

PROJECT VANGUARD REPORT NO. 21
Minitrack Report No. 2
The Mark II Minitrack System

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NAVAL RESEARCH LABORATORY
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ABSTRACT

During the International Geophysical Year an artificial earth satellite containing a 108-Mc transmitter is to be launched and placed in an orbit around the earth. Although the Department of Defense is building and installing a number of Prime Minitrack stations - installations to detect and plot the course of the satellite and to record various types of scientific data - a Mark II Minitrack system, based on the interferometer principle in like manner to the primary system, has been developed, and this will permit amateur volunteer groups to spot and measure the track of the in-flight satellite. This latter system, which may be built and installed by amateur groups for a nominal cost, consists in its simplest form of two Yagi antennas on a single baseline from 20 to 500 feet long, a tee junction at the midpoint, a converter to shift the 108-Mc satellite frequency to one that could be amplified by a standard communications receiver, and an "S" meter to be used as an indicator of satellite transit. In this simple version the system will indicate passage of the satellite but would provide no lasting or accurate record of scientific value.

By adding improvements in the system, a highly precise installation can be built that will yield data of interest to Project Vanguard personnel at the Naval Research Laboratory where orbit computation of the satellite is to be conducted. Some of these improvements consist of a hybrid junction rather than a tee junction in the transmission line, a graphical or magnetic tape recording in place of the "S" meter, a precise time signal fed to the record, a baseline of 1000 feet between antennas, high quality-transmission lines and amplifier equipment, antenna systems installed with high precision, and multiple antenna-baseline systems to provide an increased quantity of geodetic information.

Data read and recorded by the precision Mark II systems may be transmitted to the Vanguard Computing Center in Washington, D. C., where it can serve as important computational material to study the flight and characteristics of the satellite and can also add to the store of scientific knowledge desired for the IGY objectives.

This document presents all the aspects of the design, construction, and calibration of the Mark II system for the serious-minded amateur desiring to carry out radio observations of the satellite.

PROBLEM STATUS

This is an interim report; work on the problem is continuing.

AUTHORIZATION

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MINITRACK REPORT NO. 2
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INTRODUCTION

During the International Geophysical Year an artificial earth satellite containing a 108-Mc transmitter is to be launched and placed in an orbit around the earth. The Department of Defense is building and installing a number of Prime Minitrack stations at strategic points on the earth to detect and determine the coordinates of the satellite and to record various types of scientific data which will be telemetered from it. These Minitrack stations are complex installations containing specialized antenna systems and a large trailer of electronic equipment, requiring the services of some ten specially trained electronics personnel for proper operations and service.

Inasmuch as radio and telemetry signals coming from the satellite may also be received by relatively simple "amateur type" stations, the Naval Research Laboratory has devised the Mark II Minitrack — a comparatively inexpensive system which may be built and installed using materials and supplies within reach of many serious amateur groups. This system, based on the interferometer principle in like manner to the Prime Minitrack system, may actually be built in quite simplified form to indicate merely the passage of the satellite or it may be built in somewhat more complex form to record and measure the flight of the satellite.

The Mark II Minitrack Satellite Observation Program represents a joint NRL-ARRL Program designed to aid interested volunteer groups wishing to track the earth satellite. It is felt that two types of groups will be interested. The first type will want to observe satellite transits only out of curiosity. For this group a very simple system is described. The second group will wish to track the satellite and record useful data. It is for this group that this document is primarily intended.

A question often asked is "Why, if optical observations can be made more accurately than radio measurements at this (108 Mc) frequency, are radio observations needed?" The answer is that optical observations will be rare and dependent on the time, the weather, and the range to the satellite, whereas radio observations can be made each time the satellite passes the station.

The exact position of the satellite will depend on the influence of gravity among other things. Since the gravitational field varies because of anomalies in the shape and mass of the earth, the satellite will not describe a perfectly smooth path in space; rather, its path could be described as "noisy." Under these conditions a great many moderately accurate observations may give significantly more orbital data than a very few highly precise observations.

The precision needed at any one station really depends upon the proximity of this station to other stations. Since there are three Prime Minitrack stations in the United States, it is felt that Mark II stations here should have the same order of accuracy (20 seconds of arc). The added stations can further increase the amount of useful data obtained by having their baselines oriented at a considerable angle to the East-West line, since the Prime Minitrack system gives its best data on meridian crossing.

Other stations, far removed from the Prime Minitrack system, can have poorer accuracy and still contribute significant data to the program. It is difficult to assess the required accuracy, but certainly stations having an accuracy of 1 minute of arc will obtain useful data when isolated from more accurate stations by 1000 miles or so.

THE SATELLITE TRANSMITTER

Four groups of satellites are planned, each group being designed for special experiments and therefore requiring its own specialized transmitting equipment. The Group I satellite, measuring solar Lyman-alpha radiation and environmental parameters, will transmit telemetry signals continuously through an 80-milliwatt unit (Fig. 1). The information will appear as bursts of audio modulation on the carrier frequency, and modulation will be confined within a band from 2.6 to 15 Kc.

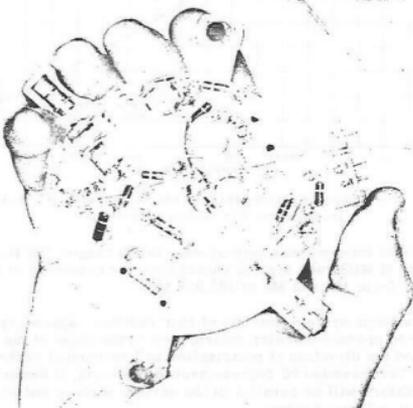


Fig. 1 - Modulated 80-milliwatt Minitrack transmitter

The Group II satellite, measuring meteor erosion of the skin and cosmic ray intensity, will have both continuous telemetering and command telemetering at a power level of about 50 milliwatts.

The Group III satellite, measuring the geomagnetic field, will have two transmitters: a cw tracking transmitter operating at 108 Mc and a command turn-on transmitter operating at 108.03 Mc.

The Group IV satellite will perform one of two currently proposed experiments. In one case this satellite will be similar to Group II, and in the other case it will have a command transmitter, capable of emitting about 1 watt, in addition to the tracking transmitter.

The tracking transmitters for Groups I and II will be crystal-controlled at 108 Mc within about 2 Kc. The Group III satellite will be crystal-controlled but the crystal will be cut to have a definite frequency-temperature characteristic. The frequency can vary in the range 108 Mc \pm 5 Kc, but should vary only slowly. A typical frequency-temperature curve is shown in Fig. 2.

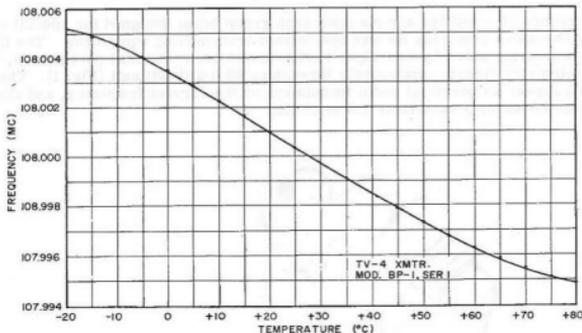


Fig. 2 - Frequency-temperature characteristic of tracking transmitter for Group III satellite

Since the satellite transmitters may operate in the ranges 108 Mc \pm 5 Kc and 108.03 Mc \pm 5 Kc, the Mark II Minitrack system should have the capability of tuning to receive signals over a band from 107.995 Mc to 108.035 Mc.

