7 Observations on pilot visibility and space acclimatization.

8 Meteorological observations of phenomena not previously known.

9 Demonstration of usefulness of manned balloon systems for upper atomsphere research and for study of temperature control of manned space cabins.

10 Establishment of a new world altitude record.

With the information from this flight, it will be possible not only to build floating laboratories carrying larger crews but also to extend flight to sustained periods for medical and other studies preliminary to manned space flight. In addition to the actual research work, which can now be carried out by scientists relieved of pilotage duties, one of the most fascinating facets of these experiments may well be the study of human reactions in isolation, comfort, relaxation, environmental influence, training and acclimatization criteria, as man selects crews in preparation for his invasion of space. The balloon-borne sealed cabin, if adapted to the rocket vehicle, may serve as the proven prototype of the manned space cabin.

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Microlock: A Minimum Weight Radio Instrumentation System for a Satellite[1]

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The design, construction and laboratory testing of a satellite tracking system are described. The tracking mechanism employs a low power, lightweight flight transmitter in conjunction with a receiving system of advanced design. The flight transmitter will radiate 3 mw for three months and will provide two narrow band telemetering channels in a unit having a total weight of 2 lb. The ground receiving equipment is capable of acquiring and tracking the beacon signal at a line-of-sight distance of 3000 miles and at any azimuth and elevation angle. Interferometer antennas could be used to determine the angular position of the satellite with an accuracy of one milliradian, which is equivalent to approximately ±0.04 sec in the determination of the period.

Introduction

Purpose of Microlock System

THE launching of a small vehicle into an orbit around the earth is pointless unless some means is available to demonstrate the existence of the orbited object. A minimum weight tracking mechanism independent of lighting and weather conditions is required. The utilization of a minimum weight radio transmitter with associated ground receiving equipment for a satellite vehicle was studied by the Jet Propulsion Laboratory from the standpoint of a low level communications system. This study (1)[5] specified a communications system in which the transmitter was minimized as to power and weight, and complexity was added to the ground equipment (where weight is no problem) in compensation. The system is built upon basic electronic circuits and techniques, but uses new combinations of these to accomplish the aims set forth here. This paper describes the design and testing of the communications system as it has developed from the feasibility study discussed in (1).

General Characteristics of System

A block diagram of the overall Microlock system is shown in Fig. 1. The missile transmitter consists of a radio-frequency oscillator which is phase-modulated by frequency-modulated subcarriers, of which as many as five can be accommodated in the present system.

The primary unit of the ground station is a phase-locked receiver which is designed to detect the beacon signal and to provide automatic tracking of the doppler shift as the satellite transits the station. The phase-locked receiver provides phase-coherent reference signals to an interferometer receiver, to allow correlation detection of the signal received on a two-aerial interferometer such as is commonly used in radio astronomy. Correlation detection rather than linear or square-law detection in the interferometer receiver results in much less noise in the angle-of-arrival data. The system is designed for an accuracy of 1 mil.

The telemetering subcarriers are received in the phase-locked receiver and sent through discriminators to recover the

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[5] Numbers in parentheses indicate References at end of paper.

original data. In order to provide the best possible data outputs, it is expected that phase-locked discriminators will be used.

Frequency and time standards are obtained from transmissions of the National Bureau of Standards radio stations WWV and WWVH. In this way, data taken from several tracking stations can be correlated with a timing accuracy equivalent to 0.25 mil.

Signal Detection—Lock Loop Principles

Use of a priori information The performance of any signal detection system can be maximized only when all available a priori information has been used to the best advantage. For example, the ordinary AM receiver used on the broadcast band would hardly provide satisfactory operation if the listener were denied access to the list of assigned frequencies of operation for stations within the tuning range of his receiver. In this example the a priori information (signal frequency) allows the listener to locate the desired station rapidly; without this information the listener is forced to perform a laborious series of trial and error operations searching for some other a priori characteristic of the desired signal (e.g., station call letters).

A little reflection on this same example will show the desirability of another feature, memory. The listener who has to search all over the dial each time he wants to find a station is faced with the problem of finding a station rapidly at some future time in order to listen to a particular program. The obvious solution is to find the station ahead of time and to leave the dial set at the desired frequency. In this further example, use is made of the ability of the system to remember information obtained by the original search.

Two classes of a priori information important to the satellite tracking problem are target dynamics and signal characteristics. Target dynamics include target position relative to the receiving station and all of the derivatives of position. The equations of motion of the satellite and the known forces (gravity, thrust, drag) allow us to at least place limits on the variation of important derivatives of position with all possible target aspects. The a priori knowledge of signal characteristics is based firstly on known features of the transmitted signal, and secondly on the modification of that signal by propagation and target dynamics. Characteristics of the transmitted signal, such as frequency, bandwidth, power and modulation are important as are propagation effects, such as distance, absorption, refraction and doppler effect. This a priori information should be used to the fullest extent possible in determining such system parameters as antenna directivity, detection method and tracking schemes.

Correlation detection This is one means of employing some of the a priori information about signal characteristics. The basic operation of correlation detection is the multiplication of incoming signal plus noise (S + N) by a locally generated estimate of signal S* which embodies to the greatest possible extent the known signal characteristics. This product

$$S^* (S + N) = SS^* + NS^*$$

when averaged by a low-pass filter, yields the correlation coefficient $(SS^*)_{av}$ contaminated by a small amount of noise $(NS^*)_{av}$. This process is said to be linear in that the signal-to-noise ratio at the output SS*/NS* is the same as that at the input S/N. This linear detection process is to be contrasted with square-law detection in which the input signal plus noise (S + N) is passed through a square-law detector forming

$$(S + N)^2 = S^2 + N^2 + 2SN$$

In this process the desired signal appears as S^2 contaminated by noise $(N^2 + 2SN)$. Furthermore, the output signal-to-noise ratio is not equal to that at the input

