambda^2}{4m\ 4\ \pi^3\ D} \sec^2 \phi$$

The maximum power received is shown by the following equation:

$$P'_R \max = P'_R \left(\frac{\mathcal{T}'}{\epsilon} \right)$$

$$P'_r \max = P_T \left[\frac{G_T G_R \lambda^3 \sin^2 a}{16 \pi^4 r_T r_R (r_T + r_R)(1-\cos^2 B \sin^2 \phi)} \right] \left[\frac{\pi \mu_o e^2}{4 \epsilon \; 4 m} \right]^{\frac{1}{2}} g^{\frac{1}{2}}$$

Note:

ϵ = natural log base

When the equations are considered as having some analogy to forward-scatter from ionospheric objects, the following conclusions can be drawn.

1. The geometry between the object's trail, the vertical plane of the receiver and transmitter, the incident electric vector, and the reflected wave will have a strong influence on received signal strength.
2. Polarization definitely should be taken into consideration.
3. By increasing transmitted power and antenna gains, the received signal for a particular path should be increased.
4. Despite the number of variables over which little or no control may be exercised, the possibility of using forward-scatter techniques for detection of passive ionospheric objects seems quite plausible.

Time Duration of Signals

During his work on the detection of satellites, Dr. Kraus noted that meteor echos usually have a time duration of one or two seconds and rarely exceed 10 or 15 seconds. This approximate time duration for meteor reflections also is borne out in work on meteor-burst communication systems and in meteor astronomy.

Dr. Kraus further noted the time duration of ionospheric reflections from the Sputniks as one or two minutes. In the case of the Explorer satellites, the time duration of the signals was of the order of less than one half minute. However, the amplitude of the ionospherically reflected Explorer I and III signals was quite large. The relatively short time duration of the Explorer signals probably can be attributed to the small size of the objects. This, of course, points out that larger objects can be expected to have longer time duration signals.

The detection of the longer time duration signals only (ionospheric objects) while rejecting those of shorter duration (meteor bursts) will be investigated subsequently.

In order to relate the ionized trail left by an object to that of a meteor, one should consider the object's trail to be overdense or having an electron density greater than 10^{14} electrons per meter. Under these circumstances Brown and Lovell (9) have shown that the time duration of the signal from a meteor trail is equal to:

$$T = \frac{a \lambda^2}{4 \pi^2 D} \left(\frac{e^2}{m C^2} \right)$$

where

a = electrons

λ = wavelength

D = diffusion coefficient

e = electron charge

m = electron mass

c = speed of light

Considering the object and the meteor trail to be at approximately the same point in space and using the same detection equipment, the following assumptions are made:

1. The time duration of the meteor signal is 10 seconds, which is quite a long time for a meteor trail.
2. The density of the meteor's electron trail is 1×10^{15} electrons per meter.
3. An object reflection at the same point in space gives a signal having a time duration of 25 seconds.

Simplifying in the basic equation:

T = aK

where

K = a constant

and $K = \frac{T}{a} = \frac{10}{10^{15}} = 10^{-14}$

and a value has been obtained for K.

Since $T = aK$

$$a = \frac{T}{K} = \frac{25}{10^{-14}} = 2.5 \times 10^{15} \text{ electrons per meter.}$$

From this comparison it can be seen that ionospheric objects will leave a stronger trail in terms of electron density than meteor trails.

By knowing the average time duration of a signal from an ionospheric object, one should be able to estimate its size and calculate the electron density of its ionized trail. This information should aid the investigation of the physics of the upper atmosphere and assist in calculations necessary for determining the parameters of a system for passive detection and tracking of ionospheric objects.

Radar Method of Detection and Tracking

As pointed out in the introduction, one method of tracking and detecting ionospheric objects without transmitters is by means of radar. A radar set achieves its maximum capability when practically all of its energy is concentrated into a so-called pencil-beam pattern. Of course, when radar energy is concentrated in this manner, its search capability is greatly reduced.

By the use of suitable circuits a pencil-beam radar can be made to lock-on to a target, once it has been located, and to continuously track it.

One of the uses to which the envisioned system could be put would be to detect and properly locate ionospheric objects so that pencil-beam radars could lock onto the object and continue to track it. The use of pencil-beam radars for tracking would be necessary only when very highly accurate continuous tracking information was essential.

Present ionospheric objects present extremely small target areas for any form of radar detection or tracking. As the size of ionospheric objects increases, their radar target areas also will increase. Of course, it is believed that larger objects will leave larger ionized trails which would make their detection and tracking by forward-scatter or back-scatter methods easier.

The presently envisioned system for the detection and tracking of ionospheric objects by radar methods is known as the Ballistic Missile Early Warning System (12). Plans call for two sites having detection and tracking radars, computers, and communication equipment. Each site will have an estimated cost of 720 million dollars.

At each site four detection radars will each sweep a 30 degree arc to obtain 120 degree coverage. The detection radars will employ split beams vertically offset by a few degrees which will be swept back and forth horizontally at high speed by means of an organ pipe antenna scanning system. From the azimuth angle of interception of a detected missile, the angular difference between beam interceptions, and time of travel, a computer will make a rough determination of the incoming missile's trajectory. This information will aid acquisition by tracking radars.

The proposed detection radars will operate in the UHF region with an average power of 1 megawatt. They will employ truncated parabolic reflectors, measuring about 165 feet high and 400 feet in length. A separate building will be necessary to house the organ pipe scanners. The radars will have a range of 3,000 miles and will be able to detect missiles as their trajectory brings them above the radar horizon.

The tracking radars, by a system of complex scanning, could scan the area of an out-of-service detection radar. The tracking radar also must attempt to identify a detected object as a missile rather than as a meteorite or falling satellite.

CHAPTER III

SYSTEM PARAMETERS AND METHODS

The foundations have been found and explained, so it becomes necessary to study different methods which could be employed to perform the functions of the system. After the methods have been chosen, the specific parameters of the system will be examined.

Doppler Effect

A method which might provide information about a passively detected ionospheric object is the measurement of the Doppler shift of the received signal. Briefly, the Doppler shift is the change in frequency of the received signal from an object when it is either approaching or traveling away from the point where the signal is received. The basic Doppler equation is given as follows (13):

$$\frac{f}{f_o} = \frac{C + V_o}{C - V_1}$$

where

f = frequency before Doppler shift

f_o = frequency of Doppler zero

C = velocity of light

V_o = velocity of observer (assumed zero)

V_1 = velocity of vehicle

The application of the Doppler equation to measure the velocity of ionospheric objects will not be attempted here. There are a number of other factors which, when taken into consideration, make the problem quite difficult. Also, the successful engineering of a system to measure Doppler shift is quite a formidable task. Other methods, which will provide the same information by a simpler system, will be developed.

Computers

The equations, which will be developed along with the system and which will require solution in order to accurately fix the point in space of the detected object and to track it, are fairly simple mathematical operations. Whether or not high speed computers would be required to provide solutions would depend upon how soon the information would be needed.

For the routine tracking of satellites, the computations could be accomplished manually, and the information could be sent into a central digesting agency. When missiles are being detected and tracked by the system, seconds are, of course, at a premium, and arrangements probably would be made to automatically transfer all information instantaneously from each station to a central computer for high speed computation, tracking, and plotting of all objects suspected to be missiles. The use of computers also would practically require automatic means of separating received signals so that manual operators would not be required to discriminate object reflections from other received signals.

Theoretical Range Investigations

Since meteor burst communication systems operate successfully with stations situated as far apart as 1,500 miles, a rough approximation of the theoretical range possibilities due to the forward-scatter of waves from ionized trails will be investigated.

In practice it has been found that optical line-of-sight distances are less than radio line-of-sight distances, so the ranges obtained should be considered theoretical minimums. The formulas found in most references for line-of-sight distances can not be used since they are based upon the height of the object being quite small when compared to the earth's radius of approximately 3,956 miles.