The satellite antenna system consists of four radiators spaced equally around a great circle on a sphere to produce circular polarization in the plane of the radiators. When the satellite is launched the direction of polarization will be normal to the direction of travel. When the satellite has travelled 90 degrees around the earth, if disturbing torques are negligible, the radiators will be parallel to the earth's surface and station below would receive a circularly polarized signal.

In areas where the polarization of the signal from the satellite is linear, a linearly polarized ground antenna will receive a signal that will vary as a function of the degree of polarization. As the satellite passes through the antenna pattern, the received signal strength will vary approximately sinusoidally because the Faraday rotation is dependent on the angle between the radio path and the ionosphere. The frequency of the variation can be used to measure the total ionization content in the radio path, and this information can be used to correct the measured satellite position for ionospheric refraction.

THE MINITRACK SYSTEMS

Two tracking systems, known as "Minitrack," have been designed for this project. The more complicated "Prime Minitrack" will be used at a number of stations in the Western Hemisphere and Australia to obtain basic orbital data. This system is nonambiguous and will provide satellite ephemerides so that after the first few satellite orbits the future path of the satellite over the earth's surface can be predicted.

Since the Prime Minitrack system requires a large installation, a simpler tracking system called the "Mark II Minitrack" has been devised. While this system in its simplest form will give ambiguous data, the ambiguities can be resolved at the Vanguard Computing Center in Washington, D. C., by the use of data from the Prime Minitrack stations. Thus it will be possible to determine the position of the satellite over any ground point as accurately with the Mark II system as with the Prime Minitrack system.

The Mark II system, like the Prime system, is based on the interferometer principle. This principle is well known to radio astronomers and to students of optics but may not be familiar to all radio amateurs, so it will be described in some detail.

The interferometer principle as applied to the Mark II Minitrack system is illustrated in Fig. 3. Here two antenna arrays are separated by many wavelengths and are connected together by transmission lines. The mid-point of the transmission lines is connected to a hybrid tee and to a receiver (or receivers) which actuates a meter or recorder.

The geometry of the situation is shown in Fig. 4. It is assumed that the satellite S is a distance which is great compared to the separation between antennas. If we make the distance $SP = SA_1$, then A_1P will be approximately perpendicular to SA_2 , since the angle A_1SP is small. The phase difference that will be read will be proportional to the distance PA_2 and $\cos \alpha$ will equal PA_2/A_1A_2 .

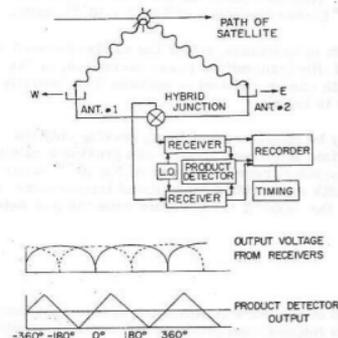


Fig. 3 - Radio interferometer principle as applied to Mark II Minitrack system

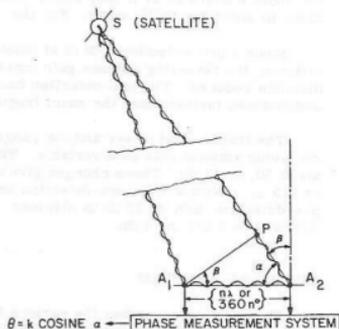


Fig. 4 - Geometry of Minitrack phase-measurement angle tracking system

Now assume that the distance PA_2 is an integral number of wavelengths. Then the voltages from the two antennas, arriving at the hybrid in Fig. 3., will be in phase and the meter will record a maximum output. If the distance PA_2 is an odd number of half-wavelengths the voltages from the two antennas will be out of phase and will cancel at the hybrid in which case the output will be at a minimum.

As the satellite travels across the antenna pattern the distance PA_2 will vary so that the receiver output will vary from a maximum to a minimum nearly sinusoidally. The number of maxima and minima which occur during a transit can be increased by increasing the baseline distance A_1A_2 . For a 100-wavelength baseline a minimum will occur for

approximately each angular half-degree travelled. For Example, if the satellite is at an altitude 200 miles and is travelling at 25,000 feet per second, null will occur about three times per second.

The antenna and receiver system needed will depend on the signal strength received from the satellite, on the received signal-to-noise ratio required for the system, and on the noise in the system.

Assuming a transmitted power of 10 milliwatts, a transmitter antenna gain of 0.5 (referred to isotropic), a receiving antenna gain of unity, a wavelength of nine feet, and range of 1000 miles (5×10^6 feet), we can compute a theoretical signal strength from the following well-known formula:

$$P_r = \frac{P_t G_r G_t \lambda^2}{(4 \pi R)^2}$$

$$= \frac{(0.01) (1) (0.5) (81)}{16\pi^2 (25) 10^{12}} = 10^{-16} \text{ watts.}$$

The noise power in a perfect receiver at 300°K is about 4×10^{-21} watts/cycle or 204 dBW/cycle. A noise figure of 4 db and a pre-detection bandwidth of 10 Kc gives the noise as 160 dBW or 10^{-18} watts. The temperature of the sky at 100 Mc is perhaps 500°K , and for about 2 hours in 24 it may reach 5000°K . This increases the noise (for the 500°K case) to about 2×10^{-16} watts. For the 5000°K case the noise will be 2×10^{-15} watts.

Since a pre-detection S/N of at least 10 db is desirable, either the bandwidth must be reduced, the receiving antenna gain increased, the transmitted power increased, or the distance reduced. The pre-detection bandwidth can be reduced to perhaps 5 Kc initially and reduced further when the exact frequency is known.

The transmitted power and the range may be considered as fixed, leaving only the receiving antenna gain as a variable. The Prime Minitrack antenna can provide a gain of about 50, or 17 db. These changes give a theoretical received power of 5×10^{-15} watts or $0.5 \mu\text{V}$. With a 5-Kc pre-detection bandwidth and a 500°K background temperature, a pre-detection S/N of 13 db is obtained. For the 5000°K temperature case the pre-detection S/N will be 2.5:1, or 4 db.

THE MARK II SYSTEM

This section describes the various forms of the Mark II Minitrack system that can be built. One must select that unit which fits his finances and produces his desired results. The components required for construction of these systems — antennas, rf transmission lines, hybrid junctions, receivers, and preamplifiers, phase detectors, recorders, and timing units — will be described in greater detail in later sections.

The Mark II Minitrack system in its simplest form is shown in Fig. 5. It utilizes only two Yagi antennas on a single baseline from 20 to 500 feet long feeding a tee junction centrally located on the baseline. The output from this junction feeds a converter to shift the 108.0-Mc satellite frequency to a frequency that could be amplified by a standard communications receiver. The "S" meter on the receiver would probably suffice for an indication of satellite transit.

Such a system provides a meter indication of the presence and passage of the satellite, but because no accurate recorded correlation of the data is obtained with respect to time, these data are of little scientific value except in the improbable event that the satellite had

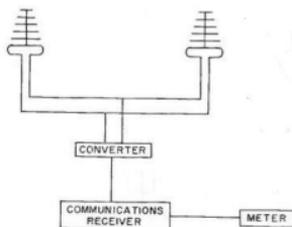


Fig. 5 - Simplest form of Mark II Minitrack system

the placement of these lines to afford temperature equalization, and in making their lengths identical. (6) A low-noise preamplifier can be included in the converter unit to increase the system sensitivity. (7) The antennas can be located precisely and assembled carefully to provide a baseline with an accurately known mid-point. (8) Additional baselines, requiring additional electronics and recording, can be added. While East-West baselines can give valuable data, other baselines at, say 60 degrees to the East-West line can give information even more valuable. The most accurate Prime Minitrack data are taken on the East-West baseline transit. For geodetic reasons, measurements on other baselines are very desirable.

