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GODDARD SPACE FLIGHT CENTER

GREENBELT, MARYLAND

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OPLE EXPERIMENT

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OPLE EXPERIMENT

1. INTRODUCTION

The purpose of the Omega Position Location Equipment (OPLE) Experiment is to demonstrate the feasibility of using the Omega Navigational System in conjunction with synchronous satellites to establish a global location and data collection system. The OPLE concept can be applied to various platform user requirements such as oceanographic buoys, commercial aircraft, ocean vessels, animal migration studies, etc. However, the platform which presents the most stringent packaging requirements and, which is of primary concern in the OPLE Experiment, is the meteorological balloon. An operational balloon system (Reference 1) with the capability of providing synoptic global weather information suitable for fast and accurate weather prediction would require thousands of balloons. Such a system would be required to determine the location of each balloon and provide a communications link over which meteorological data could be transmitted and yet not exceed the payload packaging requirements that would be imposed on such balloons. A basic premise for the conception of any balloon system is then the degree of simplicity inherent in the balloon's electronic package.

Once the feasibility of the OPLE concept is demonstrated, it will be possible to design an operational data collection and location system capable of serving a wide variety of users on a global scale. Using the OPLE concept as a basis, commercial aircraft, including the Super Sonic Transport, could be tied together in an air traffic control system capable of safely directing the anticipated air traffic for many decades to come. Also, flight schedules and terminal traffic would be better controlled if timely knowledge was available as to exact arrival times. Steamship lines could also use this system for scheduling arrival times and use of port facilities to more economically operate and regulate their overall traffic. Another possible application is as a recovery aid for the Apollo reentry vehicle. With OPLE type equipment aboard the Apollo vehicle and the various units of the recovery force including the helicopters, it would be possible for a control center to know the relative position of all the recovery units and spacecraft to within a few hundred yards and the absolute position of any one of them to within one or two miles, regardless of the landing location. Meteorologists using an OPLE system would have a means of gaining atmospheric and surface data through the use of balloons and buoys. In the case of tethered buoys the Omega portion of the receiver could be off with only the data channel activated. In the event of a broken tether the Omega receiver could be activated to give the position of the wayward buoy to service vessels. Oceanographers desiring ocean current and sea state data could use the system in much the same way. Zoologists could utilize the basic concepts of the OPLE system to ascertain the migration routes of various land and air-breathing sea animals.

One control center operating the entire system would greatly increase the economy of the system for individual users. Anyone desiring to use the system would inform the center of the intended region of operation, the platform frequency, and the number and time of the interrogations. The retrieved data and locations could then be sent to the user on a real time basis or be provided in a more leisurely manner depending on the users requirements. An unmanned platform could thus be tracked for scientific data and a manned conveyance would be tracked for safety, control and scheduling purposes and in addition have a communications channel to a central control center. It would then be possible to learn more concerning the global phenomena of the earth and for the higher speed and more complex transportation systems to operate in a safer and more efficient manner.

2. OPERATIONAL SYSTEM DESCRIPTION

An operational system, as shown in Figure 1, would consist of: (1) an OPLE Control Center (OCC), (2) a synchronous satellite, and (3) the OPLE Platform Electronic Packages (PEP's) working in conjunction with the Omega network.

The OPLE Control Center originates all the control signals that determine the sequence of platform addresses and times of interrogation. The OCC monitors the Omega transmissions to derive timing and to determine the overall state of the Omega system. Upon receiving satellite availability times from the Satellite Control Center, the OCC initiates a preprogrammed platform interrogation sequence which is transmitted to the platforms through the synchronous satellite. At the end of this interrogation sequence, the correctly addressed platforms transmit an acquisition/reference (A/R) tone to the satellite for transmission to the OCC where phase-lock-loops acquire the signals. Following the OCC acquisition period, the A/R tone is modulated with platform generated data by phase-shift-keying using a deviation of approximately ±60 degrees. Following this data transmission period, the A/R tone is reduced in level and transmitted along with the received Omega signals for approximately three minutes. The A/R tone is present throughout the PEP transmission sequence and is continually tracked to provide a constant reference signal, which minimizes the effects of variations in the transmission link from the PEP to satellite to OCC.