$$\frac{S^2}{(N^2 + 2SN)} = \frac{S/N}{(2 + N/S)}$$

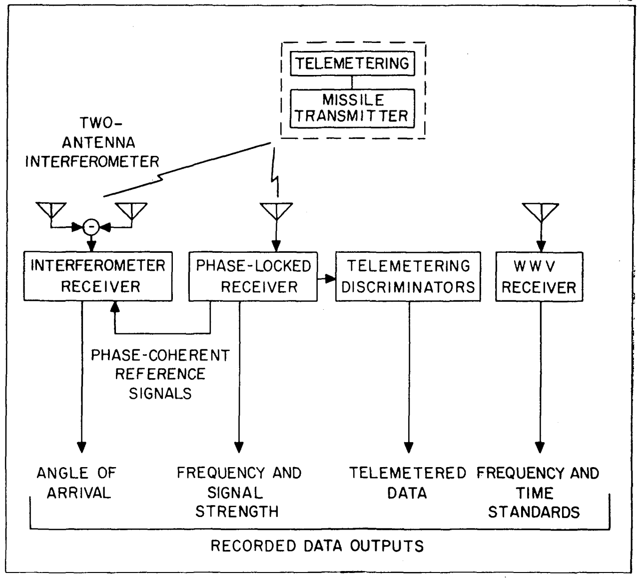

Fig. 1 Block diagram of Microlock System

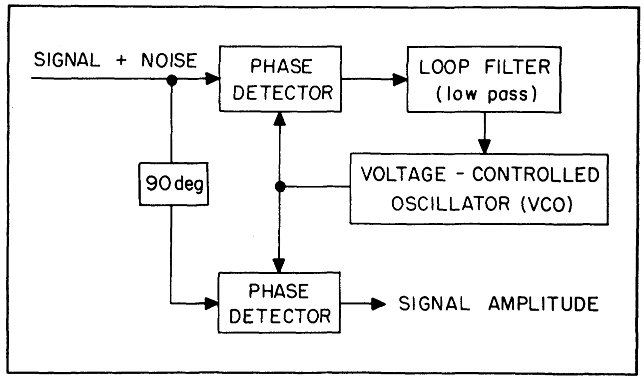

Fig. 2 Basic phase-locked loop

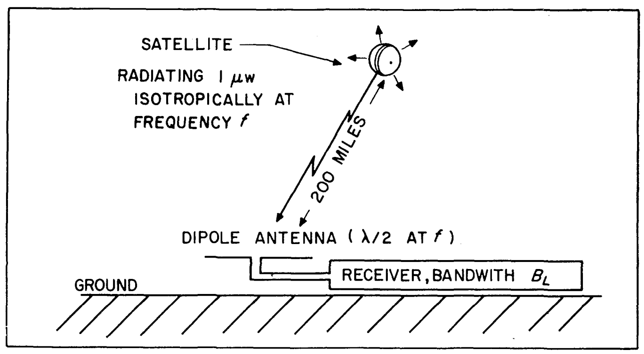

Fig. 3 Elementary satellite-detection system

Thus, the signal-to-noise ratio for square-law detection is less than that for correlation detection by the factor (2 + N/S). The degradation of signal-to-noise ratio for a square-law detector becomes particularly important when the signal-to-noise ratio is less than unity. For instance, when S/N = 0.10 (−20 db), the degradation factor is 12.

Phase-locked loop One method of mechanizing correlation detection in practical receiving systems is the phase-locked loop which is particularly applicable when the transmitted signal is a pure sine wave. In the phase-locked loop (Fig. 2) the local estimate of the tramsmitted signal is generated by a voltage controlled oscillator (VCO), and the mathematical operation of multiplication is performed by the phase detector. This phase detector provides a dc output voltage which is proportional to the phase difference between the incoming signal and the local estimate generated by the VCO. The dc error voltage is separated from noise by the low-pass filter (integrator) to provide a control voltage to the VCO. In this way the phase-locked loop is an electronic servomechanism which accomplishes signal detection using only linear mixing. This system provides memory by virtue of the voltage stored on the integrating capacitor in the low-pass filter. This voltage is always a "best guess" of the present signal frequency and is retained for some time after disappearance of the signal, thus providing a means for reacquiring the signal should it appear again at the same frequency. The design of a phase-locked loop for a particular application requires detailed knowledge of target dynamics and their effect on signal characteristics.

The simple phase-locked loop shown in Fig. 2 is a servo system which locks a VCO in phase synchronism with a sine wave signal input, in spite of a large amount of noise that may also be present at the input. If the system is assumed to be initially in lock (i.e., if the VCO has exactly the same frequency as the input signal), the output of the phase detector will be directly proportional to the cosine of the phase difference between the signal and the VCO output. This phase detector output, when filtered by the low-pass filter, is a control voltage which will maintain phase synchronism with the VCO output 90 deg from the input signal. The low-pass filter effectively removes the noise from the control voltage so that VCO output is very clean and is a good measure of signal frequency and phase. In a second channel, the signal is shifted in phase by 90 deg, so that it is in phase with the VCO output. The phase detector in this channel then produces a dc voltage which is proportional to the signal amplitude. In this manner, the signal is completely detected by the phase-locked loop; i.e., the frequency, phase and amplitude are determined.

This description of the phase-locked loop assumes that the loop is initially locked. Initial acquisition of the signal may be accomplished by slowly sweeping the VCO frequency across the signal frequency. As the beat between the signal and the VCO output goes to zero, the system acquires phase-lock and thereafter retains synchronism, unless the signal level becomes so small that the available control voltage can no longer overcome the effects of the small amount of noise which appears at the output of the low-pass filter.