A system embodying all of these modifications is shown in block diagram form in Fig. 6. This system, utilizing 1000-foot baselines, provides a time indication of satellite position about every 1/4 degree in the East-West direction. The output data consist of (1) two detected output voltages which carry the angular position data, (2) two agc voltages, and (3) recorded time. If the antenna field for this system is established with sufficient precision, these data may be considered for use as an input to the Vanguard orbital computer to aid in determining the orbit.

This system is the most complete that is suggested for construction by amateur or university groups. There is, however, a similar but somewhat more complicated version of the Mark II system that has been constructed and tested by the Naval Research Laboratory for use by the Department of the Army. This system utilizes the standard Mark II hybrid junction conversion from phase angle to amplitude, but utilizes a dual-channel receiver with common local oscillators feeding a phase-sensitive detector to improve the system signal-to-noise ratio. This system will be described in detail in a forthcoming Naval Research Laboratory report.

The Baseline

The baseline is required to separate the antennas so that rapid changes in output phase will be obtained as the satellite passes the station. The longer the baseline the faster this phase will change and, all other things being equal, the more accurate the measurement that can be made. As the baseline becomes long, however, the readings become more ambiguous and the transmission line loss becomes important.

For the standard Mark II Minitrack system it is desirable to have a baseline of the order of 500 to 1000 feet long. Baselines shorter than this can be used, but with reduced accuracy. Baselines longer than 1000 feet may be used with low-loss transmission line.

been established in an orbit that was very different than planned and none of the other tracking stations had yet acquired it. To those who wish only to observe passage, this simple meter indication would be adequate.

To improve this system, a number of modifications can be made. (1) The Tee Junction can be replaced by a hybrid junction feeding two converter-receiver units, thereby doubling the amount of data obtained. (2) The output indication of phase data can be changed from a simple meter to a graphical or magnetic tape recording. (3) A source of time precise to 10 milliseconds or better can be included in the system to be recorded simultaneously with the phase data. (4) A longer baseline (from 500 to 1000 feet) can be used to provide a greater system angular resolution. (5) Special care can be taken in the quality of the rf transmission lines used, in

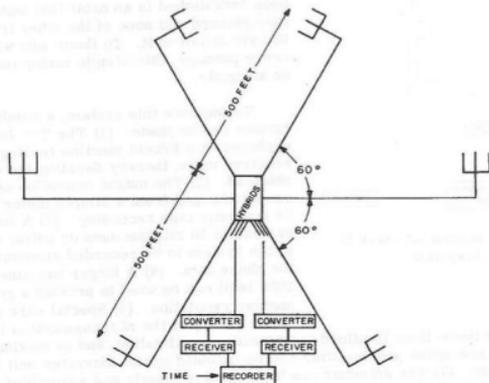


Fig. 6 - Advanced Mark II Minitrack system

The most satisfactory system uses both long and short baselines. The numerous interference lobes obtained with the long baselines are used to give accuracy and the fewer lobes obtained with the short baselines are used to identify the central lobe of the fine pattern. If no short baseline is used, the central lobe must be identified either by counting the total number of lobes or by using information (such as will be available from the ephemerides issued by the Vanguard Computing Center) concerning the position of the satellite at the time given. If the center lobe is to be found by counting the lobes, the antenna bandwidth should be made narrower the longer the baseline, so that the number of lobes will be constant. Ten lobes in an antenna pattern are about the maximum that can be counted and even with this number the possibility exists that the wrong lobe will be selected as the central lobe.

For the inclined equatorial orbit of the Vanguard satellite, an East-West baseline ordinarily will give the most rapid phase changes. Additional baselines should be placed to have an East-West component; for example they could be placed NE-SW or NW-SE. The additional baselines (Fig. 7) would give additional information and would require only additional antennas, transmission lines, and hybrid junctions. The same receivers could be used for the different baselines by switching receiver inputs. Except for the case of a near-zenith pass, there will be enough time to switch between baselines so that all of the information can be obtained from one receiver system.

The components required for a Mark II Minitrack interferometer baseline are the antennas, the transmission line, and the hybrid junction. Since the main cost of a satellite tracking system may be in these components and since the better stations will have at least two baselines, much work has gone into the making of components with the desired quality, yet which are reasonably inexpensive.

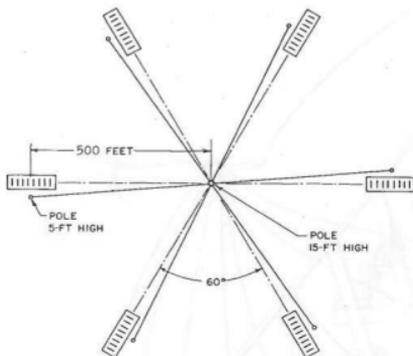


Fig. 7 - Mark II Minitrack antenna field

The Antennas

The most expensive single component is the antenna. It must meet many requirements: it must be unaffected by wind and weather and must provide high gain and yet have a broad beam in one direction so that a large number of satellite transits can be recorded.

To provide a gain of about 50, an eight-element array has been designed (Fig. 8). It can be extended to any larger number of dipoles, as desired. Extending the length of the antennas reduces the beamwidth only in the direction of the extension, so the gain can be increased as desired without changing the width of the broad antenna beam.

Another antenna requirement is that the gain of the sidelobes and backlobes be so low that direct and reflected signals will not interfere appreciably. This requirement, the most limiting from an antenna design point of view, can be analyzed approximately in the following manner. First, the system error that can be tolerated must be determined. A 100-wavelength baseline contains 36,000 electrical degrees. The measurement error resulting from a phase error in the antenna system is given by the following equation:

$$\sin(\text{error angle}) = \frac{\text{antenna phase error}}{\text{baseline in electrical degrees}}$$

The desired system accuracy of 20 seconds of arc is approximately equal to 0.0001 radian, so the tolerable antenna phase error is 3.6 degrees. If this is considered to be an RMS error, i.e., half of the time less than 3.6 degrees and half of the time more than 3.6 degrees, the maximum phase error will be $3.6^\circ \times \pi/2$, or 5.6 degrees. In each antenna the error can be as great as