The range determination merely entails determining the distance to the horizon from objects at various heights and then doubling the distance for forward-scatter. This determination would be correct only when the object is equidistant between the receiver and transmitter. At other positions between the receiver and transmitter, the range would be less decreasing to the object's distance to the horizon when the object was directly over one of the stations.

A diagram for the minimum theoretical range of an object at an altitude of 200 miles equidistant between two stations is presented in Figure 7.

By the application of the principles of simple geometry and trigonometry, the distance from R to T along the arc is approximately 2,500 miles. If the object were directly over one of the stations at the same height of 200 miles, the range would be one half, or 1,250 miles. For an equidistant object at a height of 100 miles, the station separation comes out to 1,700 miles. When the altitude is increased to 1,000 miles for an equidistant object, the spacing for detection by forward-scatter would be, theoretically, slightly more than 6,000 miles.

It has been well established by meteor astronomy that the approximate maximum height of detectable meteor trails is 120 kilometers, or 75 miles. Therefore, it seems possible that a receiver and transmitter spaced far enough apart, at say 1,800 miles, would experience forward-scatter signal propagation only from objects at heights greater than those usually occupied by meteor trails. This presents one rather simple method of eliminating meteor trails from the detection system. Two stations separated by 1,800 miles should respond to signals from ionized trails at a height of 120 miles equidistant between the stations.

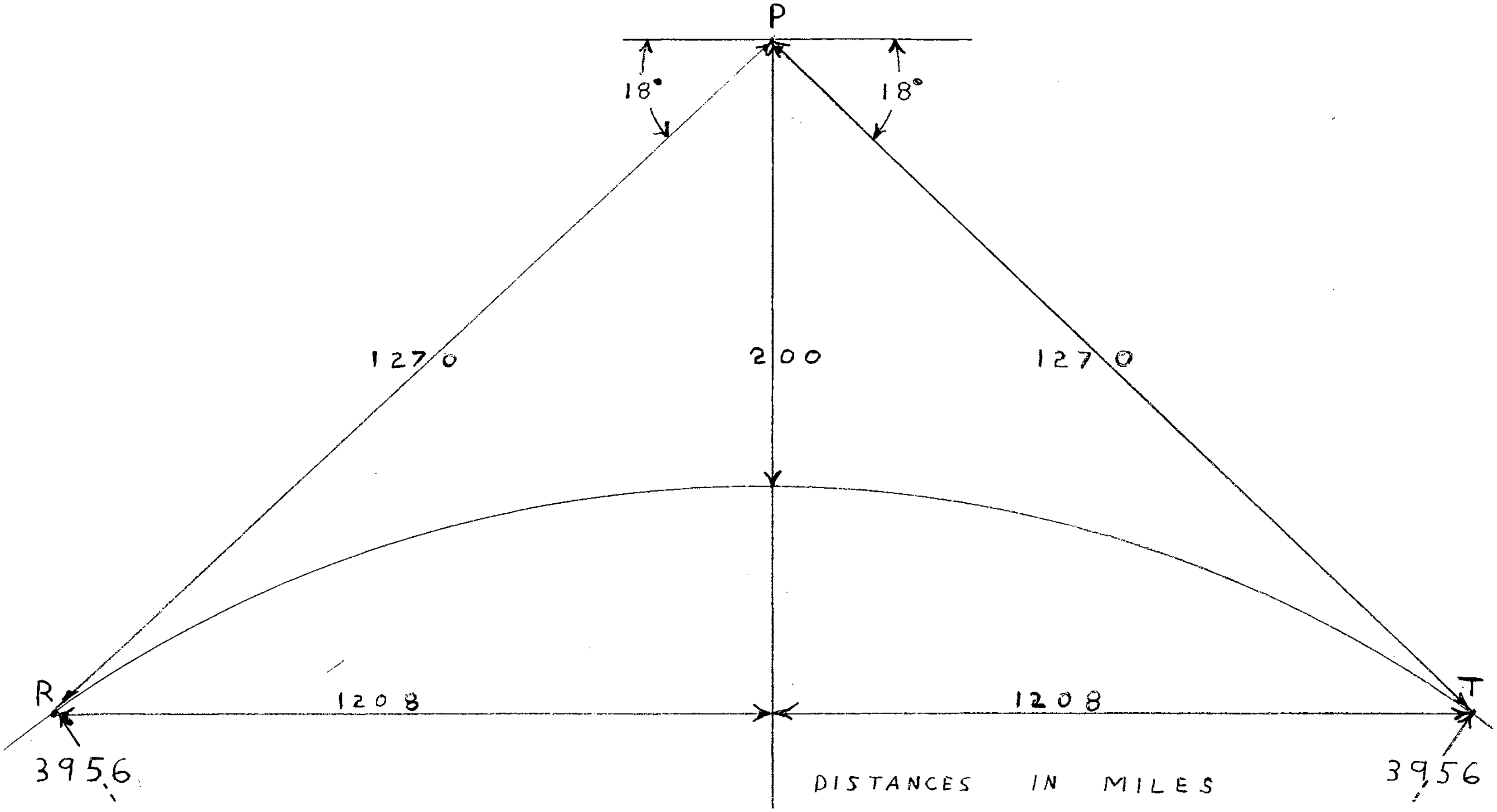

Figure 7. Theoretical range determination for an object at an altitude of 200 miles.

However, as the location of the ionized trails approached one of the stations, the height of the trail would have to increase in order to afford detection.

After preliminary results had been obtained from actual range measurements, it would be a fairly simple process to calibrate each transmitting and receiving station as a pair. The range to the horizon for different altitudes would be plotted as shown in the accompanying graph, Figure 8. As an example of the calibration, consider the previously mentioned case of a transmitter and receiver separated by 1,800 miles. An object passing equidistant between the receiver and transmitter at an altitude of 120 miles should cause a reflected signal, while an object passing directly overhead would require a height of approximately 430 miles in order to cause a signal. The area from which any particular set of stations could expect a signal could be plotted in a number of different forms. A hypothetical plot for the example considered is shown in Figure 9.

The information obtained from plots of this type would be of extreme value. For example, if the system were being used for the detection of objects, the information from all station pairs necessarily would have to be presented in the form of a master chart or model which would reveal which areas of the ionosphere were under surveillance by the entire system. This information also would be of extreme value if the system were used for tracking of objects.