2.1 Omega System Description

The Omega Navigational System (Reference 2) was developed at the Naval Electronics Laboratory with assistance from several other organizations including the Harvard Cruft Laboratory and the Naval Research Laboratory. Evolution of the Omega system followed an extensive investigation of very-low-frequency (VLF) propagation characteristics throughout the last decade. One result of

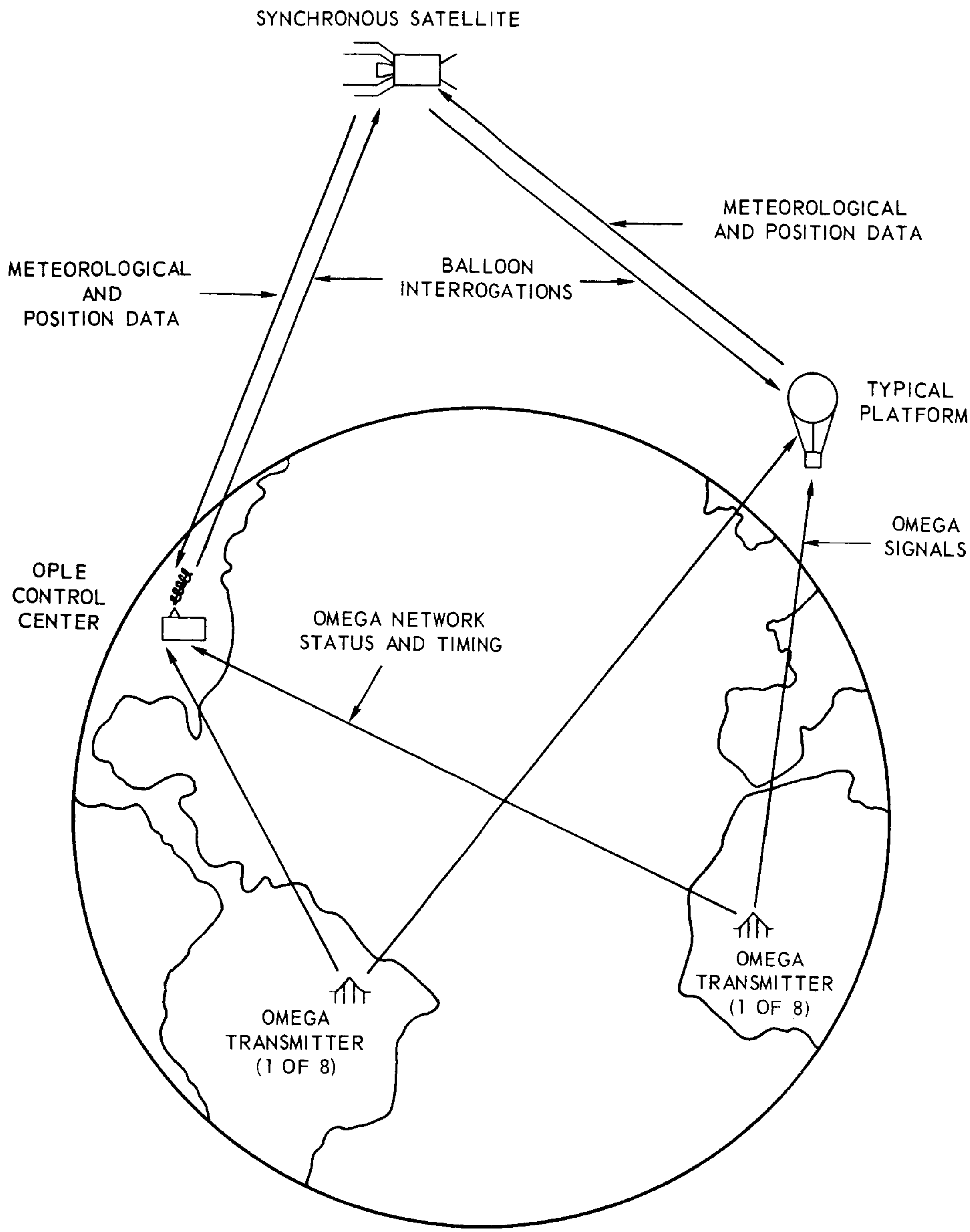


Figure 1. OPLE Configuration

these investigations has been to show that the 10 kHz region of the VLF spectrum has a very low attenuation rate and exhibits exceptional phase stability. These characteristics permit worldwide propagation of radio waves and allow phase measurements with an rms variation of less than five microseconds. Within this frequency range the radiated energy is propagated as a guided wave in the space between the earth and the reflecting ionosphere with an attenuation rate of nearly that due to inverse spreading loss. Near the transmitter interference between the ground wave and the single-mode guided wave transmission cause phase shifts of considerable magnitude. Beyond a few hundred miles the single-mode propagation dominates and the signal can be used for position measurements up to a distance of at least 5000 miles from the transmitter. Frequencies between 10 and 14 kHz were chosen for use with Omega because of the high excitation of the first mode and the low interference effects at sunrise and sunset of the higher mode.