$$\frac{5.6 \text{ deg}}{\sqrt{2}} = 4 \text{ deg.}$$

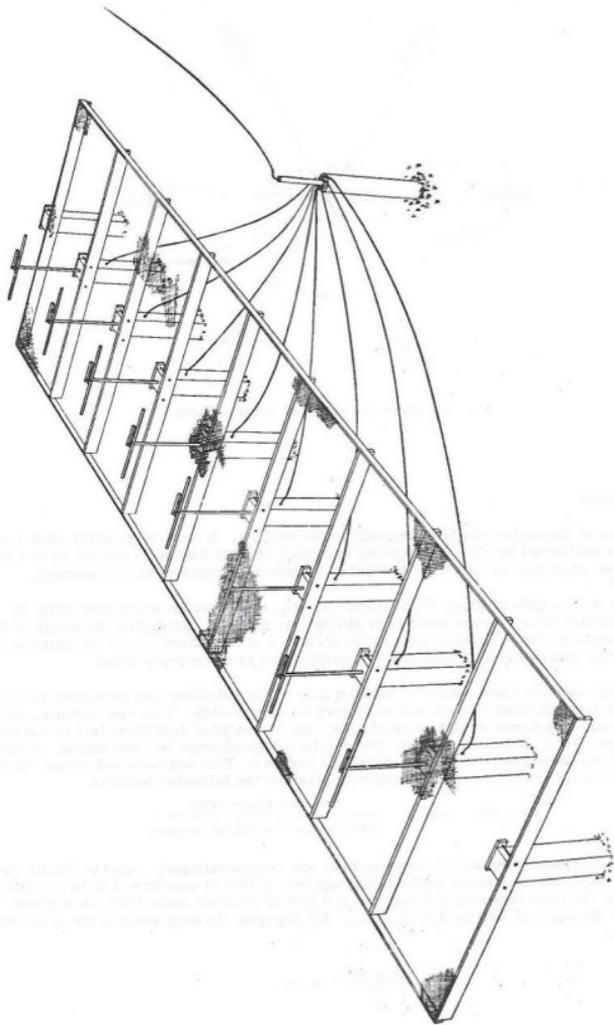


Fig. 8 - Mark II Minitrack eight-element broadside antenna array

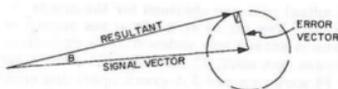


Fig. 9 - Diagram showing relationship of error vector to error in phase angle

The geometry of the problem is shown in Fig. 9. The error vector can have any phase with respect to the signal vector, so that angle B can have any value less than the maximum angle shown.

$$B = \arcsin \frac{\text{error vector}}{\text{signal vector}}$$

For small angles,

$$B = \frac{\text{error voltage}}{\text{signal voltage}}$$

For $B = 4^\circ$,

$$\frac{4}{57.3} = \frac{\text{error}}{\text{signal}} = 0.07 \text{ voltage ratio.}$$

The power ratio is 0.005 or 23 db.

Since one important part of the error signal is the signal reflected from the ground, the reflection coefficient of the ground is important. This coefficient may be as low as 0.35 for dry soil, about 0.5 for ordinary soil, and 0.96 for salt water. If the value of 0.5 is taken, the error signal is reduced by one half. The minimum ratio of sidelobe to main-lobe response can be as low as 17 db under these conditions.

Colinear Array

Two types of arrays have been investigated—the colinear and the broadside dipole arrays. At first glance the colinear array appeared to be nearly ideal. The H-plane pattern could be made broad and the elements placed a full wavelength apart, thus providing a narrow E-plane pattern with a minimum of elements. The full-wave spacing results in negligible mutual coupling between elements so that all elements can be individually matched before being placed in the array. Since the elements are polarized along the length of the array, the ground screen can be made of long wires.

The difficulty with the colinear array above the ground screen is that the theoretical H-plane pattern is realized only for an infinite ground screen.

The reason that the actual H-plane pattern differs from the theoretical is that the dipole has no directivity in this plane. The reason the signal is low along the ground screen is that the image dipole current interferes with the current from the real dipole. At low angles, with a limited ground screen, it may be impossible to see the image when the real dipole is visible. In this case a finite signal will appear along the ground screen.

The theoretical and actual patterns obtained for the dipole 39 inches above the ground screen are shown in Fig. 10. The signal strength at the screen is about 9 db below the peak value. When the ground screen was widened to an equivalent 32 feet, the resulting signal strength at the screen was about 15 db below the peak value. When the solid ground screen was replaced by #8 wires spaced 2 degrees apart and centered on the dipole, the resulting signal strength at the screen again was about 10 db below the peak value and the depth of the dip in the center was increased to 6 db.

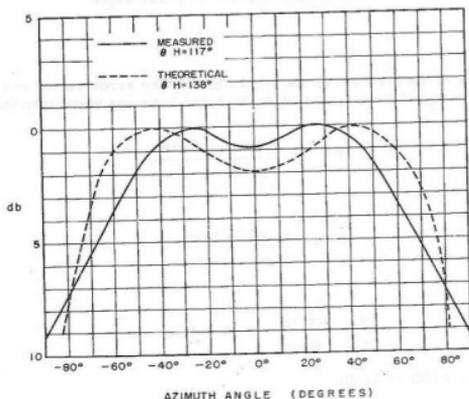


Fig. 10 - Theoretical and actual H-plane patterns for dipole 39 inches above solid ground screen

From this work it was apparent that with the colinear array it would be practically impossible to have a ground screen large enough to make the ground effects negligible. For this reason the broadside array was investigated.

Broadside Array

The broadside array has the advantage that the dipole elements have directivity in the plane perpendicular to the array, the E-plane; consequently a true null always appears in the plane of the ground screen, even when the ground screen is so small that ground effects are present. Ground effects can be inferred if the antenna patterns change when the size of the screen is increased. Figure 11 shows the patterns obtained from a 1080-Mc model with the equivalent screen widths shown and with the dipole-to-screen spacing held at a distance equivalent to 45 inches. From these patterns it is concluded that the minimum ground screen width is about 15 feet.

The patterns obtained for different radiator-to-screen spacings are shown in Fig. 12. These patterns were taken with a full-sized gamma-matched dipole above a chicken-wire screen 16 feet wide. From these patterns a spacing of about 44 inches appears nearly optimum, giving a beamwidth of 104 degrees.

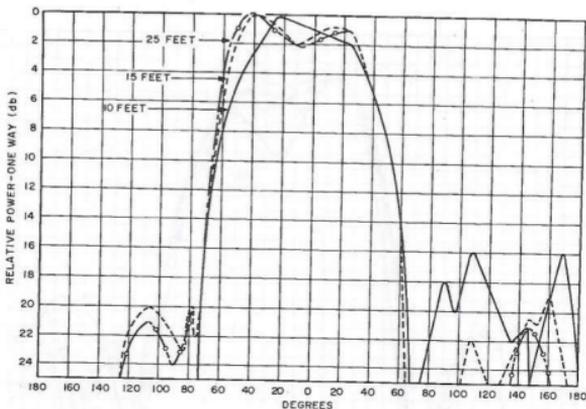


Fig. 11 - Patterns of 1080-Mc broadside array with dipoles 4.5 inches from screen, for three equivalent screen widths

For the broadside array the maximum element spacing is about $3\lambda/4$. The H-plane pattern obtained from a 1080-Mc model is shown in Fig. 13. Since all the elements are fed in phase with equal currents, it would be expected that the first sidelobe would be 13 db down from the main lobe. The 10-db lobe on one side can be attributed to errors in the phasing of the elements. At 90 degrees the response of this pattern is less than 25 db, so it can be expected that a broadside array will give a low response in the plane of the ground screen in all directions.

The Dipole Element

The dipole element should be rigid, easily tuned, and simple to manufacture. After several types of matching devices had been investigated the gamma-matched dipole was selected for further study because of its inherent simplicity and rigidity.

The simplest type of gamma-matched dipole (Figs. 14 and 15) is inherently unbalanced and would therefore be expected to have an E-plane squint as is shown by the pattern of Fig. 11; the direction of this squint is on the same side as the feed loop. Although unsymmetrical, the response at the ground screen is at least 19 db below the maximum response, so it is satisfactory from an interference standpoint.

More important than the squint would be currents on the vertical support rod; however, negative results were obtained on pattern measurements run to determine whether radiation existed due to support rod currents.