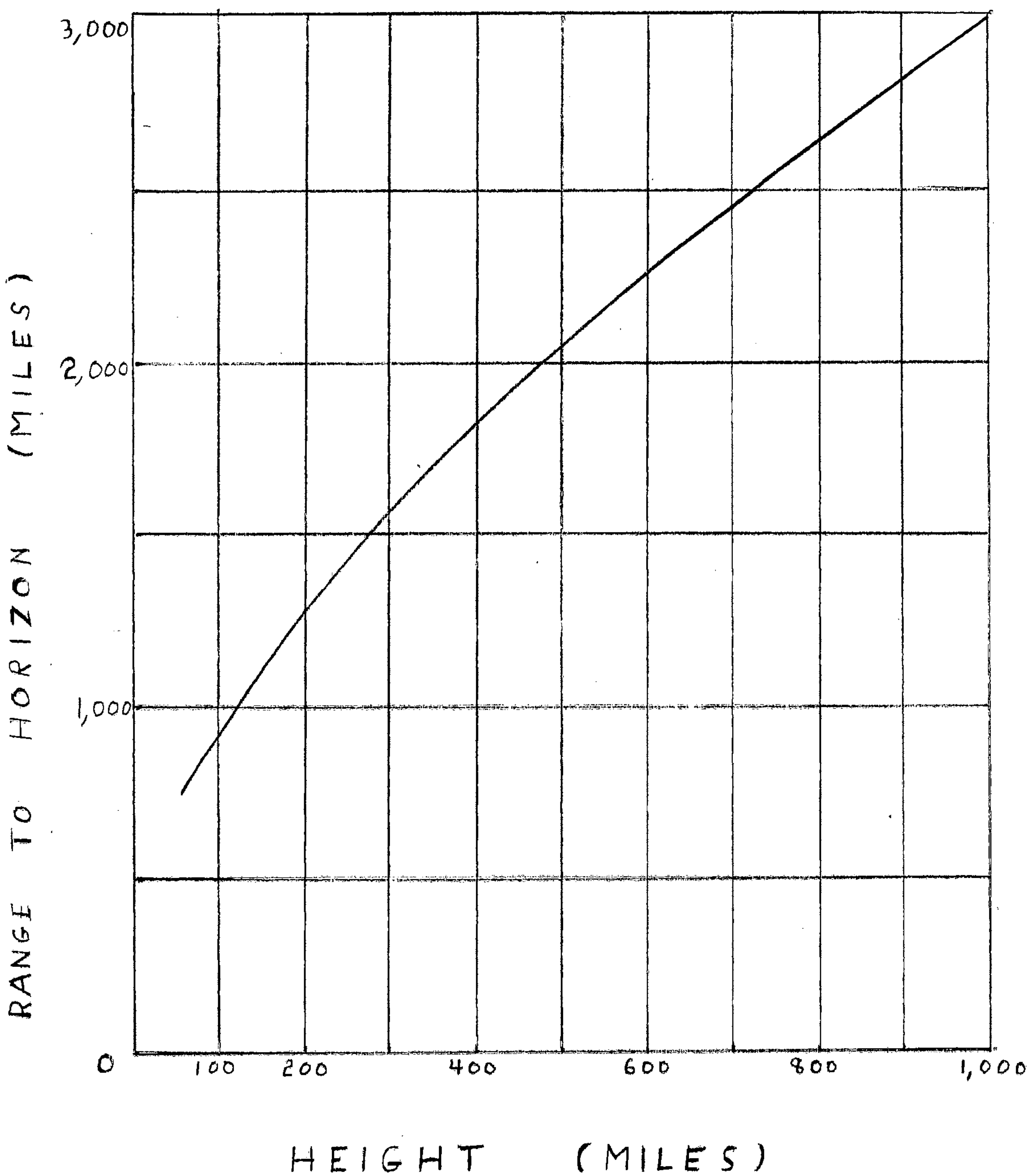

Figure 8. Graph of object height versus range to the horizon.

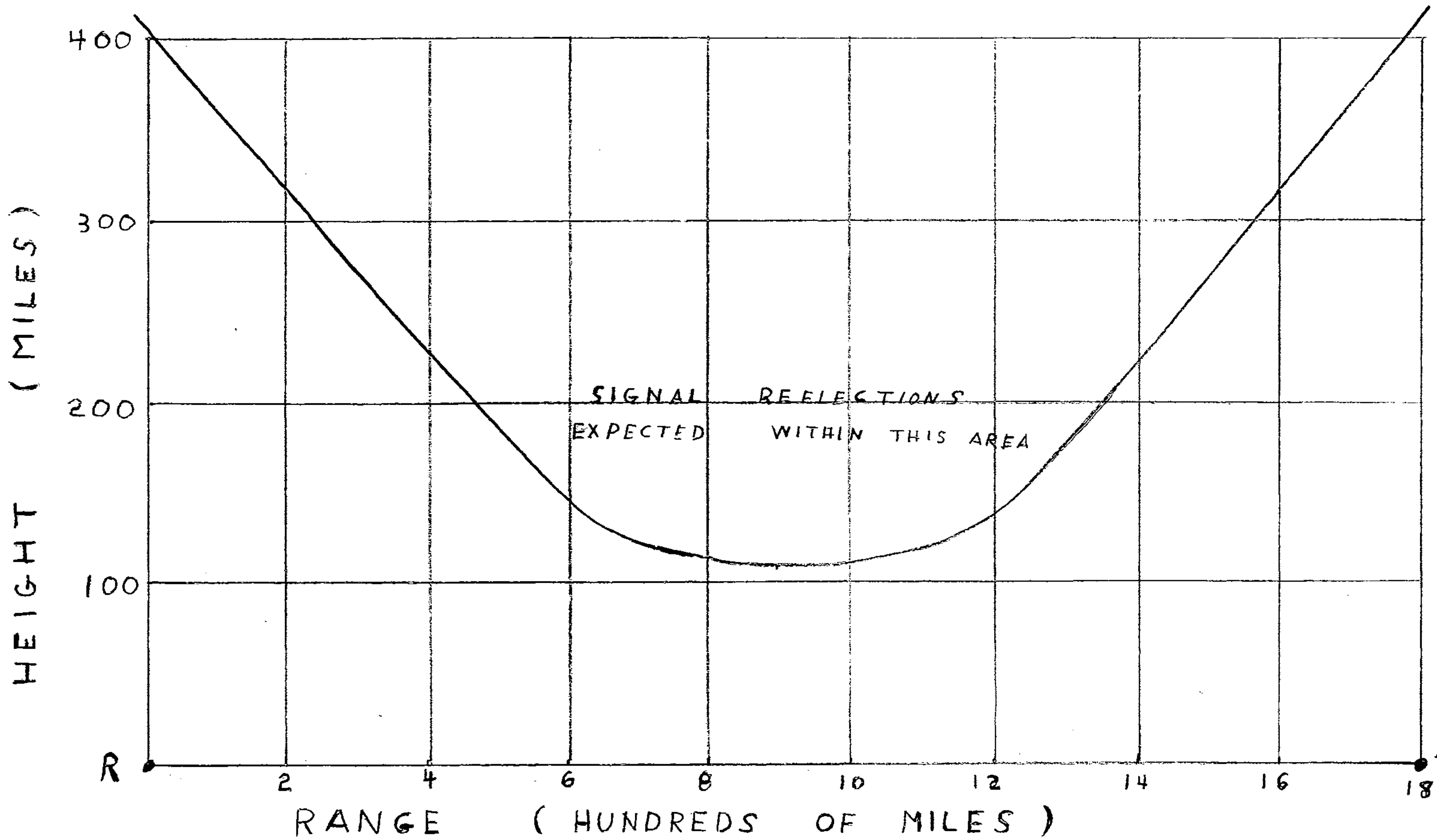

Figure 9. Calibration of the effective detection area for a transmitter and receiver at 1,800 mile separation.

In this case the coverage data from each set of stations would be information pre-set into a computer prior to the actual tracking problem.

In all of the range investigations, the heights of the transmitting or the receiving antenna above the earth's surface have been neglected for simplicity. This would not cause any appreciable error, as the heights usually encountered would be negligible when compared to the altitude of an ionospheric object.

Transmission Patterns and Techniques

There are three distinct choices in the realm of transmission patterns for detection by forward-scatter. They are:

1. Omnidirectional transmission such as is employed by radio station WWV on frequencies of 20 and 25 megacycles. This method was used by Kraus (3) in his experiments.
2. A concentrated beam of energy which is rotated constantly either mechanically or electrically. This method usually is employed in search radars.
3. A fixed concentrated directive beam such as used for point to point communication in the VHF range.

Due to the erratic relatively short time duration of signals expected from an object's trails, any rotational method does not appear feasible. The fixed directive beam is to be preferred over the omnidirectional beam due to the higher antenna gains which are obtainable.