The optimization of the Omega frequencies with respect to the above characteristics of the transmission medium has been verified by experimental results. The experimental phase of the Omega program is essentially completed and an overall operational design of considerable flexibility has been established and is being implemented. The Omega Project Office, under the Chief of Navy Material, has been established to direct the construction of the entire Omega network. Three operational stations have been constructed and are providing coverage over the northwestern quadrant of the earth. The complete Omega network could be operational by 1971 with the construction of five additional stations.

The operational Omega system will use eight VLF transmitting stations radiating 10 kilowatts of power each, with an average separation between stations of about 5000 nautical miles. It is expected that all eight transmissions will be receivable at nearly every point on earth and that at least five of the eight will produce usable signals with only a short monopole receiving antenna. The Omega receiver measures the relative phase of the signals from at least two pairs of stations, i.e., three transmitters. Two lines of position (isophase contours) are generated by the phase difference between each of the two transmitter pairs and the position of the receiver is established by the intersection of the two isophase hyperbolic contours. The very long base lines between stations results in position lines that diverge only slightly and that cross each other at nearly right angles. This geometric excellence, along with the high degree of phase stability and low attentuation rates of VLF radio signals, results in a reliable system with good absolute accuracy that varies little with geographical position.

The uncertainty in an Omega line of position can be summarized as one standard deviation of about three-tenths of a mile over a daytime propagation path and about twice that at night. By the time the Omega network becomes operational, it is expected that the rms fix error, for all causes combined, will be about one mile in the daytime and two miles at night (Reference 3). In recent tests performed by the Naval Research Laboratory, the rendezvous or station keeping accuracies attained were around 200 yards (Reference 4). Thus, a fixed station can provide very accurate relative position measurements (and velocity measurements through continual tracking) of platforms over a large area.

The Omega system, as presently being implemented, provides for considerable flexibility and future expansion. The transmitted signal spectrum is shown in Figure 2, while the transmitting station time multiplexing scheme is shown in Figure 3. The primary transmission frequencies are 10.2 kHz, 11.33 kHz and 13.6 kHz with additional lane resolution difference frequencies of 11.33 Hz, 45.33 Hz, and 226.66 Hz tones. In addition, eight other frequencies are shown in Figure 2, all of which are subharmonics of 408 kHz. Each of these eight frequencies is assigned to one of the eight transmitting stations in accordance with the time multiplexing method shown in Figure 3. These eight frequencies permit transmitter station identification, but they are not essential to the position location function.

Ambiguity resolution is performed by successive measurements of the received phase of the tone difference frequencies. These frequencies have been selected to permit construction of the difference frequencies listed in Table 1 along with the resulting ambiguity resolution steps. No dead reckoning, lane counting or log keeping is necessary and the transmitted sequence will permit completely automatic operation on an "as required" basis.

2.2 Satellite System

The circle of illumination on the earth by an equatorial synchronous satellite has a radius of about 81 degrees of longitude at the equator. This circle is centered on the equator, and extends to within about 9 degrees of each pole. With two synchronous satellites in equatorial orbits spaced on opposite sides of the earth, the total coverage would include all but a 17 degree wide segment circling the earth, as illustrated in Figure 4a. With three synchronous satellites in equatorial orbits equally spaced around the earth, complete coverage is provided from about 73 degrees north latitude to 73 degrees south latitude. This coverage would extend to the arctic and antarctic circles (located at approximately ±66 degrees latitude) with a minimum platform-to-satellite elevation angle of about 7 degrees. The two spherical triangular areas, located at the poles, which are not covered are illustrated by Figure 4b. By using one synchronous satellite with an inclined plane, along with two synchronous satellites in the equatorial plane, coverage of each pole could be obtained for one continuous period of time each day. The length of this time period depends on the angle of inclination of