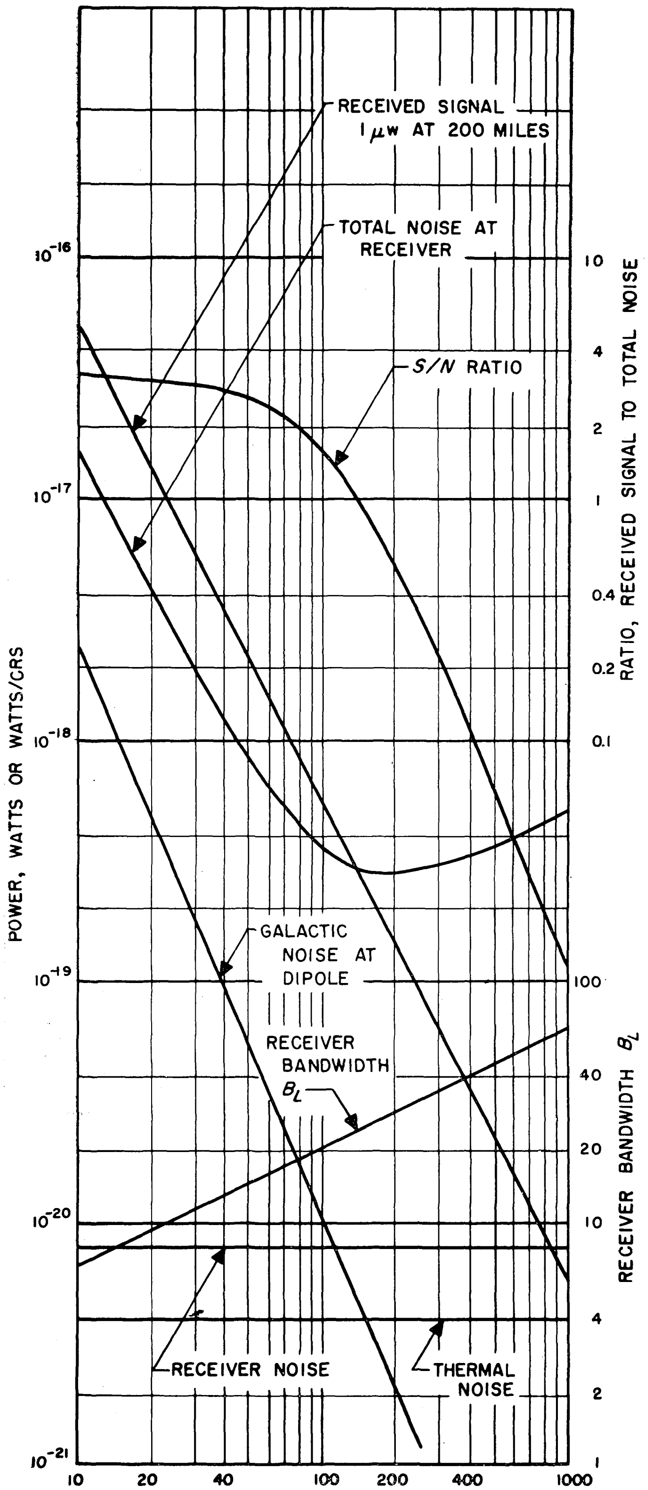

Fig. 4 **Signal and noise for elementary satellite-detection system**

Radio Link

Operating Frequency and Power

A brief study has been made to determine the minimum transmitted power which would assure detection of the satellite during favorable transits. The system to be considered first is shown in Fig. 3. This elementary system is based on three assumptions:

1 The satellite transmitter is crystal-controlled at a frequency f.

2 Certain trajectory features, such as radial velocity and acceleration, are known.

3 No a priori information is available as to the angular direction to the satellite.

The first and second assumptions determine the required receiver noise bandwidth B_L, and the third assumption requires the use of an omnidirectional antenna at the ground station.

Required power Receiver noise and the expected receiver signal for this system are shown in Fig. 4. A receiver internal noise figure of 3 db was assumed. Galactic noise received on a half-wave dipole varies with frequency as $f^{-2.4}$ and is approximately equal to thermal noise at 150 mc (2). It is assumed that all man-made interference sources can be eliminated. The receiver bandwidth, as shown in Fig. 4, is that required of a phase-locked receiver so it tracks a crystal-controlled source with a phase error of 10 deg peak-to-peak. The contributions of galactic noise and receiver noise within the receiver bandwidth are indicated in the curve showing total noise at the receiver. The signal received at a dipole antenna from a $1-\mu$w source at a distance of 200 miles is also indicated in Fig. 4 along with a curve of signal-to-noise ratio. From these curves it is apparent that a $1-\mu$w crystal-controlled signal can be detected at a distance of 200 miles if its frequency is below 150 mc.

In the region below 100 mc there is relatively little advantage to changes in ground antenna size, since the primary

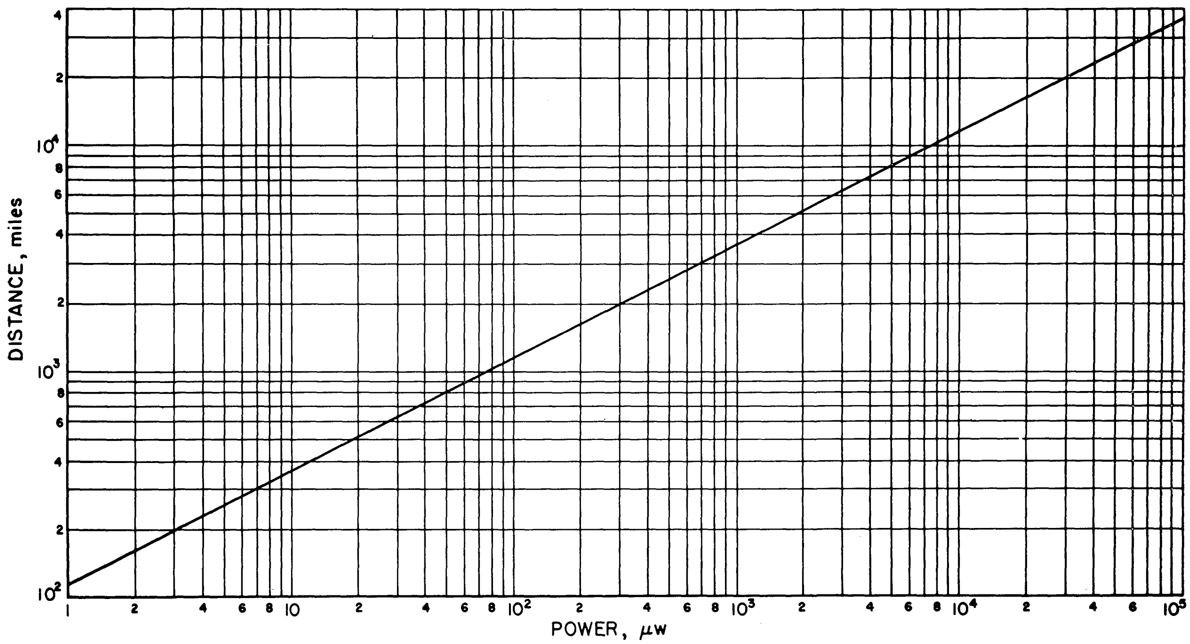

Fig. 5 Maximum detectable distance as a function of radiated power for isotropic antennas

noise sources are external to the receiver. Antenna directivity may be of some advantage when the satellite does not appear close to the galactic equator; however, an object circling the earth near the equator is often close to the Milky Way. Antenna directivity may also provide additional isolation from man-made and atmospheric noise which usually come from near the horizon.

CHOICE OF OPERATING FREQUENCY Items requiring further consideration in the choice of operating frequency are: Antenna efficiency in the satellite, possible operating frequencies for transistors and characteristics of the ionosphere.

It will be assumed that transistors should be available for use in the satellite instrumentation which will permit operation at 100 mc or above. The properties of the ionosphere in this frequency range are not well known. The only experience available is that gained by workers in radio astronomy (2). They have found that radio waves above 20 mc successfully penetrate the ionosphere without attenuation, except at very low angles of incidence.

Performance and Signal Calculations

After a receiver design has been chosen, the ability of such a receiver to acquire and lock onto a signal depends on the nature of the signal. The principal factors that must be considered are the signal-to-noise ratio in the receiver passband and the phase stability of the signal source. Although doppler-frequency offsets and doppler-frequency rates also affect loop performance, in the Microlock system they can be compensated for or are small enough to be neglected.

A study has been made of the expected performance of the phase-locked receiver designed for the signal conditions expected from an orbiting beacon in a circular orbit 200 miles distant from the earth's nominal surface. Since a zenith pass of the beacon presents the maximum range of signal-amplitude variations that might be encountered for any pass, a zenith pass is used to demonstrate the expected receiver performance.