Appropriate action should be taken so that the vertical transmission consists of waves going off into the ionosphere (sky waves) rather than along the ground. This may be accomplished easily in the case of vertical radiators by making the length of the grounded antenna a full wavelength long rather than the quarter wavelength usually used for Marconi antennae when a ground wave as well as a sky wave is desired. For the case of horizontal radiators, a high angle of radiation may be obtained by careful spacing of the antenna above the ground plane. For example, a horizontal half-wave dipole would have a radiation angle of 40 degrees when placed .75 or 1.5 wavelengths above the ground plane. By reference to suitable antenna manuals, any desired radiation angle may be obtained (14).

In some instances it may be plausible to use transmission facilities already erected and in operation in much the same method as was employed by Kraus (3).

The fixed directive beam method of transmission would be the most efficient for servicing receivers at up to four separate azimuth angles. In fact, a pattern in the form of a cross could be formed when the receivers were at four equally spaced azimuth angles.

When a great number of receivers at many different azimuth angles are to be serviced by one transmitter, the omnidirectional technique would be resorted to of necessity.

Unless total range determination is required, the techniques employed for transmission will be quite straightforward. The problem of determining the type of polarization to be employed probably would require a great amount of experimentation. However, it appears that, perhaps, there will be little to choose between the two major types (vertical and horizontal) so that one type might be used for transmission and another for reception without detrimental effects.

The type of antenna used for transmission would depend upon whether omnidirectional or directional transmitting patterns are desired. Power output also would depend upon the transmission pattern. Omnidirectional transmission probably would require one kilowatt or more, while directional transmission should operate satisfactorily on 500 watts. Of course, the power output also would depend upon the altitude to which detection is desired and the range to the receiving station being serviced.

Frequency of Operation

The choice of the proper frequency of operation for a system to passively detect ionospheric objects is indeed a complex problem. One very practical consideration will not be examined here, and this is the fact that frequencies are assigned by treaty or regulation to particular classes of use.

Since both the received power and time duration of signals very well may be proportional to the wavelength squared, it might seem feasible to pick as low a frequency as possible. The lowest frequency that could be used well might be determined by the normal reflections expected from ionospheric layers. However, the possible effect upon ionospheric layers of sunspot maximums and minimums as well as solar storms should not be neglected, as unusual ionospheric layer propagation could cause complete disruption of any practical use of the system. With all this in mind, a minimum operating frequency of 45 megacycles will be chosen.

The maximum operating frequency should not exceed 75 megacycles, for in the case of meteors this frequency seems to be the upper limit due to second order effects (15). Tropospheric and ionospheric scatter transmission signals also are present at the frequencies under consideration. R. C. Kirby (7) of the National Bureau of Standards reports that, for the frequency range under consideration, the signal power received from ionospheric scatter transmission falls off 4.5 decibels for every 10 megacycle increase in operating frequency. This information was obtained using scaled antennae with identical gain at each frequency.

The reception of ionospheric and/or tropospheric scatter signals by a system designed to receive forward-scatter signals from ionospheric objects should not prove detrimental. The same effect has been experienced with the Janet system of meteor-burst communications. It very well may be a definite aid to the checking of receiver tuning and sensitivity.

With consideration of all of the facts mentioned, the optimum frequency band appears to be in the range of 50 to 55 megacycles.

Total Range Determination

The total range for the case of a system which passively detects ionospheric objects by forward-scatter would be the total distance traveled by the wave from transmission to reception. The time for wave travel can be measured, and when this time is known, the total distance traversed by the wave also is known. For example, if two stations are separated by 500 nautical miles, and one considers radio waves to travel at a speed of 6.1 micro-seconds per nautical mile, a signal is received at the receiver, and the time of transit is known to be 6,100 micro-seconds or .0061 seconds during which the wave has traveled a distance of 1,000 nautical miles. By a simple plot one may determine that all points in space which could give a return of this type are on a common line which is part of an ellipse. The diagram illustrates this in Figure 10.

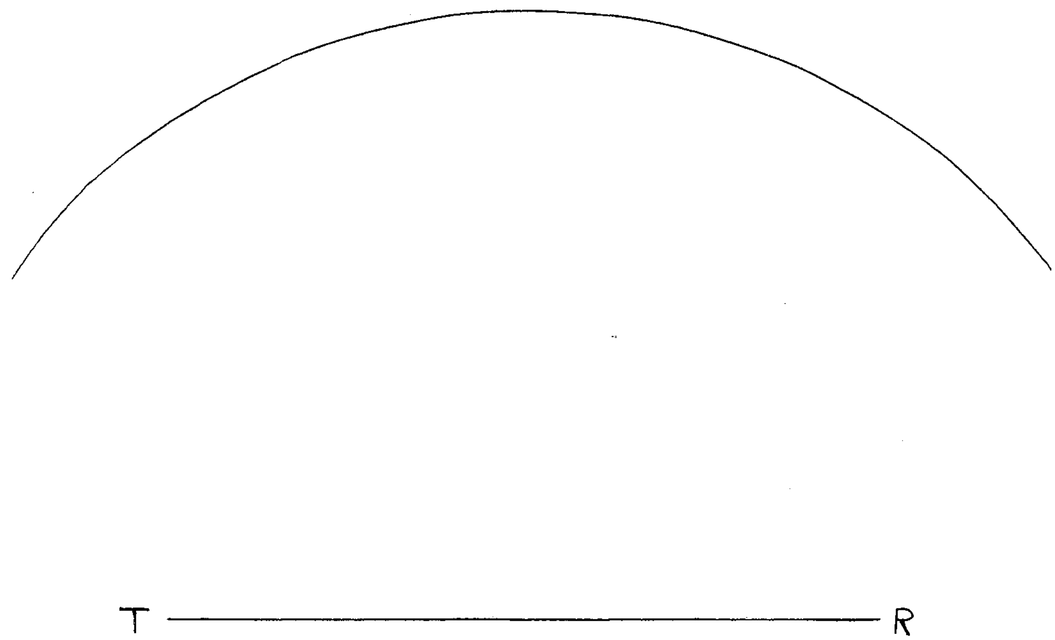

Figure 10. Points in space which have a common total range.

The problem of determining the elapsed time of the received wave since transmission now will be given consideration. A frequency modulated system could be used; that is, the transmission is frequency modulated continuously and periodically over a specified band. The frequency at the instant of maximum reception would be measured and a comparison made as to the time when the measured frequency actually was transmitted. The elapsed time between when the frequency was transmitted and received can be converted into total range.

Another method of total range determination would be by the use of markers or pips superimposed on the transmitted signal as an amplitude modulation component. When a signal was received, the time differential between the maximum received signal and the nearest marker would be determined. The time elapsed between when the marker was transmitted and received also could be determined. Using these two bits of information, the total range could be calculated.

There are two major shortcomings to both of these methods. They require very sophisticated transmitting and receiving equipment. In addition, a very reliable instantaneous communication link must be established between the receiver and transmitter.

Elevation Angle Measurement

As will be shown later, one of the most important pieces of information in the passive detection system is the elevation angle of the signal arriving at the receiver. This information could be obtained by the use of highly directive movable antennae; however, the signal duration is of such a relatively short time duration as to make this method impractical.

The method employed to measure the elevation angle will be by the use of an interferometer (16). The interferometer outlined here will be the simple two antenna type. There are quite a number of modified interferometers which have certain advantages over the simple type; however, only the simple type will be considered here. An interferometer consists of two antennae spaced a calibrated distance apart. The two antennae feed into a receiver where the phase difference between the two received signals is measured. Consider the diagram in Figure 11.