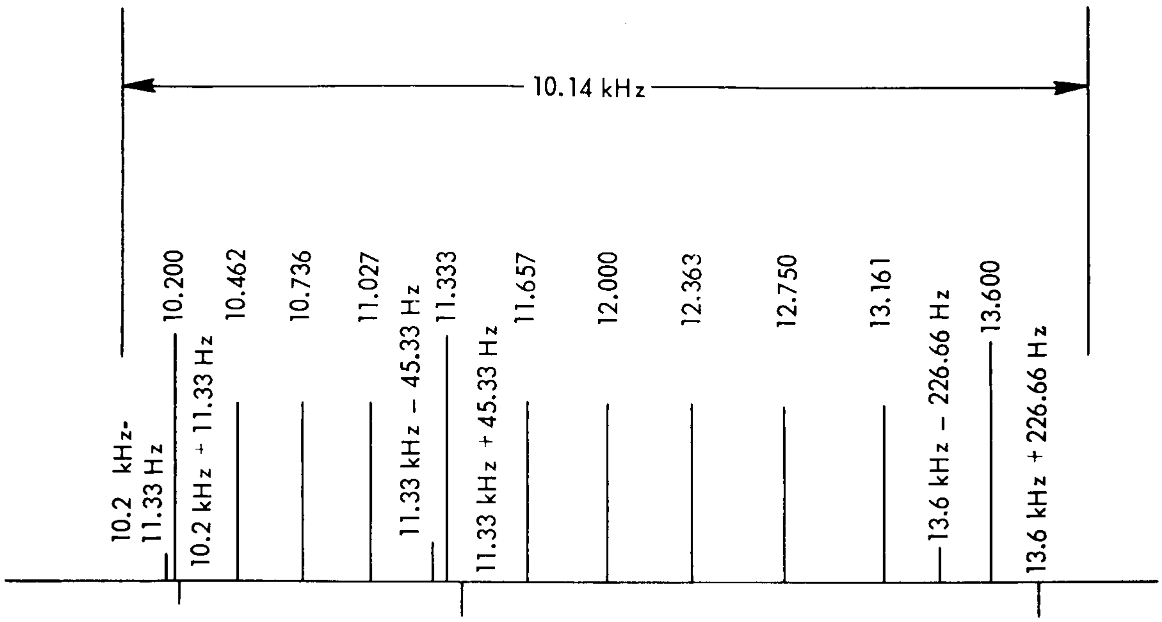


Figure 2. Omega System Signal Spectrum

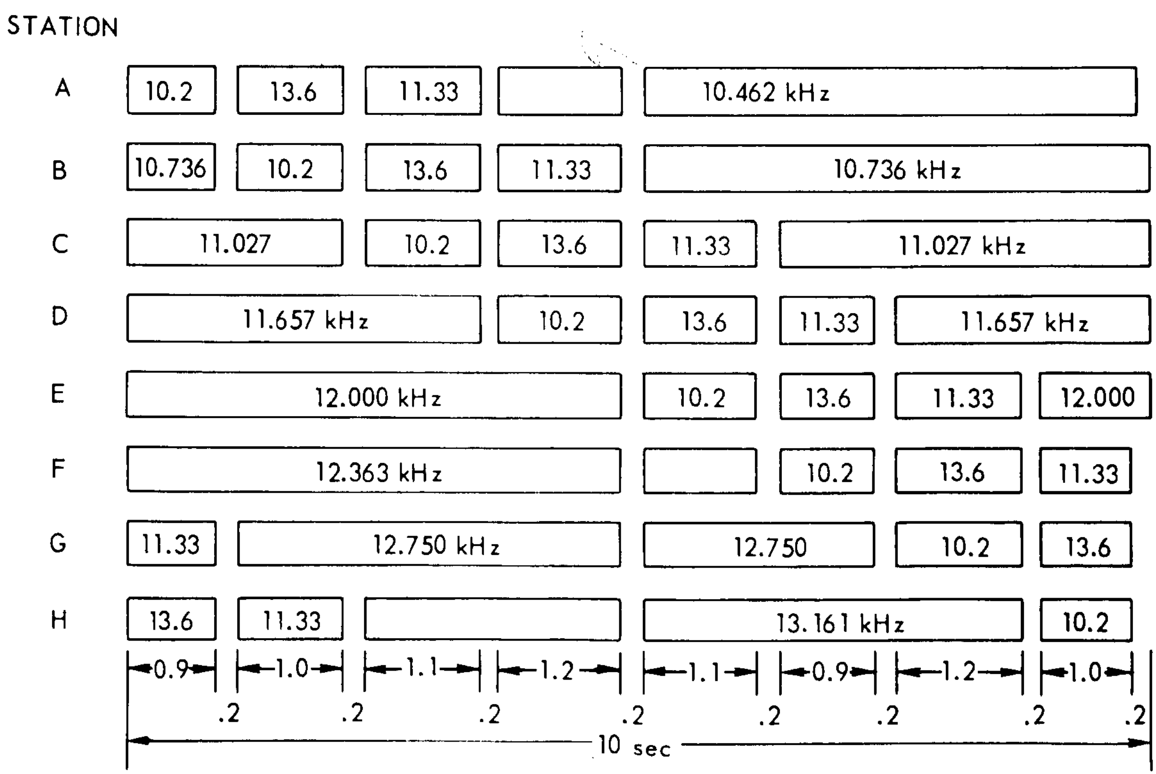


Figure 3. Omega Transmitted Signal Format

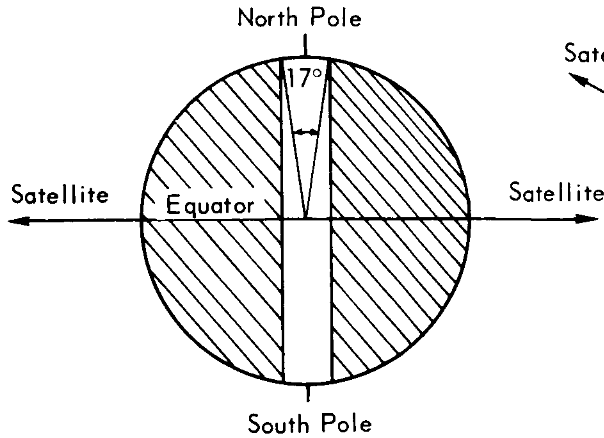


Figure 4a. Coverage by Two Equatorial Synchronous Satellites

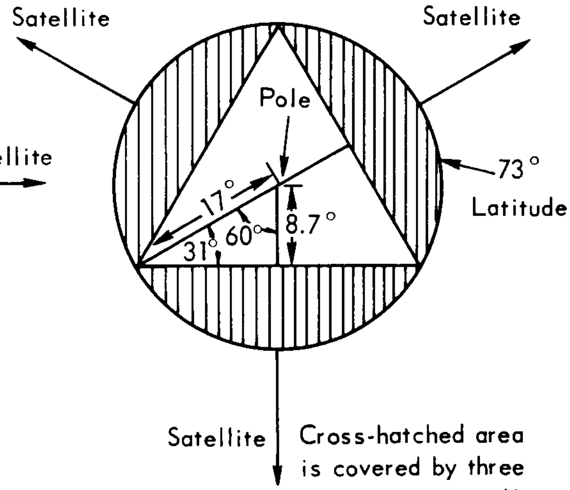


Figure 4b. Polar Blind Region for Three Equatorial Synchronous Satellites

Figure 4. Polar Coverage

the orbital plane to the equatorial plane. A plot of the pole visibility time in hours is given in Figure 5 for antenna elevation angles of 0, 5 and 10 degrees.

Table 1
Omega Ambiguity Resolution Steps

Frequency	Period	λ/2 K Meters	λ/2 N. Miles	λ/2 S. Miles
10.2 kHz	98 μs	15	8	9
3.4 kHz	294 μs	44	24	27
1.13⅓ kHz	882 μs	132	71	82
226⅔ Hz	4.41 ms	662	357	411
45⅓ Hz	22.06 ms	3,309	1786	2056
11⅓ Hz	88.24 ms	13,236	7142	8224