Construction of the dipole is quite simple. It consists of three pieces of standard galvanized pipe and a standard tee, modified as shown in Fig. 14. The only machining needed, apart from the drilling of holes, is that required to produce the flat on the tee; this can be done conveniently on a lathe or a mill, but can also be done with a file. The capacitor is

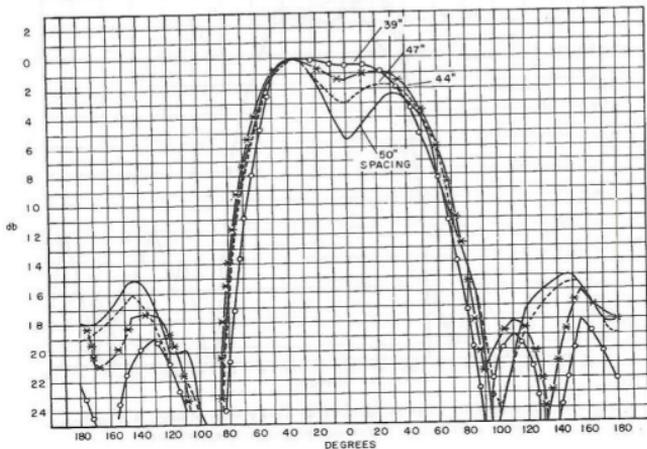


Fig. 12 - Patterns of broadside array for four radiator-to-screen spacings, taken with full-sized gamma-matched dipole above 16-ft wide screen

soldered to the jack terminal before the external tube is soldered to the cable jack. Either a tube of insulation or several turns of insulator tape can be placed around the capacitor to prevent its shorting to ground. If it is deemed necessary the entire metal tube can be filled with silicone grease. The lucite block insulator effectively centers the brass tubing. The top of the capacitor is sealed by means of the pipe cap threaded to the capacitor base and the pipe cap at the top of the nipple. The parts for this dipole element should cost less than \$7.00.

Probably the most rigid and simple means of supporting the dipole is by embedding it in a concrete pier as shown in Fig. 16. To permit threading the coaxial cable through the vertical tubing, an opening to the outside of the pier must be provided. This opening can be made in a number of ways. A greased block which can be removed when the concrete has set is one means. Another is a curved or angled tube which extends to or through the form boards. These form boards should be extended as shown in Fig. 16 to hold the radiating element. In this manner all the radiating elements can be made level and parallel. In addition the dipoles of the two antennas on a single baseline should lie in as straight a line as possible.

After the form boards are removed the ground screen can be built as shown in Fig. 17. The ground screen must fulfill one principal requirement—it must be sufficiently large to isolate the antenna from the conditions of the surrounding terrain.

Pattern measurements have indicated that the minimum screen width required is about 15 feet. A width of 16 feet has been selected because it is the nearest larger length that is a standard lumber size. The screen can be laid either parallel to the dipoles or perpendicular to them. If placed perpendicular to the radiators, the separate pieces of

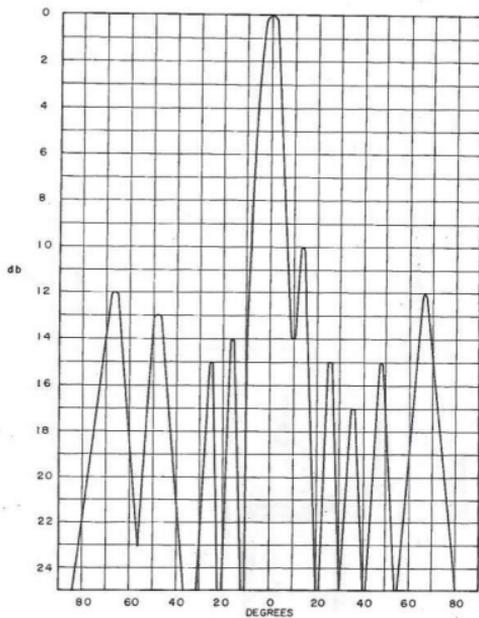


Fig. 13 - H-plane pattern of 1080-Mc broadside array

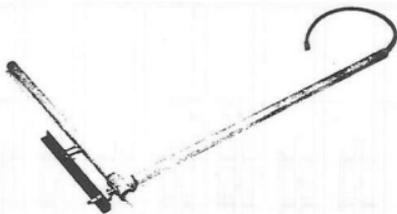


Fig. 15 - The completed dipole

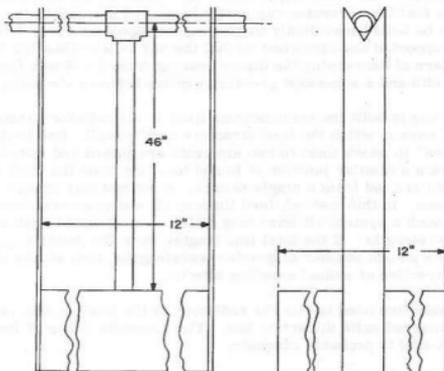


Fig. 16 - Temporary supports for embedding dipoles in concrete

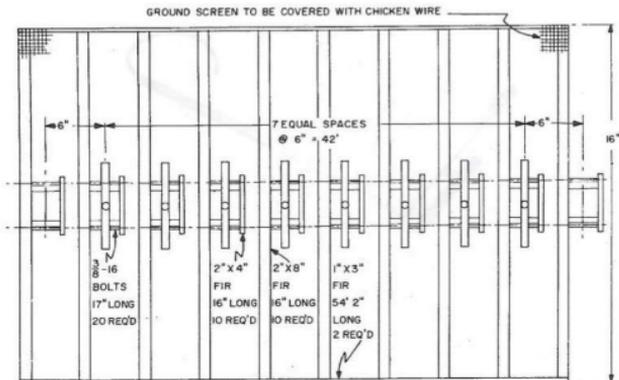


Fig. 17 - Ground screen

netting should be bonded by twisting and soldering or wiring together and soldering every few inches. To eliminate the soldering problem the radiators can be placed a standard wire width apart so that the screening can easily be placed parallel to the dipoles. Such a configuration can be built conveniently by placing the dipoles an even 6 feet apart. The screen should be supported and stretched so that the sag is less than $1/2$ inch. The effect on the antenna pattern of decreasing the dipole spacing from $3\lambda/4$ to 6 feet will be a slight increase in beamwidth and a somewhat greater coupling between elements.

Before the screen is built the transmission lines to all radiators should be installed. There are several ways in which the feed structure can be built. One is the common "corporate structure" in which lines to two elements are joined and matched impedance-wise, then a line from a similar junction is joined to a line from the first junction and so on until all elements are fed from a single source. A method that appears simpler is proposed for this antenna. In this method, feed lines to all elements originate at a single junction box. For such a system all lines may differ in electrical length only by exact multiples of full wavelengths. If the total line lengths from the junction to the antenna feed points are made an odd number of quarter-wavelengths, then all the antenna currents will be equal, irrespective of mutual coupling effects.

The transmission line used to join the radiators to the junction box can be RG-8/U, RG-9/U or metal covered solid dielectric line. The aluminum covered line is preferable for this use but RG-8/U is probably adequate.

Junction Box

The construction of a junction box for an eight-element array is shown in Fig. 18. For arrays with more elements, more feed points must be provided and the impedance of the quarter-wave matching transformer must be reduced.