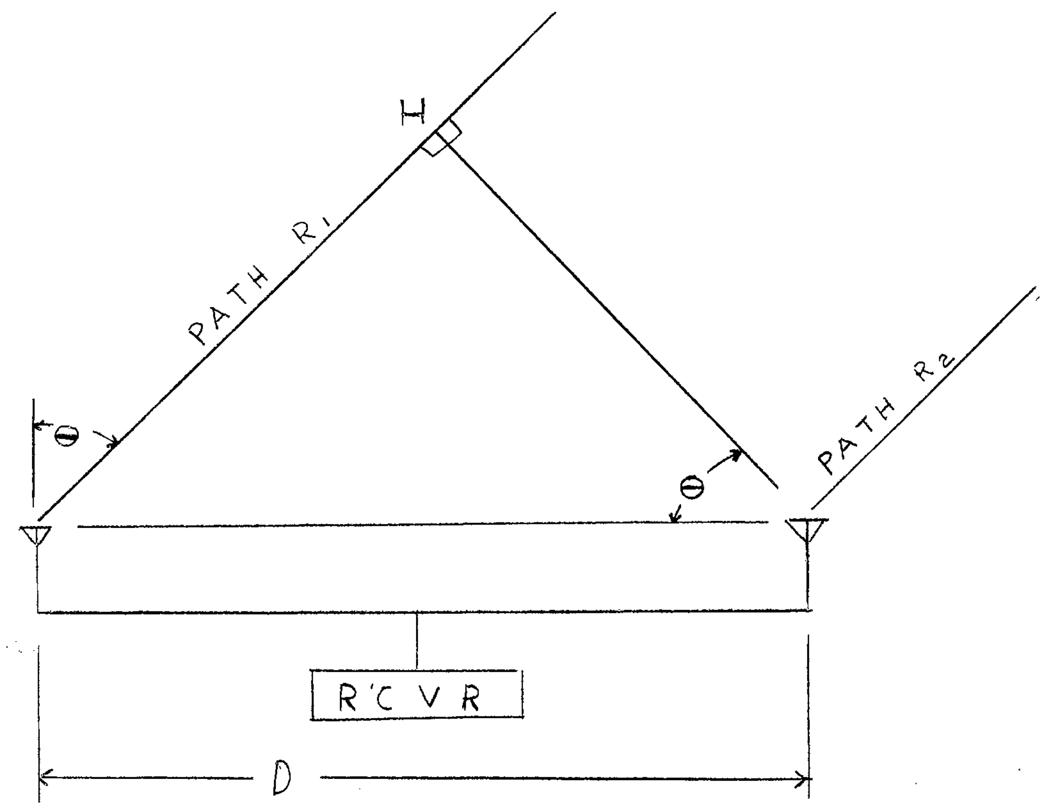

Figure 11. Interferometer principles.

The two signals come from the same distance source and may be considered to be parallel. A short study of the diagram will reveal that as the angle θ changes, the difference in length between the two paths changes and, of course, the phase angle difference varies correspondingly. The difference in length between the two paths is GH = $(R_1 - R_2)$ $= D \sin \theta$. The difference in phase angle between the two signals is $\phi = \frac{2\pi}{\lambda}(R_1 - R_2) = \frac{2\pi}{\lambda} D \sin \theta$ where λ is the wavelength of the frequency being used. In general, the greatest sensitivity occurs when the angle θ approaches 90 degrees. The separation of the two antennae need only be in the order of a few hundred feet so that no particularly difficult transmission line problems are encountered.

For a practical system the baseline of the two antennae would be in line with the transmission path from the transmitter. The equation of the system would be $\sin \theta = \frac{\lambda \phi}{2\pi D}$. The solution of this simple equation would give the elevation angle of arrival of the forward-scatter signal from the ionospheric object. The true utility of this method of elevation angle measurement lies in the facts that no extraordinary type of transmission is required, the receiving antennae are fixed in position, and a transmitter designed and perhaps used for other services could be utilized in the system. A further advantage is that no direct instantaneous communication link need be established between receiver and transmitter.

Position Determination

The determination of a detected object's position in space is, of course, essential information. Two methods are available to determine the position in space of an object passively detected by forward-scatter propagation. By the measurement of total range, one determines an elliptical line on which the object must be, while by the interferometer method one can determine the elevation angle of the received signal. In order to utilize either method, two receiving stations in line with the transmitter but separated by a fairly substantial distance must be employed. Only the method utilizing the interferometer will be discussed here, as it is the simpler of the two and does not require complicated modulation at the transmitter or an instantaneous communication link between the transmitter and receiver.

Two interferometer equipped receivers are located on a common baseline from the transmitter. When an ionospheric object crosses the line it will cause reception at both receivers. The angle of reception at each receiver could be determined by the use of the interferometer. The essential features of this method are shown in Figure 12.

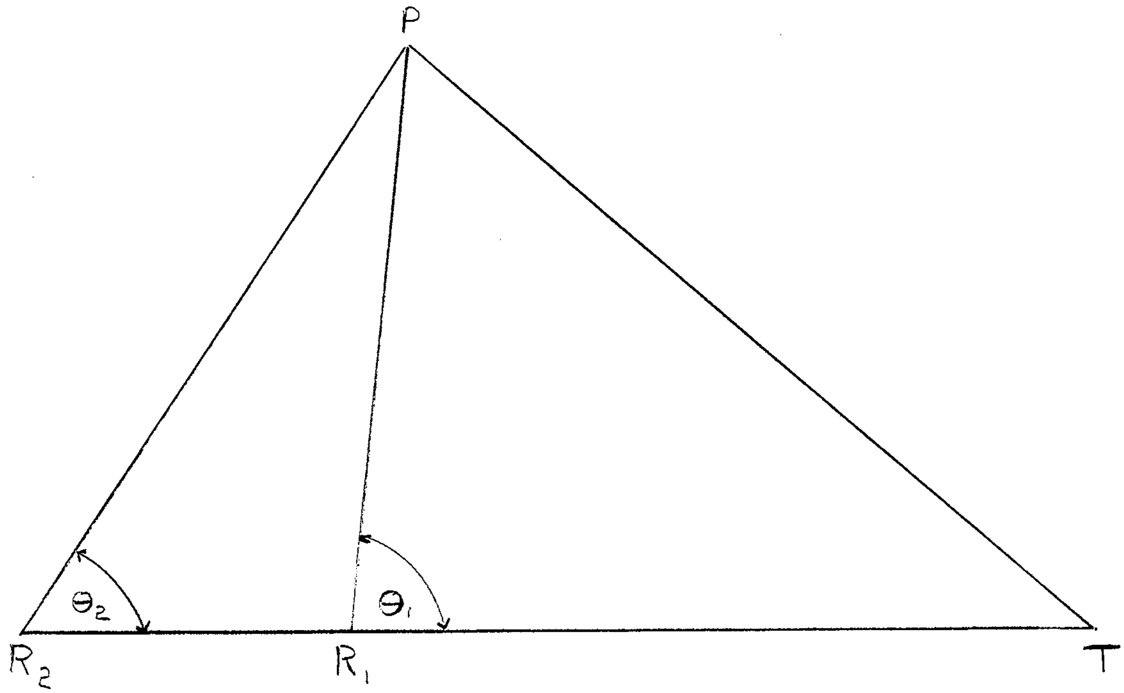

Figure 12. Position determination by angular measurement.

By setting up a coordinate system with perhaps the transmitter at the origin, the location of the object in reference to the transmitter (for example) in both range and altitude could be readily determined. The system could be employed with more than two receiving stations which would increase the accuracy of the fix obtained. The solution of the problem is not difficult; however, it does necessitate a number of calculations involving a fair amount of trigonometry. Of course, all possible solutions could be worked out in advance and either filed for ready reference, presented in the form of a graph, or stored in a computer. The exact time when the object crossed the baseline is also readily determinable by an inspection of the received signal. In this manner the exact position of an ionospheric object at a precise time could be determined.

Receiving Systems

Unlike the transmitting system, which would be fairly routine, the receiving system necessarily would contain a number of features which are not too common in normal receiving installations. The writer shall enumerate the unique features and also later show typical circuits for obtaining these features.