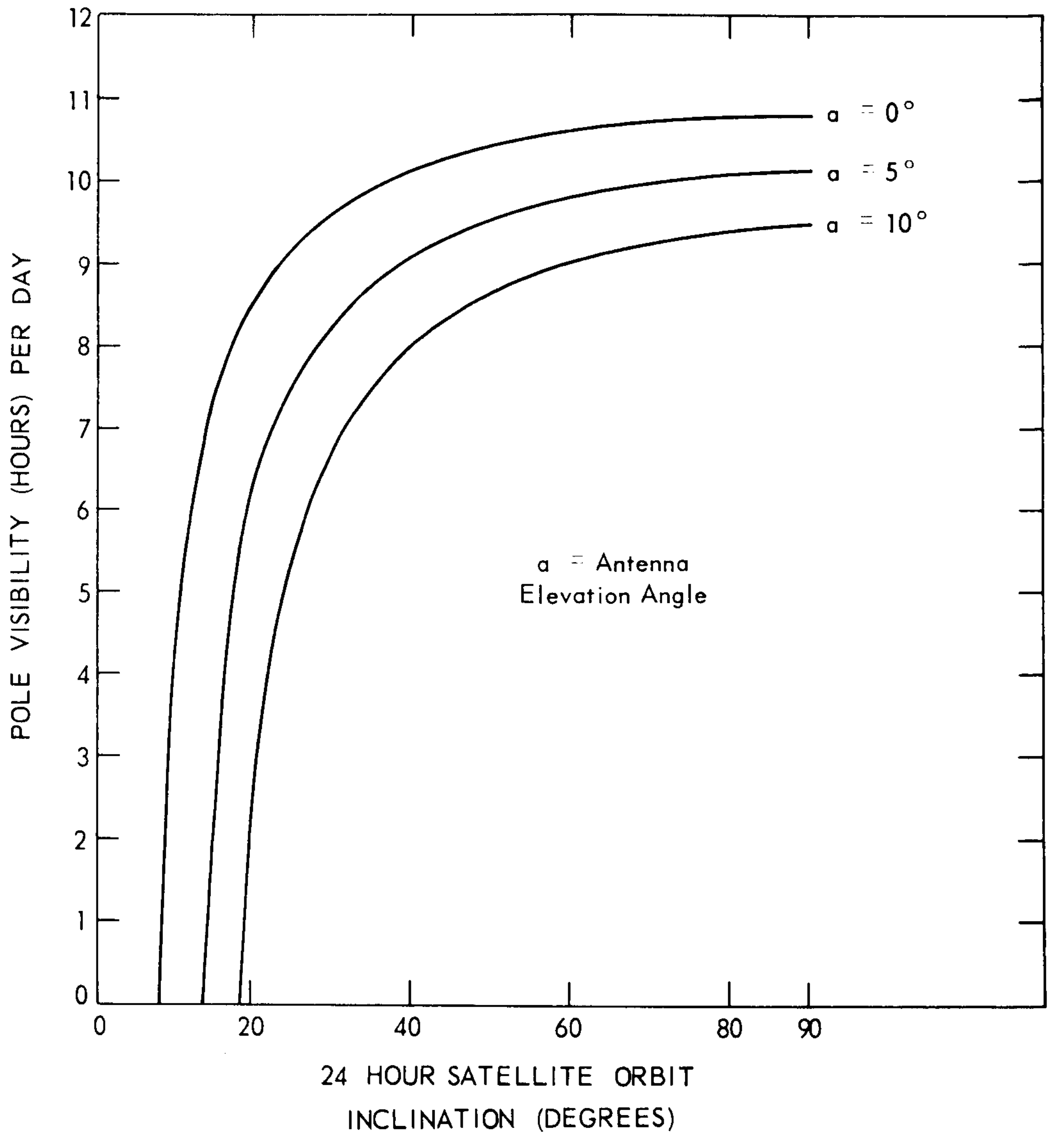


Figure 5. Synchronous Satellite Pole Visibility Time vs Orbital Inclination

The combination of three synchronous satellites properly phased, where one has an orbital plane inclined by 30 degrees would allow full earth coverage over each 24-hour period. The inclined plane allows the satellite to look over the poles and view the entire area not seen by the other two satellites. Each polar area would be entirely covered for a minimum of 4 hours per day. It seems that virtually any realistic operational requirement could be met by three phased synchronous satellites, each with properly selected inclination angles.

At synchronous altitude, the angle subtended by the earth is 16.4 degrees. This would allow use of an antenna with approximately 20.1 dB gain which would, assuming zero pointing error, provide a minimum of 17.1 dB of gain over the entire illuminated area of the earth. An antenna pointing error of 25% (4.1 degrees) would necessitate using an antenna with a gain of 16 dB gain, which would provide a minimum gain of 13.7 dB over the illuminated area of the earth. Thus, the maximum allowable antenna gain is determined by the antenna pointing error, and since 4 degrees of error is well within the capability of present mechanical and electrical stabilization systems, a nominal 14 dB gain antenna is feasible for an operational system. Table 2 shows the required nominal transmitter powers required for two hypothetical operational systems based on a satellite antenna gain of 14 dB.