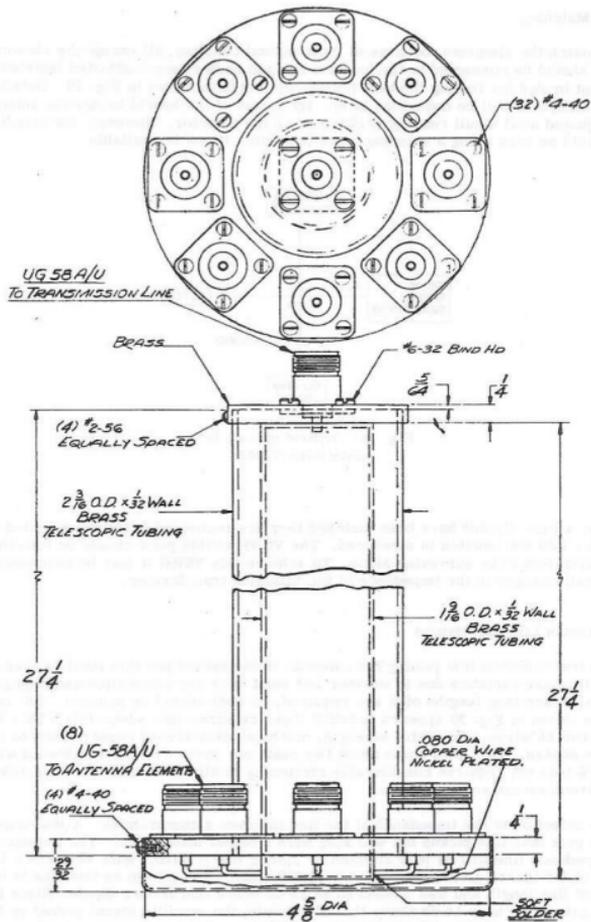


Fig. 18 - Junction box

Antenna Matching

To match the elements, because of their mutual coupling, all except the element to be matched should be connected to the junction box and each element adjusted individually. A convenient bridge for finding the best impedance match is shown in Fig. 19. Details on making the hybrid will be described later. By means of the hybrid bridge the antenna capacity is adjusted until a null reading is obtained on the detector. However, the standing-wave ratio should be read using a standing-wave indicator, if one is available.

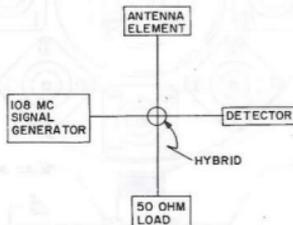


Fig. 19 - Hybrid circuit for minimizing VSWR

After all the dipoles have been matched they are connected to the junction and the impedance into the junction is measured. The VSWR at this point should be less than 1.1 if the calibration is by surveying alone. To achieve this VSWR it may be necessary to make small changes in the impedance of the matching transformer.

Transmission Line and Hybrid

The transmission line joining the antennas to the hybrid junction must be free of noticeable phase variation due to weather and must have low attenuation and negligible radiation. Since long lengths of it are required, its cost should be nominal. The open wire line shown in Fig. 20 appears to fulfill these requirements adequately. This line is made of two #8 wires. For extra strength, machine-straightened copper-covered steel wire was chosen. This wire costs about two cents per foot. The unstraightened wire costs about 10% less but requires considerable stretching to eliminate kinks; the stretching process is troublesome and dangerous.

The selection of the impedance of the line involves a compromise. A low-impedance line will give less line pickup but will also have a higher attenuation. The impedance of a high-impedance line will be less affected by motion due to wind. With #8 wires a line spacing of 1.8 inches gives an impedance of 400 ohms. The pickup on this line is independent of line length and was measured as 26 db below that from a dipole. Since the antenna gain is perhaps 14 db above that of a dipole, the satellite signal picked up by the line is negligible (-40 db) compared to the signal.

Although balanced transmission lines with balanced-line hybrids have been built for phase-comparison purposes, it is preferable to build the hybrid from coaxial line. The transmission line is matched to 50 ohms at both ends. A quarter-wave matching section

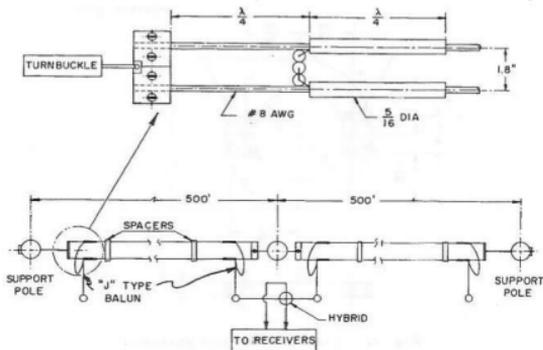


Fig. 20 - Open wire transmission line

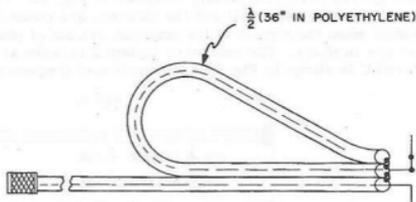


Fig. 21 - J-type balun

made up of two 5/16-inch quarter-wave capped tubes slipped over the wire as shown in Fig. 20 matches the line to 50 ohms. The J-type balun shown in Fig. 21 matches the 200 ohms balanced impedance to 50 ohms unbalanced. For best weatherproofing, the balun should be supported so that its loop extends above the transmission line.

The copper-covered steel wire will support itself for at least 500 feet. If a 1000-foot baseline is used, the two lengths of line should be made equal before installation. The spacing of the wires can be kept uniform by using spacers built as shown in Fig. 22. Spacers placed every 30 inches or so appear to keep the line spacing satisfactorily uniform.

It appears advantageous to terminate the transmission lines at the center of the baseline and to transform to unbalanced line before adding the signals in the hybrid. A termination pole at the center will in addition permit the use of several baselines all with the same center.

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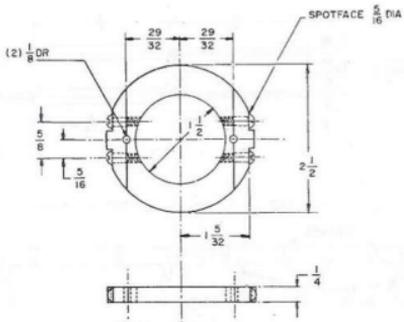


Fig. 22 - Transmission line spacers

The Hybrid

A hybrid that has proved to be satisfactory is shown in Fig. 23. The ring is made of 70-ohm cable (preferably double-shielded) and the antennas are connected to A and C. Then B has a null output when the signals at the antennas are out of phase, and D has a null output when they are in phase. The measured isolation between arms B and D with matched loads on A and C is shown in Fig. 24 as a function of frequency.