The rms phase jitter of the loop is a measure of how solidly the loop is locked to the beacon signal. An rms jitter of 30 deg is considered marginal lock; 10 deg of jitter indicates solid lock. Fig. 4 shows that a reasonably solid lock should be possible even at very low angles of elevation. This is important, since many of the passes do not rise very far above the horizon.

Another way of presenting the receiver performance is illustrated in Fig. 5, which shows the maximum range at which the receiver should be able to acquire and lock onto a beacon, given a specified radiated power from the beacon.

One can compute the expected signal-to-noise ratio in the 3 kc bandwidth of the IF amplifier. The received signal calculations of Fig. 6 are based on a 3 mw signal radiated isotropically from the beacon. Although the antenna pat-

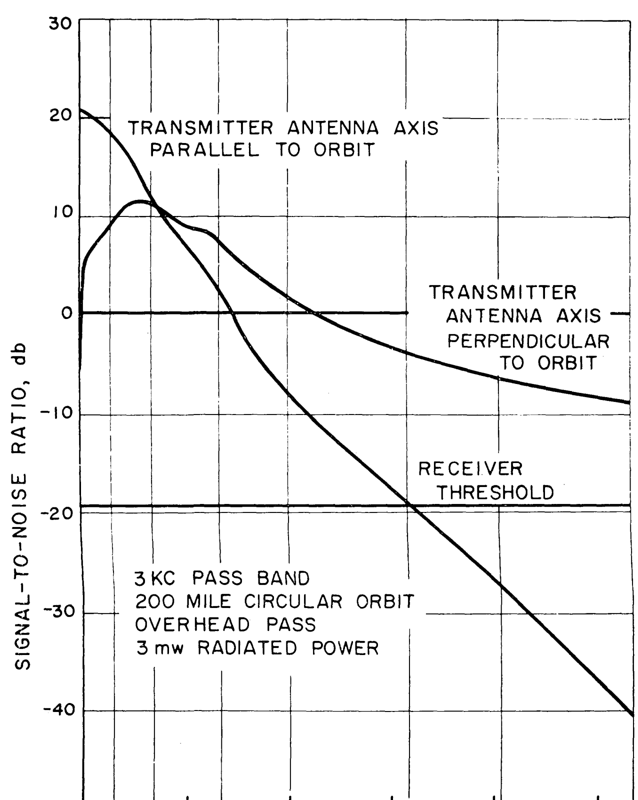

Fig. 6 Signal-to-noise ratio vs. time from zenith crossing

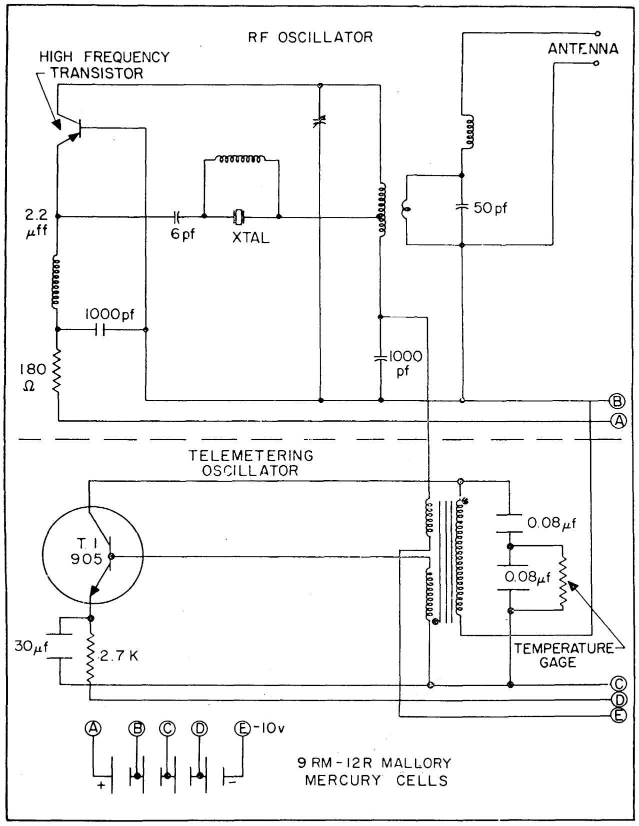

Fig. 7 Circuit of beacon transmitter and telemetering oscillator

tern of the orbiter is known, the spatial orientation of the pattern is not known for general observations, since it depends on the attitude of the orbiter at the time of observation. The attitude depends on the observer's location, the time at which the satellite is launched and the particular pass which is being observed. Thus, an isotropic antenna is chosen for the purpose of this study.

It is expected that the ionosphere will cause unknown rotation of the plane of polarization in the received signal. For this reason, the receiving antenna is of the helical type. Since, for linear polarization, the helical antenna has essentially zero db gain over a wide angle, it may be assumed to be isotropic for the general case.

Ground station locations should be selected in such a manner that actual noise levels closely approach the calculated values. In making the selection, factors that should be considered include power line noise, propagation shadows from known FM and TV broadcasting stations, industrial noise radiations, interference from high power radiations at the receiver image frequencies and automobile ignition interference.

Criteria for Beacon Design

Before design work can progress very far on a beacon transmitter, a number of interrelated decisions must be made. These are concerned with frequency of operation, radiated power, operating life of flight equipment and duplication of function for improved reliability. Presumably, an upper limit on the weight alloted to flight communications equipment has been set from other considerations (propulsion and structure). A compromise must now be made between operating ife and power radiated, the product of the two being a constant (ignoring the change of efficiency of the oscillator as the power level is changed). A lower limit on the radiated power can be set by the orbit expected, the anticipated receiver sensitivity and the factor of safety. If duplication of functions is desired, the weight allowed for each individual unit must be reduced.

Telemetering System

The installation of a radio transmitter in a vehicle opens the possibility of the telemetering of information. The details of the telemetering circuit incorporated in the Microlock system are given in a following section. The technique employed is the conventional one of using one or more subcarrier oscillators, each restricted to a small audio-frequency range, into which the data to be transmitted are encoded. The nature of the Microlock communications system is such that restrictions must be placed on the telemetering channel because an information bandwidth of, at most, a few cycles per sec is available. This means that the information to be telemetered must be in such a form that it does not vary rapidly with time since a narrow bandwidth audio locked loop circuit must be able to track the frequency of the telemetering signal.

There is a large amount of data that could be telemetered, including data of value to the design of future satellite vehicles. One of the most important design considerations, and the most difficult to predict, is the temperature variation and equilibrium temperature of the instrument compartment in the payload. An analytical attack on this problem has been made (3). Actual measurements under orbiting conditions are desirable in order to learn how much control of temperature has been accomplished. The operation of many of the electronic components in the payload is possible only within certain temperature limits; and, in the event of failure of part or all of the flight electronic equipment, a record of the actual temperature of the compartment would be useful information.