Table 2
Operational Performance Predictions

2.5 KHz CHANNEL BANDWIDTH	136-148 MHz TRANSPONDER	400-450 MHz TRANSPONDER
SATELLITE RECEIVER NOISE POWER	-165.4 dBW (1000°K)	-168.4 dBW (500°K)
SATELLITE RECEIVER MARGIN	+10.0 dB	+10.0 dB
SATELLITE CABLE AND DIPLEXER LOSSES	1.5 dB	1.5 dB
SATELLITE ANTENNA GAIN	14.0 dB	14.0 dB
MAXIMUM RANGE PATH LOSSES	168.0 dB	173.0 dB
PLATFORM ANTENNA GAIN	0.0 dB	0.0 dB
PLATFORM CABLE LOSSES	0.5 dB	0.5 dB
REQUIRED PLATFORM TRANSMITTER POWER	+0.6 dBW (1.2 Watts)	+2.6 dBW (1.8 Watts)

3. OPLE EXPERIMENT DESCRIPTION

The OPLE experiment[1] has been designed to fully exercise and evaluate the techniques and concepts (outlined in Section 2). The experiment will utilize the

[1]A preliminary description is given in References 5 and 6.

ATS/C satellite VHF communications repeater which can provide up to 40 simultaneous PEP transmission channels. A small number of platforms (approximately 12) will be placed at various locations in the Northern part of the Western Hemisphere. The OCC along with the primary VHF antenna will be located at the GSFC while the Rosman CDA station will be used to receive the SHF transmissions for landline relay to the OCC. The following sections describe, in detail, the satellite transponder, PEP and OCC equipments. The operation of the system transmission links and timing sequence is also discussed.

3.1 Satellite Repeater Description

The ATS/C VHF transponder is an active frequency translation (Class B) repeater receiving at 149.22 MHz and transmitting at 135.60 MHz. Figure 6 is a functional block diagram of the transponder. The major satellite characteristics that are important to the OPLE system are listed in Table 3. The transponder utilizes a despun phased-array to allow the antenna beam to always remain positioned on the earth, thereby compensating for the stabilizing spin of the satellite. The antenna is linearly polarized with a minimum specified gain of 7.5 dB. The antenna is composed of eight elements, each of which has individual receiver, phase shifters, and transmitter all coupled together with a common intermediate frequency conversion section. The incoming signals at

Table 3
VHF Transponder Characteristics

Total Transmitter Power Output	16.0 dBw (40 watts)
Antenna Electronic Despun Phased Array	
Antenna Gain	7.5 dB minimum
Transmitter Losses (Diplexer and Cables)	1.8 dB
Receiver Losses (Diplexer and Cables)	1.3 dB
Receiver Noise Figure	3.5 dB maximum
Nominal Receiver Bandwidth	100 kHz
Transmitter Center Frequency	135.60 MHz
Receiver Center Frequency	149.22 MHz