1. A means of measuring the difference in phase angle between the two antennae of the interferometer is essential to elevation angle measurement.
2. Since ionospheric objects should return larger signal amplitudes than meteor trails or noise, a means by which the receiver may automatically discriminate between the two different amplitudes is necessary.
3. The time duration of signals received from ionospheric objects should be longer than those received from meteor trails or noise, and, therefore, the receiver should be able to differentiate between signals on the basis of time duration.

It should be pointed out that, if the received signal is connected to an oscillograph, an operator could discern object reflections from other received signals without the necessity for the circuits outlined in two and three. However, in order to make the system automatic, the circuits of two and three are necessary.

There are a great number of different ways of measuring the phase difference between the two signals in an interferometer setup. Only one of the basic methods will be considered here (17). The circuit used in this method has a great deal of similarity to a frequency modulated receiver's discriminator. The two signals are hetrodyned until they are below 100 kilocycles. The two signals then are applied to the illustrated circuit in Figure 13 as inputs e_1 and e_2. Assume that

$$e_1 = E_s \sin \omega t$$

and

$$e_2 = E_s \sin (\omega t + \theta) = E_s (\sin \omega t \cos \theta + \cos \omega t \sin \theta)$$

The circuit is essentially two half-wave filtered rectifiers connected with output voltages in series opposition between points a and b. The upper rectified voltage E_{oa} is nearly the peak value of $e_2 - e_1 = E_s \left[\sin \omega t (\cos \theta - 1) + \cos \omega t \sin \theta\right]$. Likewise, E_{ob} is nearly the peak value of $-e_2 - e_1 = E_s \left[- \sin \omega t (\cos \theta + 1) - \cos \omega t \sin \theta\right]$. The output $E_{oa} - E_{ob}$, by the use of suitable circuits, can be calibrated directed in degrees or radians of phase difference.

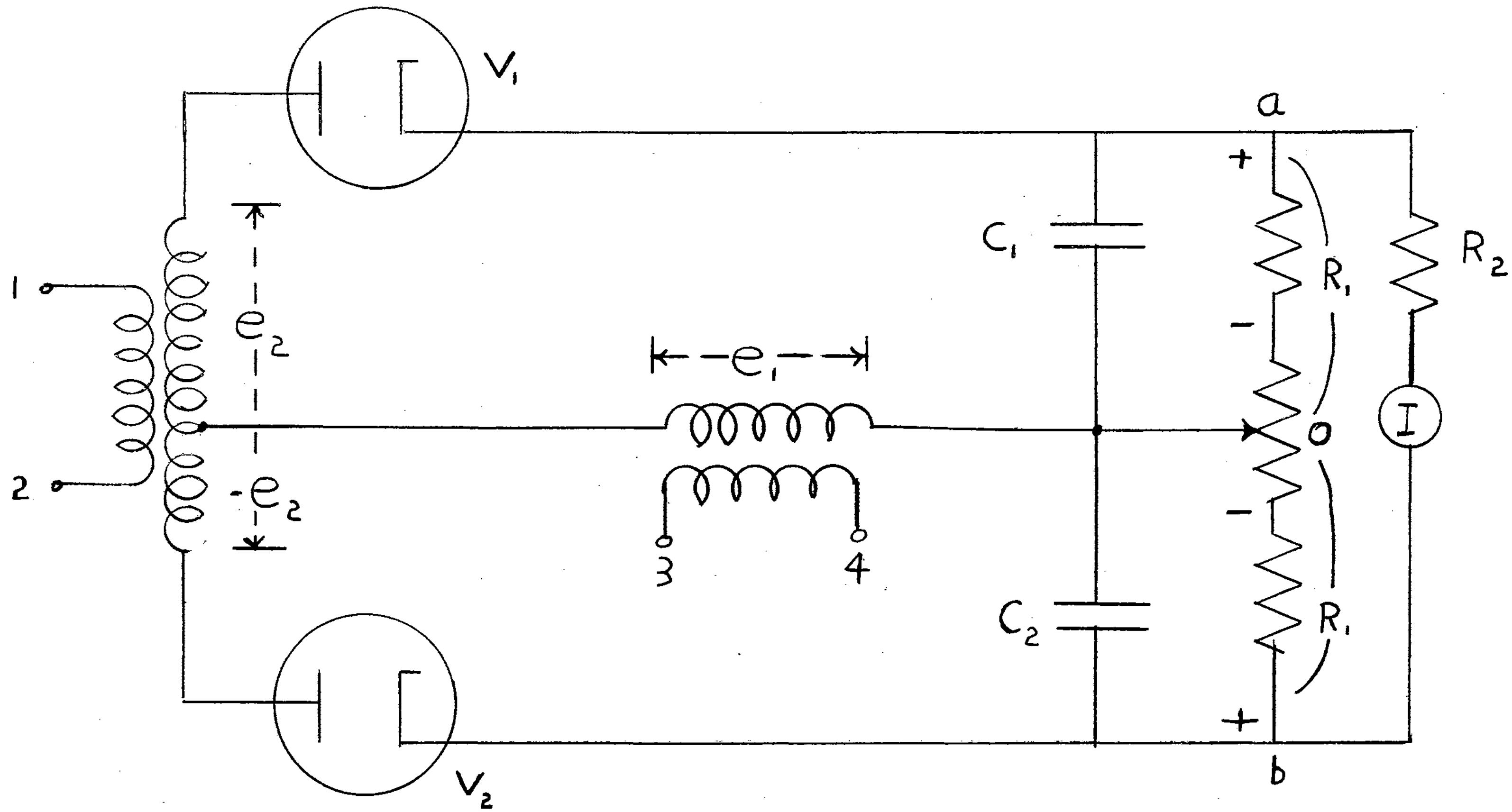

Figure 13. Electronic Phasemeter.

This method of phase measurement is characterized by the rectification of two a-c voltages. One of these voltages rises in amplitude as the measured phase angle changes in a particular direction while the other voltage falls. That is, the peak amplitude of $e_2 - e_1$ rises as $-e_2 - e_1$ drops.

The second feature, whereby the system passes signals of a certain predetermined amplitude and rejects all signals which do not possess the required amplitude, now will be discussed. The type of circuit is actually quite common. It is employed in television receivers to separate the large amplitude synchronizing pulses from the lower amplitude picture information. Perhaps the simplest device for effecting this type of discrimination is a simple triode vacuum tube. The signal is applied to the grid, and the bias is adjusted so that conduction within the vacuum tube will take place only for the larger amplitude signals.

The use of limiting circuits to perform the same function is also quite common. Consider the circuit in Figure 14. The battery or power supply sets the plate of the diode at a potential E above the ground or reference level. When low amplitude (above ground but below E) signals appear on the cathode of the diode, the plate is positive in respect to the cathode, and conduction takes place shunting all of the signal to ground. When the amplitude of the input signal is above E, the cathode is at a higher potential than the plate, and the tube does not conduct. Therefore, the large amplitude signals appear in the output. This type of limiter is known as a shunt limiter.