Flight Equipment

Basic Considerations

Several of the requirements of and limitations upon the flight equipment have already been mentioned. The design objective, obviously, is to make the most efficient use of the weight available and yet provide a system of high reliability and performance. This criterion must be applied to all parts of the flight equipment: The electronic components, circuit elements and the supporting structure. The output power-to-weight ratio as a whole must be as high as possible, consistent with reliability. The use of transistor circuitry seemed desirable in attaining this end, and experimental models of high-frequency transistors have been successfully used. Several environmental criteria must be applied in order to anticipate any limitations that must be placed upon the circuit elements or structure. The two different types of environment that are expected have been considered: The stresses and vibrations present during propulsion and during the static period after the satellite has orbited, when equilibrium temperature and temperature variations (as well as cosmic rays, etc.) must be considered. The design of the flight equipment is now presented in detail.

Environmental Limitations

Dynamic environment The environment expected during the dynamic or propulsive part of the flight may be considered as a combination of four types of action: Shock and thrust from the burning of the motors, vibrations due to the burning of the motors, the possible spin of the payload and aerodynamic heating. The first condition to be considered is the axial acceleration due to the burning of the motors. The thrust becomes progressively more severe as the later stages of the vehicle are ignited and burn. A thrust load of about 100 g toward the end of burning of the final stage is the largest that is expected. A shock is expected to occur upon ignition of each motor or set of motors, but little is known about its magnitude. Estimates place the most severe shock at about 100 g maximum.

The second condition is the vibration of the airframe due to the burning of the motors. Numerous static firings of solid propellant motors have been made, and the vibrations of different parts of the motor cases have been measured by means of accelerometers. The recordings made of the accelerometer output do not indicate any serious vibration problems, but this type of test is far from conclusive. The attachment of the motor to the airframe of the missile can greatly change the nature of vibrations because of the addition of mechanical resonances (and dampings).

If the satellite vehicle is given some angular momentum (spin) during launching, centrifugal loads on components and structure located off the spin axis must be considered.

Static environment The static (orbiting) environment of a satellite mainly involves two conditions: Spin and temperature. The spin of the vehicle is expected to damp out slowly because of the influence of the magnetic field of the earth. Electric currents are set up in moving conducting matter when a magnetic field is present, and the spin energy will be dissipated by these eddy currents, putting an end to the spin if the energy is not replaced in some manner.

The most serious effects will be those of temperature and temperature changes. When the satellite is in such a position with respect to the earth that it is exposed to sunlight, thermal energy will be absorbed and the temperature of the skin will rise. Conversely, when in the shade of the earth the satellite will radiate more thermal energy than it receives and will cool. The skin temperature will then vary between fairly wide limits, which will depend on the physical characteristics of the exterior of the vehicle. If some sort of thermal insulation is provided between the skin and the instrumentation compartment, the excursions of temperature will be reduced, and the mean temperature will now be of importance. This mean temperature must permit the electronic components to function properly. It is believed that suitable thermal insulation can be provided to restrict the excursions of internal temperature to a few degrees from the mean.

Beacon Design

Crystal-controlled oscillator The beacon must satisfy several criteria, foremost of which are: A high ratio of power radiated to gross beacon weight and good short term frequency stability. The beacon must also, of course, be capable of enduring the environment, including shock, vibration and temperature.

The crystal-controlled transistor oscillator shown in Fig. 7 can be very light in weight and still have a fairly high overall efficiency. The unit is basically a Hartley oscillator, using a series-resonant quartz crystal in the feedback path. It should be noted that an inductor is used across the crystal to raise the nonresonant impedance.

In laboratory tests, the grounded base connection of the transistor shown in Fig. 7 has proved superior. The unit shown has operated with an output of 2 to 3 mw at 108 mc, with a total input of 10 mw. At higher power inputs, the efficiency can be maintained at around 25 per cent. A special mount for the quartz crystal, which will enable the crystal to withstand the vibration and shock with as little change in the frequency as possible, is being investigated for this unit. The transistor used in the circuit shown in Fig. 7 is a Bell Telephone Laboratories development model 2039.

Changes in frequency due to changes in reflected load from the antenna can be a serious problem in a narrow band system such as this, and effort is being expended to minimize these effects. When a unit is free of the earth, and all stages have been separated, there will be no further problem from these changes in reflected impedance.

Telemetering oscillators The temperature telemetering oscillators for this beacon are simple transformer-coupled transistor devices (Fig. 7). The frequency is determined by the tuned circuit formed by the primary of the transformer, the two capacitors and the temperature sensitive resistance. The voltage developed in a secondary winding on the transformer is applied in series with the collector voltage to the RF stage and frequency-modulates the RF oscillator over very small excursions.

Power supply To provide a basis for selection of the power supply for a satellite beacon, an investigation of the properties of batteries was undertaken. The investigation, which included life and environmental tests, was restricted to commercially available batteries, because they are readily obtained, and because their production has become standardized.

Supporting structure The beacon supporting structure was subjected to a stress analysis in which the structure was assumed to be made of either 91-LD fiberglass plastic or micarta. The structure, as designed, was found to be capable of withstanding both the static and dynamic mechanical environments expected in the satellite vehicle, when constructed of either material. Although use of the 91-LD fiberglass material would have permitted thinner sections in all parts of the structure, micarta was selected as the material for the beacon structure.

Thermal properties It has been pointed out that the Microlock beacon will function only over a narrow range of temperatures. Investigations of the temperature of the shell of an orbiting missile indicate that the temperature of this shell will vary over a much greater range than the beacon can endure. The variations of temperature of the beacon unit can be limited to periodic changes of a few degrees about the average temperature, if the amount of heat transferred between the shell and the beacon is sufficiently small. Heat is transferred from the shell to the beacon by both radiation and conduction.

Flight antenna The beacon antenna can be formed by splitting the payload electrically around its circumference. The antenna gap would be fed by radial spokes of thin metal from the transmitter terminals. The radiation pattern of the vehicle can be similar to that of a dipole. As the rocket stages are connected, the antenna lobes bend toward the rear and the gain increases. Rotational symmetry of the antenna pattern is essential to the operation of such a low power satellite-detection system using a simple ground receiver.