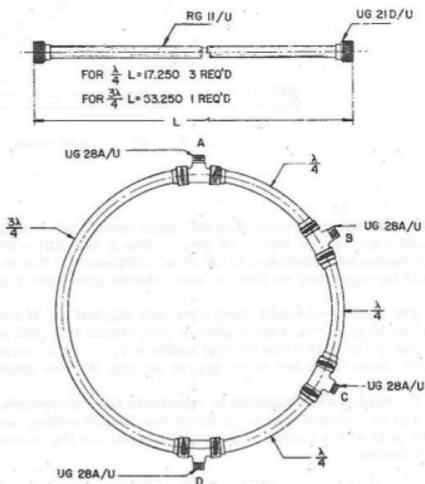


Fig. 23 - Hybrid junction

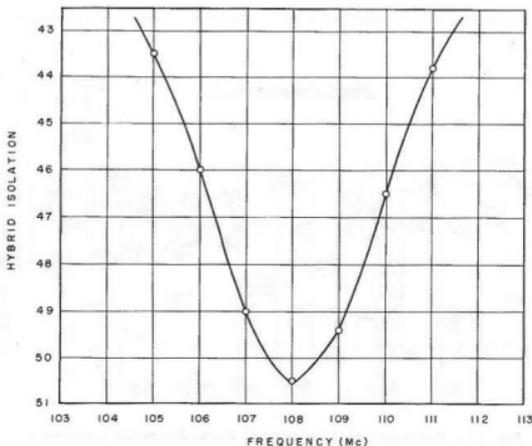


Fig. 24 - Measured isolation between arms B and D of hybrid (Fig. 23) with matched loads on arms A and C

The Preamplifier/Converter Unit

The interference of the waves from the two antennas has now been accomplished in the hybrid junction. The outputs from the hybrid must be amplified in low-noise amplifier systems. The preamplifier is the secret of the low-noise system. After sufficient low-noise amplification, the signal can be converted to a frequency suitable for amplification in a communications receiver.

It now appears that several converter manufacturers will market preamplifiers for this purpose. But since none of these were available at NRL, a description will be given of a preamplifier developed at the Laboratory for the Prime Minitrack system. It is very similar to the preamplifier described in the December 1956 issue of *QST*.

The schematic of this preamplifier is shown in Fig. 25. The input circuit is designed to match a 50-ohm transmission line. This match is desirable to assure matching of the hybrid terminals and thereby obtain maximum isolation between cross terminals of the hybrid. The use of an impedance-matched input increases the receiver noise figure referred to 300° K from less than 3 db to something under 4 db.

The low-noise amplification is obtained by means of two grounded-grid amplifiers. This circuit configuration gives a good noise figure and freedom from neutralization requirements because of its inherent stability.

Following these two stages, the signal is converted in the balanced mixer shown. For the Prime Minitrack system the balanced mixer is a necessity but for the Mark II system it is only a convenience owing to its low insertion losses, signal to local-oscillator

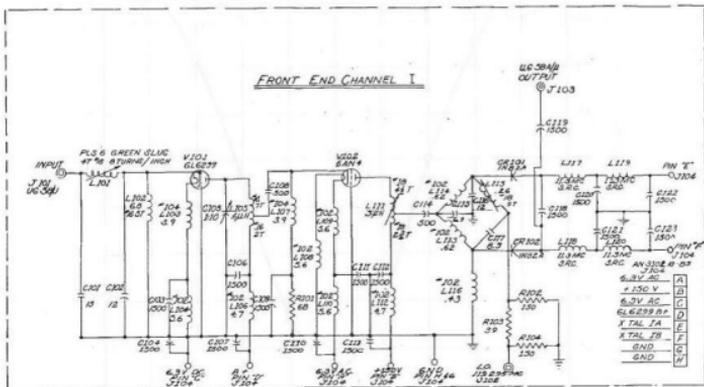


Fig. 25 - Preamplifier developed at Naval Research Laboratory

isolation and local-oscillator noise cancellation. If a single local oscillator is used for both preamplifiers, isolation of the signal oscillator from the local oscillator is desirable to prevent interaction between the two signal channels.

Local Oscillator

The local oscillator (Fig. 26) consists of a fifth-overtone crystal oscillator, a buffer amplifier, a hybrid power divider, and attenuators. Much of the circuitry is needed to permit the use of a single local oscillator for two or more well isolated receivers. The hybrid gives a cross-arm isolation of about 30 db and the attenuators contribute 10 db of attenuation each, giving a total isolation of 50 db. The balanced mixer gives an additional isolation of about 15 db. The buffer amplifier is needed primarily to provide sufficient power (approximately 1 milliwatt) to each amplifier despite losses in the hybrid and attenuators.

The crystal operates in the series mode at the fifth overtone. The exact fifth-overtone frequency was chosen to beat with 108 Mc and produce 11.295 Mc for the Prime Minitrack intermediate frequency. If the communications receiver used will tune to 11.295 Mc, this frequency can be used. If not, a crystal operation at a different frequency should be selected. In any case the coil L14 should be chosen to resonate with the crystal holder capacitance.

The amplifier is conventional. The hybrid for power division can be built out of lumped components or of transmission lines as shown in Fig. 26. The converter and local oscillator can be placed at the center of the transmission line with the intermediate frequency transmitted to the receiver by transmission line, or the signals can be transmitted to the converters and receiver by low-loss transmission lines.

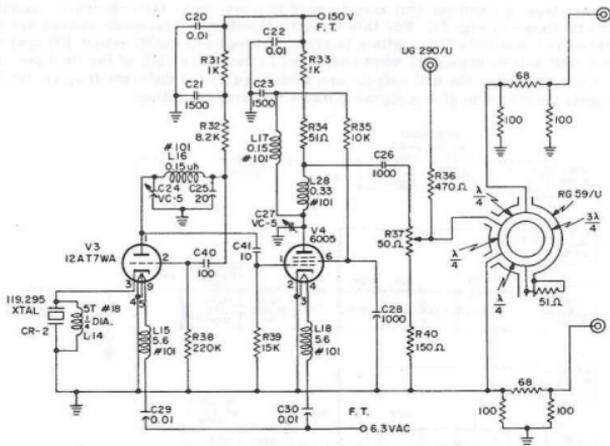


Fig. 26 - Local oscillator

The Receiver

The receiver needs only to be tuned to receive the 11.295-Mc frequency, and a suitable pre-detection bandwidth perhaps as narrow as 1 Kc can be used. The post-detection bandwidth, to maximize the signal-to-noise ratio, should be as narrow as is practical. To minimize phase shift, however, it should be about ten times the expected post-detection signal frequency. The maximum expected frequency for a 1000-foot baseline is about 3 cycles per second, so a maximum post-detection bandwidth of about 30 cps is indicated. Narrower bandwidths may be used for more distant satellite transits. For radio-star tracking, the pre-detection bandwidth should be as wide as possible and the post-detection bandwidth very narrow. Using ten times the detected signal frequency as the criterion for radio stars, this post-detection bandwidth can be 0.1 cps.

The Recorder

The recorder can be any of several types. The most desirable type is one of the direct-writing models with a frequency response up to 30 cps or so. Galvanometer-type photographic recorders may also be used, but they are not so convenient and the higher frequency response is unnecessary. The paper speed used on any of these recorders should be at least 3 inches per second. Preferably three channels should be available: two would be used for outputs from two receivers and one would be used for the time standard. The time standard can be the rectified 1000-cps WWV note. In case the satellite passes during the 4-minute WWV silent period the paper should be run until WWV reappears. Then, assuming linear paper speed the time of nulls can be approximated.

Another type of recorder that may be used is a low-noise tape recorder. Suitable circuits are shown in Fig. 27. For this type of recording the receiver outputs are detected and filtered in a low-pass filter with a fairly high-frequency cutoff (about 100 cps) so that its phase shift will be negligible when compared to the phase shift of the final post-detection filter. After this filter the null outputs are modulated by the different frequencies from the audio signal generator to give a signal suitable for tape recording.