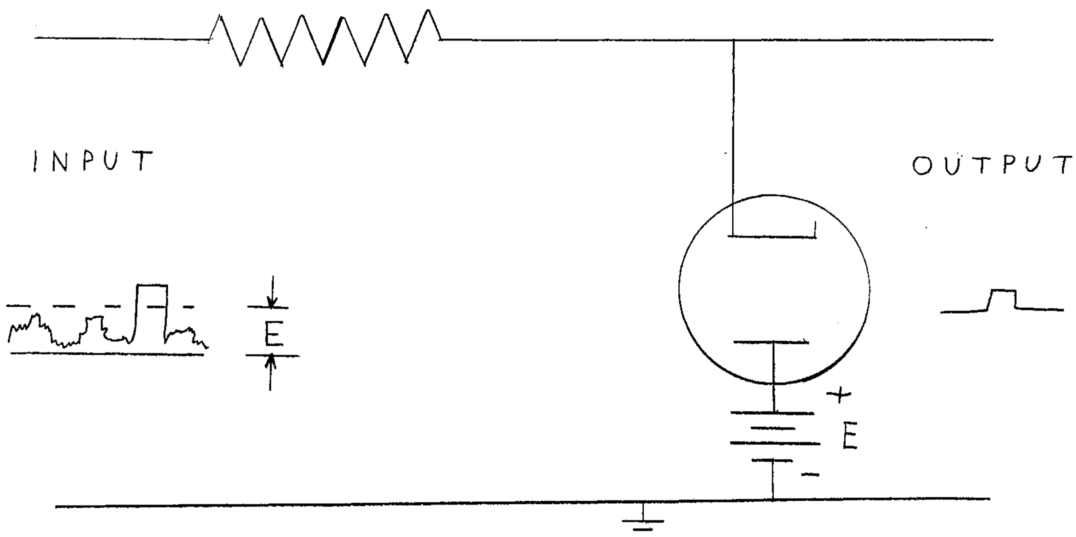

Figure 14. Shunt limiter application.

The same function also may be performed by a series limiter. Refer to the circuit diagram in Figure 15.

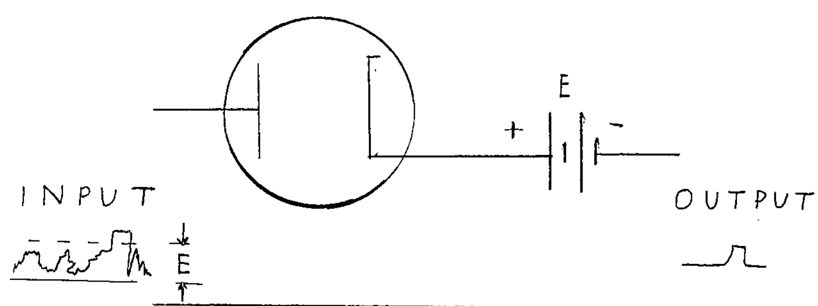

Figure 15. Series limiter application.

When the value of the input signal is below the value of E, conduction can not take place because the plate of the diode is negative in respect to the cathode, and no output appears. Of course, when the input signal is of higher amplitude than E, the plate is positive in respect to the cathode, conduction occurs, and the signals appear in the output.

The problem of discriminating between signals of different time duration also is encountered in television receivers. The solution is obtained usually by the use of some form of integrating circuit. There are a number of possible modifications of this type of circuit. Many of them employ operational amplifiers; however, only the basic concept will be considered here. Consider the basic RC circuit in Figure 16.

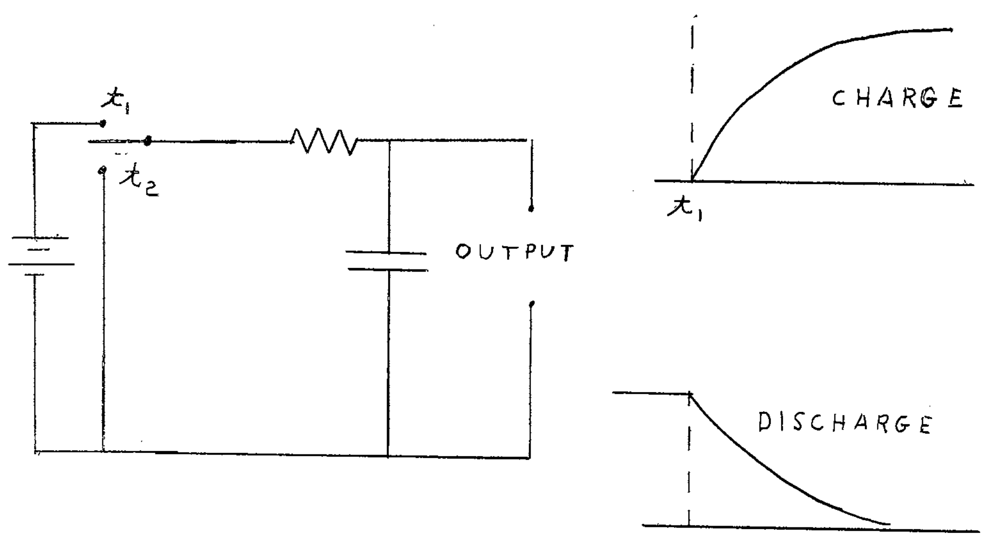

Figure 16. RC circuit charge and discharge.

At time t_1 voltage is applied to the circuit, and the capacitor will charge, as shown in the diagram. If the switch is left in this position for a sufficient period, the capacitor will become fully charged for all practical purposes. At time t_2 the battery is disconnected, and the circuit immediately is shorted through contact t_2. The capacitor will now discharge as shown. The rate at which the circuit is charged or discharged is directly dependent upon the RC product. A circuit of this type may be used to distinguish between different time duration signals by adjustment of the RC time constant. Refer to the circuit in Figure 17.

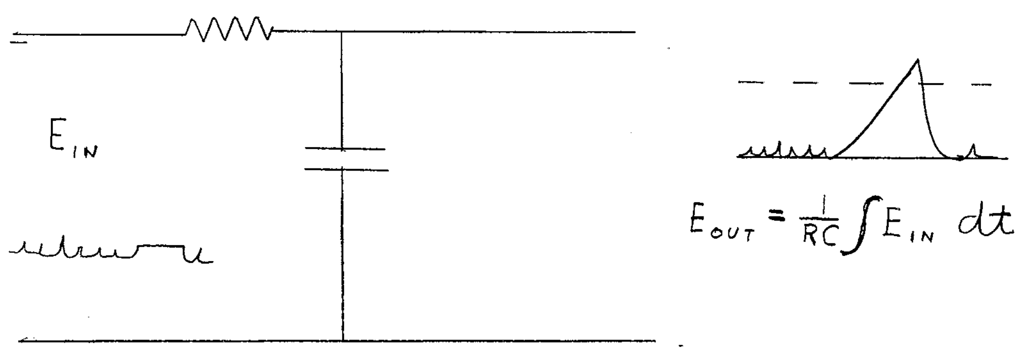

Figure 17. Integrating Circuit.

The short duration input signals have little effect upon the output, since the capacitor does not charge appreciably. When a long time duration signal occurs, the capacitor will assume a charge, and there will be a very definite output signal. Since the output is the integral of the input, the circuit is known as an integrating circuit. The amplitude of the output signal is proportional to the time duration of the input signal, and, of course, the large amplitude output signals can be separated from the small amplitude output signals.

The antenna systems associated with the receivers, of course, would be of the interferometer type. The antennae themselves probably would be yagi arrays which offer sufficient gain and directivity at the frequencies involved. Also, the yagi is relatively simple to design and to erect.

Tracking

Once an ionospheric object has been detected by its forward-scatter propagation and its position has been determined by the use of interferometers, this information should be applied to the tracking of the object's course. As has been pointed out previously, if immediate information is desired, the use of computers is mandatory. Basically, position and velocity can be provided in three ways. They are:

1. Measuring the position and differentiating the position data to obtain the velocity component.
2. Measuring rates and integrating them to obtain position.
3. Measuring the position and rate components.

To illustrate tracking using forward-scatter detection techniques, consider Figure 18.