Ground Equipment

Receiving, Timing and Recording Equipment

The basic design of a phase-locked system for satellite communication has been described in the previous sections of this paper with a description of applicable types of airborne equipment. The ground equipment required to complete the system is readily constructed using well known techniques for

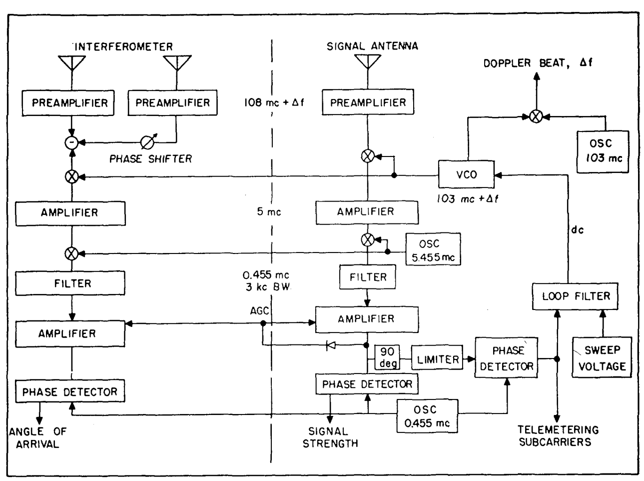

Fig. 8 Phase-locked receiver and interferometer

all electronic components. In fact, mechanization of a practical receiving system can be accomplished with standard components which are all well within the present state of the art.

Phase-locked receiver A block diagram for the phase-locked receiver appears as the right hand portion of Fig. 8. The basic layout of the receiver is a double superheterodyne with a first IF frequency of 5.0 mc and a second IF frequency of a 0.455 mc. The local oscillator at 103 mc is phase-locked at exactly 5 mc from the incoming signal at 108 mc. Crystal oscillators at 5.455 and 0.455 mc are used as reference signals in the IF channel.

The antenna preamplifier is designed to maintain a low noise figure, when several hundred ft of coaxial cable are used to connect the antenna to a receiver. For this purpose the preamplifier has been mounted in a weatherproof box to be located close to the antenna. The amplifier provides 25 db of gain with a 3 db noise figure and has 70 db image rejection.

The first mixer, a 5 mc IF amplifier, and the second mixer are contained in one subassembly which provides approximately 50 db of gain. Additional gain of 80 db is contributed by the 0.455-mc IF amplifier which is constructed as a subassembly with a mechanical filter having a 3 kc bandpass. Automatic gain control (AGC) is applied to the 0.455-mc IF amplifier.

The phase detector is a diode type of phase comparator, which produces an output voltage proportional to the cosine of the phase difference between the signal voltage and the reference voltage. Isolation amplifiers have been provided on both inputs, resulting in a gain factor of 0.88 volts/deg. The signal input amplifier also incorporates a 90 deg phase shifting network and has been adjusted to limit at signal inputs greater than $\frac{1}{2}$ volt.

The 103 mc VCO unit consists of a 34.3 mc crystal-controlled oscillator, a frequency-tripler stage and a reactance modulator packaged as a single assembly. The VCO frequency is controlled by a reactance modulator using semiconductor diodes, the diode current controlled by a differential dc amplifier stage. The VCO frequency is controlled electrically within ± 10 kc of the nominal center frequency of 103 mc. This range is adequate to adjust for expected doppler-frequency and crystal-tolerance offsets. Doppler beat notes are obtained by mixing the VCO output frequency with the output of a 103 mc crystal-controlled oscillator.

Signal-strength readout is obtained from a second phase detector operating in quadrature with the first phase detector. Construction of the two units is similar, with the exception that the signal amplifier provides neither limiting action nor a 90 deg phase shift.

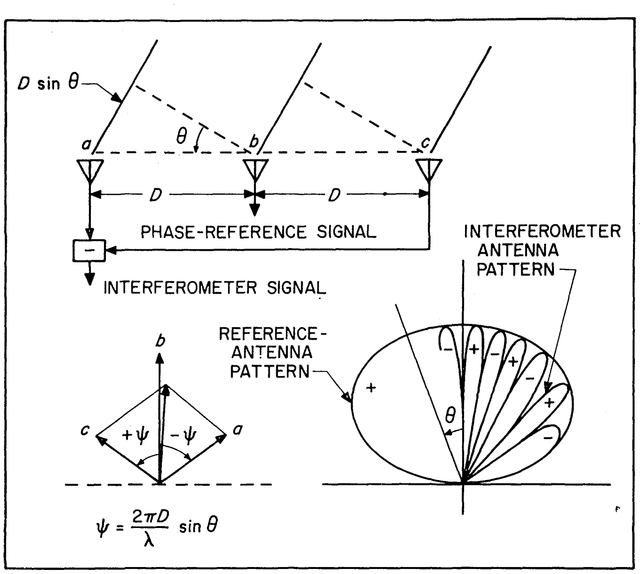

Fig. 9 Interferometer antenna

Interferometer receiver The individual components used in the interferometer channel are identical with those found in the signal channel. As may be seen from the block diagram (Fig. 8), reference signals used in the locked loop system are also used directly in the interferometer mixers. Both the signal subtractor (hybrid circuit) and phase shifter are constructed of coaxial cable and are unique to the interferometer channel.

Acquisition control For acquisition purposes, control of VCO frequency is accomplished by applying a manually controlled step function of current to the loop-filter capacitor. The circuit constants are adjusted so that the VCO frequency may be swept either up or down from its center frequency in a nearly linear fashion. Three sweep rates are available to the operator: 25 cps^2 (the maximum allowable sweep rate for acquistion of a marginal signal), 50 cps^2 and 75 cps^2. Successful acquisition is sensed by a relay circuit operating from the signal strength output of the phase-locked receiver. The presence of a signal automatically terminates the acquisition sweep.

Recording and timing All data outputs from the receiver are recorded on an 18-channel photographic oscillograph. Any four of the data outputs may also be displayed simultaneously on direct writing oscillographs. In order to correlate the data of several widely separated stations on a common time base, timing marks are generated by an oscillator that can be made to coincide with transmissions from WWV or WWVH.

Telemetering information is received as untracked phase modulation at the phase detector output (Fig. 8). The telemetering signals are detected in audio-frequency locked loops that perform the function of discriminators. Discriminator outputs are then fed to appropriate recording channels.

Antenna System

Choice of antenna A preliminary study of the effects of the ionosphere on the radiated wave indicates that the wave will arrive at the ground linearly polarized but having an unpredictable plane of polarization, because the slightly anisotropic nature of the ionosphere will cause a gradual rotation of the polarization plane. Thus, a circularly polarized antenna is necessary to insure against loss of signal due to polarization effects. The helical type of antenna was chosen because it is inherently rugged, simple and broadband.

Interferometer The interferometer antenna is a practical means of using a priori knowledge of the received signal to increase the system accuracy. The theoretical interferometer output has a distinctive and predictable form, which enables it to be readily correlated with the observed interferometer output to reduce deleterious effects of noise and interference.