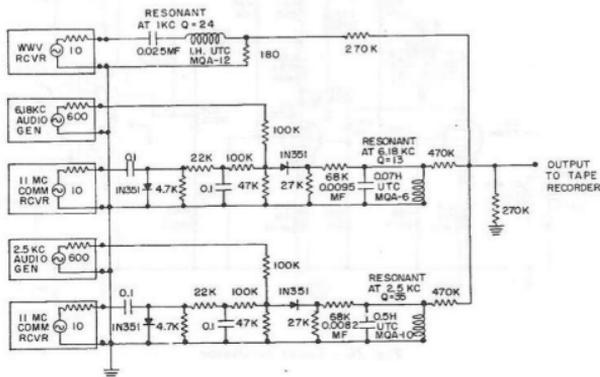


Fig. 27 - Circuits for use with low-noise tape recorder

The WWV second tick consists of five cycles of the 1000-cps signal. This signal can be filtered out by means of the filter shown, mixed with the signals containing the null information, and then recorded. The single tape now contains time information at 1000 cps and one null channel modulated by 2.5 Kc and another modulated by 6.18 Kc.

The tape recorder output can be put on a written record when convenient. A possible circuit is shown in Fig. 28. The WWV signal is taken off by means of the 1-Kc filter; the null information is taken off by means of the 2.5 Kc (or 6.18 Kc) filter, detected and integrated by means of an appropriate low-pass filter.

Figures 29, 30, and 31 show recordings taken from tape for various signal levels. For these recordings the second pulses were added to the upper signal.

The Naval Research Laboratory will have the necessary equipment for making paper copies of the data taken if the tape recordings are sent to the Vanguard Control Center at the Laboratory.

CALIBRATION OF THE MARK II MINITRACK

The purpose of calibrating the Minitrack systems is to determine the orientation of the equal phase plane of each baseline with respect to the local coordinates. The direction of the equal phase plane will depend on the orientation of the ground antennas. The tilt of the plane will be a function of the lengths of the transmission lines from the antennas to the hybrid.

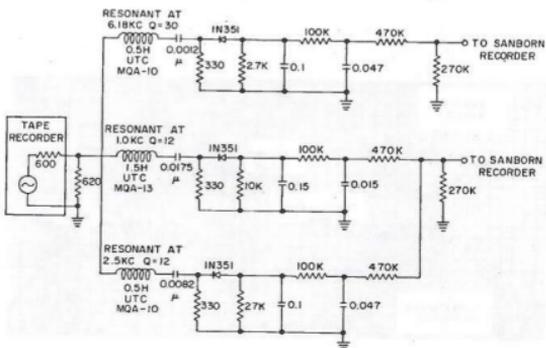


Fig. 28 - Circuit for obtaining written record from tape

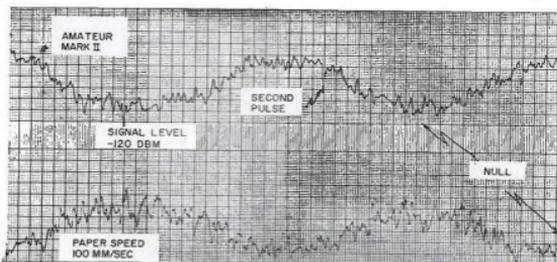


Fig. 29 - Recording taken from tape for -120 dbm level

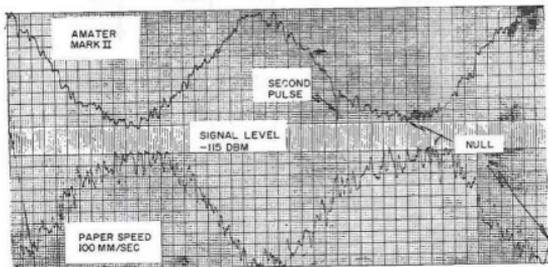


Fig. 30 - Recording taken from tape for -115 dbm level

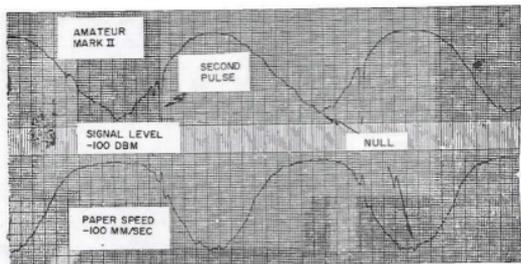


Fig. 31 - Recording taken from tape for -100 dbm level

To assure that the system will be capable of giving data accurately to 30 seconds of arc, the position of the antennas should be level to this accuracy. For a 1000-foot baseline the antennas should be level to $3/4$ inch or, if the antennas cannot be level, the angle of tilt should be known to better than 20 seconds of arc. The dipoles should be in line azimuth-wise.

Once the baseline is set up the system should be checked by an independent method of calibration. Such a method involves the passage of a transmitted signal on known coordinates over the antenna field.

A calibration transmitter could be carried by an aircraft, the position of which could be measured by an optical instrument on the ground. A system to do this has been designed for the Prime Minitrack system but is too complicated for Mark II use.

Another source of radiation from known points is radio stars, including the sun. Apart from the sun, only two of the stars, Cassiopeia A and Cygnus A are of sufficient intensity to permit detection on the system with pre-detection bandwidths of 5 Kc or so. A description of use of these sources has appeared in the April 1957 issue of QST. The intensity of 108-Mc radiation from the sun varies greatly from day to day and the center of radiation varies about the face of the sun; thus it is felt that the sun is not a good calibration source. There remains one natural object that can appear as a transmitter - the moon. The signal appears as a reflection from a powerful transmitter system on the earth.

As a calibration source the moon has a number of desirable features. The moon always presents nearly the same attitude toward the surface of the earth, so changes in the effective center of reflection will be small. The declination of the moon varies over about 40 degrees in two weeks, so the moon can be used to calibrate a large part of the ground antenna pattern in that length of time. It can also calibrate the receiving system in sensitivity and frequency of operation. The disadvantages of the moon as a source are the doubt as to its reflection center and the large amount of power needed to make it appear as an effective calibration signal.

The work that has been done using the moon has been a joint NRL-USASEL (U. S. Army Signal Engineering Laboratories) operation. The Diana radar at Fort Monmouth, operating at 151.11 Mc, was used as the transmitting source. Antennas were matched for the correct frequency, and on May 15, 1957 tests were begun.

For most of these tests the transmitting and receiving antennas were cross-polarized; thus for maximum return the transmitted signal had to be rotated by an odd multiple of 90 degrees. The signal strength varied greatly from night to night and within a single night. On most runs there were enough high-amplitude responses to permit drawing a line through regions of maximum response thereby obtaining a null reading. In view of this signal-strength change with time, the USASEL has started developing a circularly polarized transmitting antenna for this purpose.

Since this system shows great promise as a calibration scheme for all Minitrack stations over half of the earth's surface, a joint NRL-USASEL project is being initiated to furnish a calibration signal at 108 Mc. On a crash basis it is hoped that a suitable antenna and transmitter will be available during November 1957. In view of this, a suitable target date for operation of amateur stations would be late fall of 1957. The schedule of Diana operation will be announced through amateur channels.

The signal obtained from such a reflection will be weak, in the order of 130 dbm, with an antenna gain of 50, so it is important that the maximum possible ground antenna gain be utilized. The signal will be so weak that any system capable of receiving this signal reflected from the moon should have no difficulty in receiving a signal transmitted from the artificial earth satellite.

It is felt that groups so located as to be unable to use the moon reflection system will probably be widely spaced, so that system accuracy of 1 minute of arc will give valuable data. The radio stars are easily usable to this accuracy.

Moon reflections can be used for stations within 90 degrees of Belmar, New Jersey. This includes the Western Hemisphere, parts of Africa and Europe, and some Pacific Islands. For these stations calibration accuracies to about 20 seconds of arc should be possible.

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