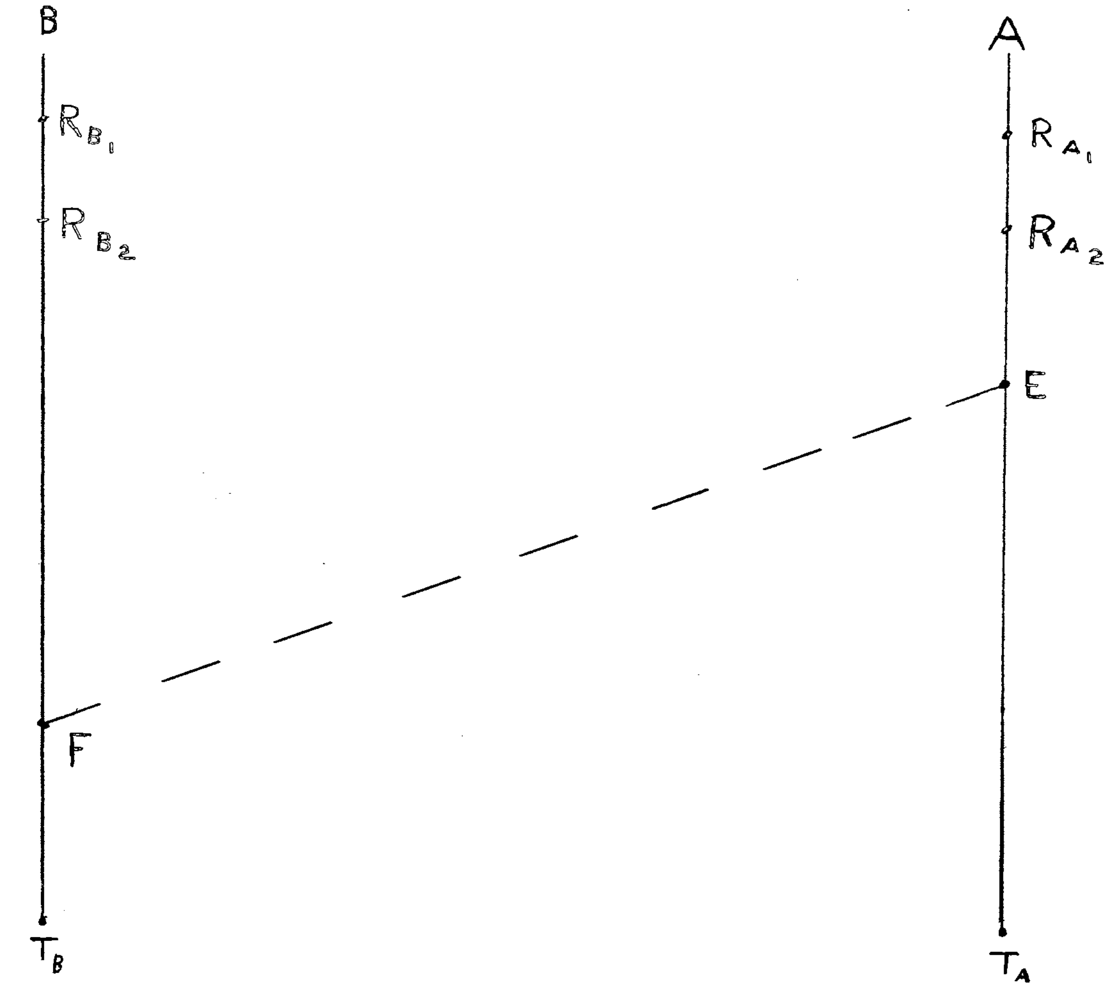

Figure 18. Tracking of ionospheric objects by using two baselines.

By the use of transmitter T_A and its associated receivers, it is determined that an ionospheric object crossed the baseline A at a precise time t at a definite altitude H and at the exact point E. In a similar manner using transmitter T_B and its associated receivers, it likewise is determined that an ionospheric object crossed baseline B at time t + x at an altitude $H \pm y$ and at the exact point F. From this information a great number of facts about the object (conjecturing that it was the same object at E and F) may be calculated. The exact distance from E to F (three dimensionally) may be computed. From the distance EF and the time x, the velocity of the object may be found. From a comparison of the altitude at the two baselines, it can be determined easily whether the object is ascending or descending and its rate of ascent or descent. Further, its future course could be projected from the information obtained.

The information received from a number of baseline crossings could be sent, of course, into a central tracking station where all of the information could be assembled and where the actual tracking of the objects would take place.

CHAPTER IV

APPLICATIONS AND ADVANTAGES

With all of the concepts of the system developed, the applications will be studied, and finally the advantages, mainly in comparison to existing or proposed systems for accomplishing the same function, will be examined.

System Uses

As pointed out in the introduction, the electronic reconnaissance of an unfriendly power's missile and satellite capability has become one of the pressing present requirements of national security. The installation of a passive detection system for ionospheric objects over the North and South American continents should detect effectively any satellites due to their globe circling orbits. The detection and tracking of long range missiles tested entirely within the boundaries of a large nation present a much more formidable problem.

It is not necessary to enumerate the great value of information concerning the number, frequency, range, altitude, and velocity of another nation's missile testings. The placing of both transmitting and receiving stations of a passive detection system for ionospheric objects around the periphery of a large nation should yield quite valuable information.

A still more subtle method of reconnaissance, however, presents itself. By a careful analysis radio transmitters within the country being reconnoitered could be selected. The transmitters would be chosen for proper location, correct frequency band, and continual service. With proper installation of receiving sites, the transmitters then could be used for the detection and tracking of ionospheric objects by forward-scatter propagation. This could be done unknown to those in control of the transmitters. This device should not only lower the cost of the system, but it would allow for a better coverage particularly at the lower ionospheric altitudes.

In addition to the reconnaissance and satellite detection uses, the system also could be employed for the detection and tracking of ballistic missiles. The system could be used to back up the Ballistic Missile Early Warning System. However, a still more important use for the system presents itself. With the ever increasing range of ballistic missiles, concern has been expressed that missiles may be fired over longer paths which would skirt present strong defensive systems. This threat of the use of flanking methods or sneak paths presents the need for an inexpensive, quickly erected system which could fill the gaps as they arise. It is believed that this system could fill just the requirements outlined.

System Advantages

The outlined system of passively detecting and tracking ionospheric objects by forward-scatter techniques has a number of very definite advantages over comparable systems which now will be enumerated as follows:

1. The system is quite impervious to jamming. This is due to the variance in signal path geometry dependent upon the object's position when crossing the baseline and to the relatively short signal bursts at unpredictable times which are characteristic of a system of this type.
2. The well spaced location of transmitters and receivers would not necessitate any great concentration of equipment at any one location. This, of course, would make the system quite invulnerable to enemy attack.
3. The cost of the system should be quite low when compared to high-powered radar equipment to perform the same function.
4. The engineering of the system at the relatively low frequencies involved should not present any real complex problems due to a great store of knowledge, experience, and highly perfected equipment and

components already available at the frequencies under consideration.

5. The time required to engineer a system of this type should be quite small compared to other systems. Further, the time required to erect and have the system operational should only be a fractional part of the time required for comparable systems.

6. Due to the relatively simple engineering required by the system, its reliability should quite exceed that of a system which would require a preponderance of newly developed components.

CHAPTER V

SUMMARY AND CONCLUSIONS

The concept of the system for the passive detection of ionospheric objects is now complete. The important basic findings are enumerated as follows:

1. It will utilize the forward-scatter from the ionized trail left by the object in its travel.
2. Directional transmitting equipment should be utilized except under unusual conditions when omni-directional transmitters would be employed.
3. The receiving stations would employ interferometers which would measure the elevation angle of the received signal.
4. By utilizing two or more isolated receiving stations, the exact point of the object in its travel may be pin-pointed by the use of the elevation angles.
5. With the aid of automatic circuits and computers, the actual tracking of the objects could be performed from position information.
6. The uses of the system are for the passive detection and tracking of missiles and satellites.

7. The simplicity of the system would assure its comparative inexpensiveness, reliability, ease of manufacture, and simplified maintenance and erection.
8. It should have a high immunity to jamming.
9. It should be a comparatively simple matter to construct models and graphs of the ionospheric area which would be under surveillance by the system.

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