As shown in Fig. 9, the interferometer is a phase comparison antenna system. The phase-reference antenna b is located exactly midway between antennas a and c. A signal arriving at antenna a, at an angle θ from the normal, travels the additional distance $D \sin \theta$ in relation to the signal at antenna b. Similarly, the signal at antenna c travels a path which is shorter by the distance $D \sin \theta$. Thus the signals at c and a respectively lead and lag the signal at b by the phase angle $\psi = (2\pi D/\lambda) \sin \theta$. When the signals at a and c are added vectorially, they form an interference signal whose amplitude is a rapid function of the angle, and whose phase is nearly identical to that of the reference channel. Slight phase variations will occur because of imperfect balance at the summing point. In general, a requirement for 1 mil tracking accuracy is thought reasonably obtainable for this interferometer with 200 ft spacing.

Physical Assembly

All of the assemblies comprising the receiver shown in Fig. 8 incorporate ruggedized subminiature tubes and parts.

The use of these components has made it possible to build each unit into an I-beam assembly 2 in. high, $1\frac{3}{4}$ in. wide and 9 in. long (Fig. 10). Possible receiver malfunctions may then be corrected rapidly by merely replacing entire subassemblies. The number of different subassemblies is relatively small, since identical components are used in the phase-locked receiver and in each interferometer channel. Therefore, only a few spare subassemblies are required to adequately maintain receiver operation.

The receiving, timing and recording equipments have been assembled in consoles located in a 25 ft semitrailer.

Fig. 11 shows a ground station set up for one of the earlier experiments. Three antenna units forming an interferometer system may be seen. Each helix antenna unit consists of:

1 A 10 ft square ground plane, constructed of perforated sheet aluminum backed by a rigid framework.

2 A 3 ft diam by 5 ft long fiberglass reinforced plastic tube with a metal-strip helix.

3 Two struts which connect to the rear of the ground plane and allow it to be tilted up to any angle.

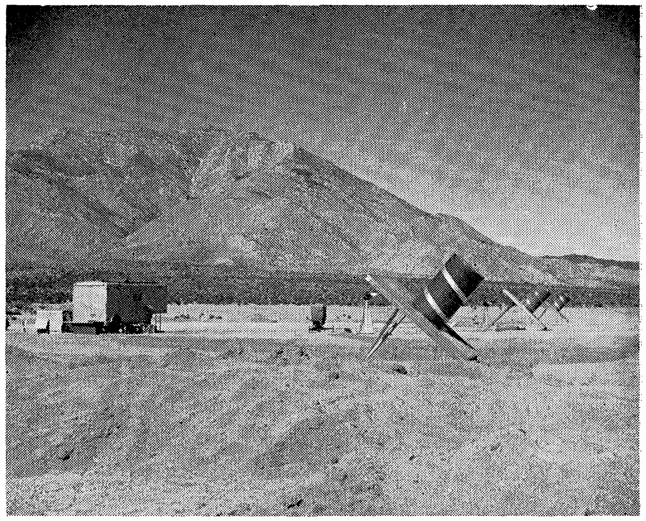

Fig. 11 Interferometer setup at Earthquake Valley

Test Program

Since the conception of the Microlock system, its various components and assumptions have been subjected to extensive testing. An important assumption was that appropriate locations could be found for ground station placement which would provide desirable observational geometry for satellite tracking and, at the same time, would be free from man-made radio interference. It was also assumed that a transitorized beacon transmitter could be constructed to provide low power output and long life (by virtue of high efficiency) at low weight. Design of the ground station equipment was based on principles already proved at this Laboratory. However, it was necessary to construct and test receivers and antennas which had been designed specifically for this task.

Testing of these components and assumptions is now complete. All the necessary electronics equipment has been constructed and bench tested. Field testing has included helicopter flights near this Laboratory and in a quiet location in San Diego County, California.

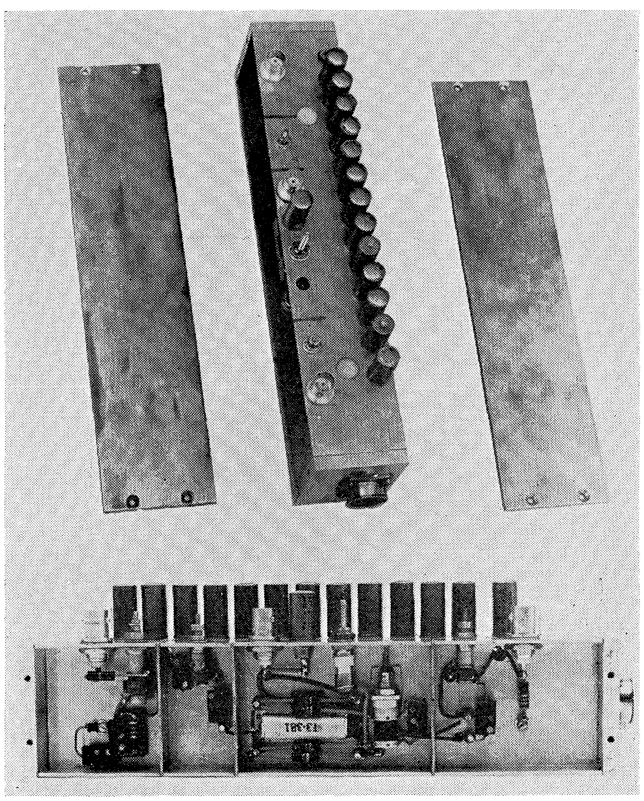

Fig. 10 Phase-detector assembly

Ground Station Sites

A ground station site for satellite tracking conducted by means of the Microlock system must satisfy two primary requirements:

1 Man-made radio interference must be small.

2 The geometry for observation of the satellite from the site must be favorable.

Some of the possible sources of man-made radio interference at Microlock frequencies are TV or FM stations, high-voltage power lines, and automobile ignition systems. In order to obtain relative immunity from such interference sources, a site is required remote from centers of population and which is shielded from nearby sources by surrounding terrain. The radio astronomer J. G. Bolton (now associated with the California Institute of Technology) was consulted for advice on possible locations of desirable sites. His experience showed that either a distance of 200 miles or shielding by two transverse mountain ranges is required to provide adequate isolation from TV or FM stations. In addition, the equipment should be located more than a mile from the nearest high-voltage power lines or regularly traveled roads.

Mr. Bolton indicated that Earthquake Valley (EQV) near Julian in San Diego County was the most desirable site in southern California. Subsequent field interference tests made on the spot have confirmed the desirability of this site.

Testing of Prototype Equipment

Receiver Construction and testing of prototype ground receiving equipment was completed in early 1956. The design of the receiver is such that the specifications for each of the individual blocks are readily realized in practice, and no difficulty was encountered in achieving the desired performance. When the receiver was assembled as a unit, the usual difficulties associated with operation from a common power supply and with shielding of high gain amplifiers were encountered. These difficulties were readily overcome, however, and the receiver was demonstrated to be capable of acquiring and tracking a signal at -150 dbm. This power level is equivalent to 10^{-18} watts or 0.007 μv in 50 ohms. In contrast, a good commercial communications receiver is capable of detecting a signal of approximately -110 dbm or about 0.7 μv in 50 ohms.

After the successful bench tests, the receiver was installed in the equipment van, together with the necessary timing and recording equipment, in preparation for field testing of the complete system.

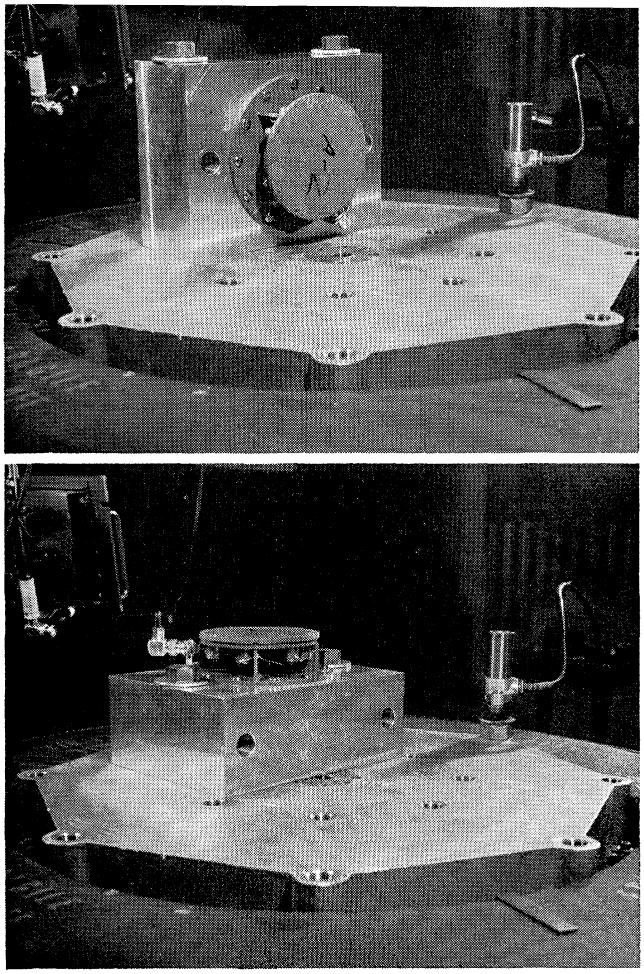

Fig. 12 Vibration test of beacon unit

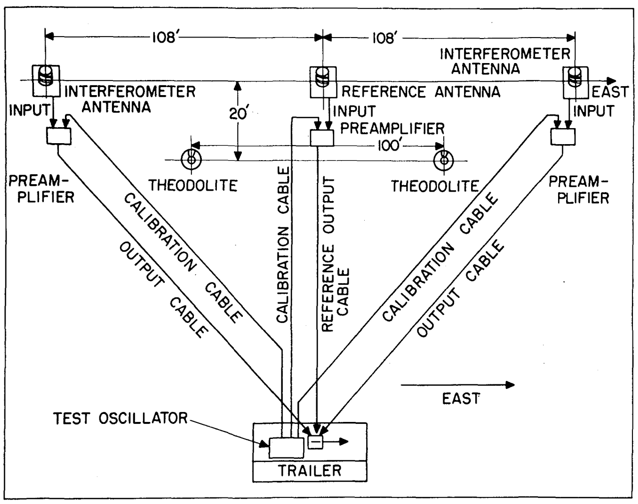

Fig. 13 Interferometer antenna system in Earthquake Valley tests

Beacon The very early prototype beacons were subjected to several bench tests. The mechanical structure of the beacon, including many electronic components, was vibration tested to 25 g of sine wave acceleration over the frequency range of 20 to 2000 cps. This unit also passed a shock test of 60 g acceleration. A complete operating beacon was tested on the random noise vibration table to 10 g rms acceleration over a 20 to 2000 cps range, while operating, and the beacon operated satisfactorily throughout the test (Fig. 12).

Earthquake Valley Tests

A complete ground station was assembled at Earthquake Valley and helicopter tests were performed for the purpose of checking the angle-measurement portions of the system. These tests were performed May 14 to 25, 1956. The primary purposes of the Earthquake Valley tests were to gain experience with the interferometer antenna system which has been proposed for angle measurement and to evaluate the accuracy of such an antenna in conjunction with the Microlock receiver. The ambient (external) noise level at EQV was found to be about 6 db above thermal noise; consequently, it was possible to measure the performance of the system when tracking very small signals under essentially the conditions assumed in the theoretical analysis of the system.

The general layout of the interferometer system, as placed at Earthquake Valley, is shown in Figs. 11 and 13. The three antenna units were set on a base line of 20 wave lengths, which, at the operating frequency chosen, required a little over 200 ft separation between the end antennas. This separation causes nulls in the multilobed interferometer pattern at intervals of about 50 milliradians. Phototheodolites were used for checking the system angular accuracy.

Electrical calibrations of the receiving system were performed by inserting equal phase signals at the preamplifiers or antennas by means of calibrated equal length cables. The electrical portions of the system were then adjusted to provide a null indication. Such a procedure is expected to result in a null in the plane perpendicular to the antenna axis.

The airborne radio source used in the Earthquake Valley field test was a low power crystal-controlled beacon transmitter, mounted in a helicopter. The antenna was a quarter-wave stub, mounted vertically in the rear section of the helicopter. The helicopter was flown at an altitude of 5000 ft above the test site. In general, the runs were in a west-east direction, i.e., parallel to the line through the three interferometer antennas, and at a ground range of roughly one mile. A few runs were made in a northeast direction, with the idea that a cyclical ground reflection error might be easily identified in this manner.

In conclusion, the interferometer system, as tested at Earthquake Valley with 20 wave length spacing, exhibited errors of 2 or 3 mils. Probable sources of the observed errors were: Antenna placement, calibration procedures, and cross-coupling between adjacent channels in the receiver. These problem areas are being studied with the aim of reducing angle-measurement errors to less than 1 mil.

The sensitivity of the Microlock receiver was measured at Earthquake Valley on May 22, 1956. A Microlock beacon was placed in a bomb and towed approximately 500 ft behind a helicopter. The power output of the beacon was attenuated to -50 dbm (0.01 mw) by placing small resistors across the antenna gap. The power output was measured by means of a dipole, a signal generator and a receiver. The position of the helicopter was determined by an optical tracker while recordings were made of appropriate voltages in the Microlock receiver. While the beacon was being towed at a distance of five miles, the signal was observed to be 12 db above the threshold of the receiver (i.e., 12 db above the point at which the receiver could no longer retain phase-lock). Extrapolating from this observation, the same received signal level would be obtained from a beacon radiating 1 mw (zero dbm) at a distance of 1500 miles. Such a beacon would have to proceed to a distance of 6000 miles before the received signal would approach the threshold of the Microlock receiver.

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