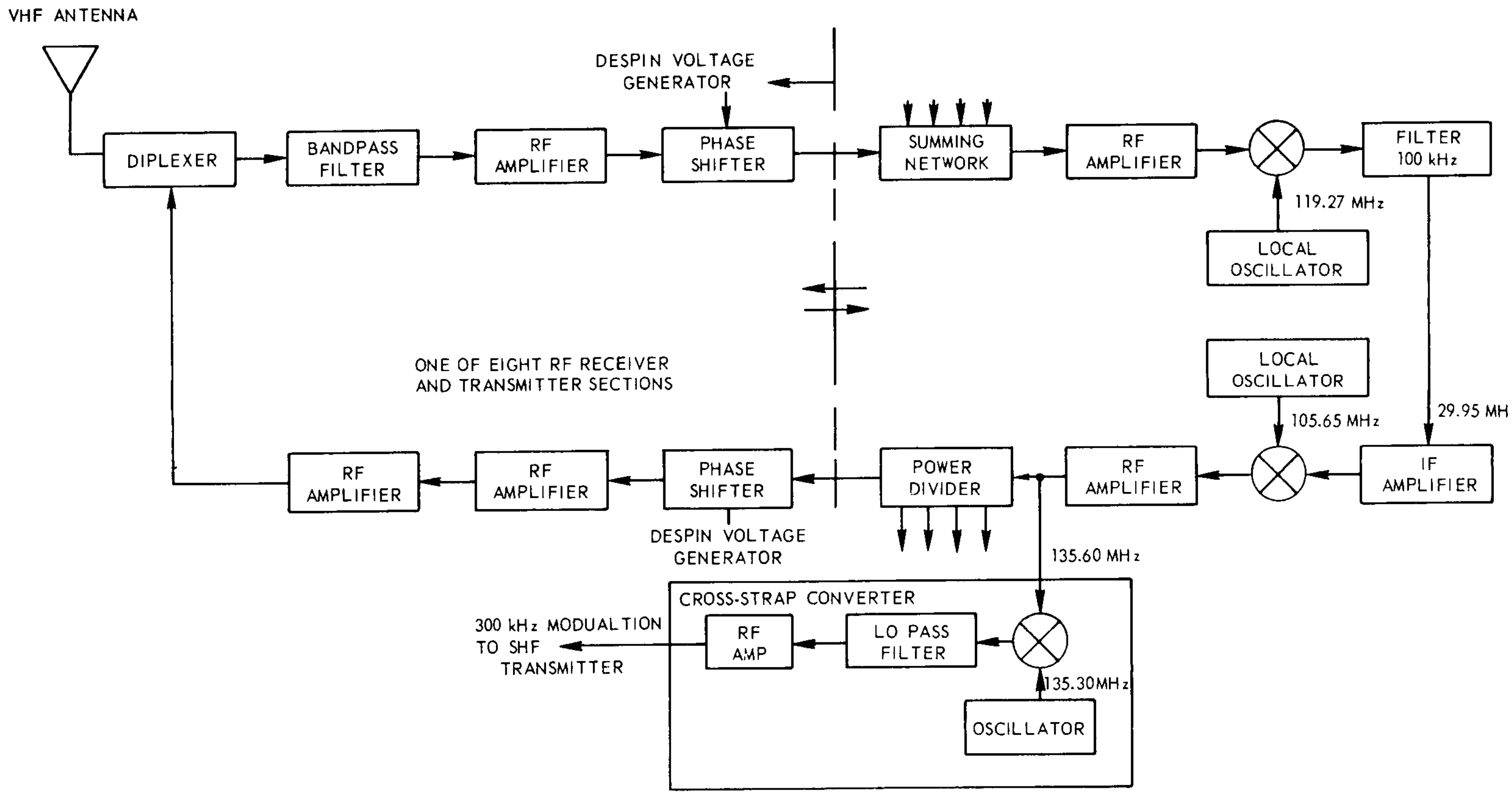


Figure 6. Satellite Transponder Functional Diagram

149.22 MHz are received on each dipole element, routed through a diplexer, amplified by a low noise receiver, and shifted in phase to compensate for the relative position of each of the antenna elements. The electronically controlled phase shifter in the receiver unit, driven by the satellite waveform generators, adjusts the output of each receiver to be in phase for only those signals that originate from the earth. The eight receiver outputs are summed, filtered, down-converted to an IF of 29.95 MHz, and passed through a crystal filter to limit the receiver bandwidth to a nominal value of 100 kHz. The IF signal is then amplified, up-converted to 135.60 MHz and divided into eight equal parts. Each of the eight signals is routed to a transmitter where it is phase shifted and further amplified to a power level of 5 watts. Each transmitter output is routed through its respective diplexer to one of the antenna elements. The transmitter phase shifter is controlled by the waveform generator, causing the signals from each antenna to reinforce in the direction of the earth.

As a backup mode for the VHF repeater, a cross strap converter (shown in Figure 6) is used to convert the 135.60 MHz signal to 300 kHz. This signal is then coupled to the SHF camera mode transponder through the voltage controlled oscillator (VCO), illustrated in Figure 7. This mode of operation can be selected by command from the Satellite Control Center. Table 4 lists the significant SHF (camera mode) repeater characteristics.

Table 4
SHF Repeater Characteristics

Repeater Output	Narrow-Band Frequency Modulation
Total Repeater Bandwidth	25 MHz
Transmitter Carrier Frequencies	4119.6 MHz 4178.6 MHz
Transmitter Output Power	3.9 dBW
SHF Antenna Type	Mechanically Despun Phase Array
SHF Antenna Gain	18 dB

The SHF camera mode transponder accepts input signals to the VCO over a baseband frequency range of 10 Hz to 5 MHz. The nominal VCO center

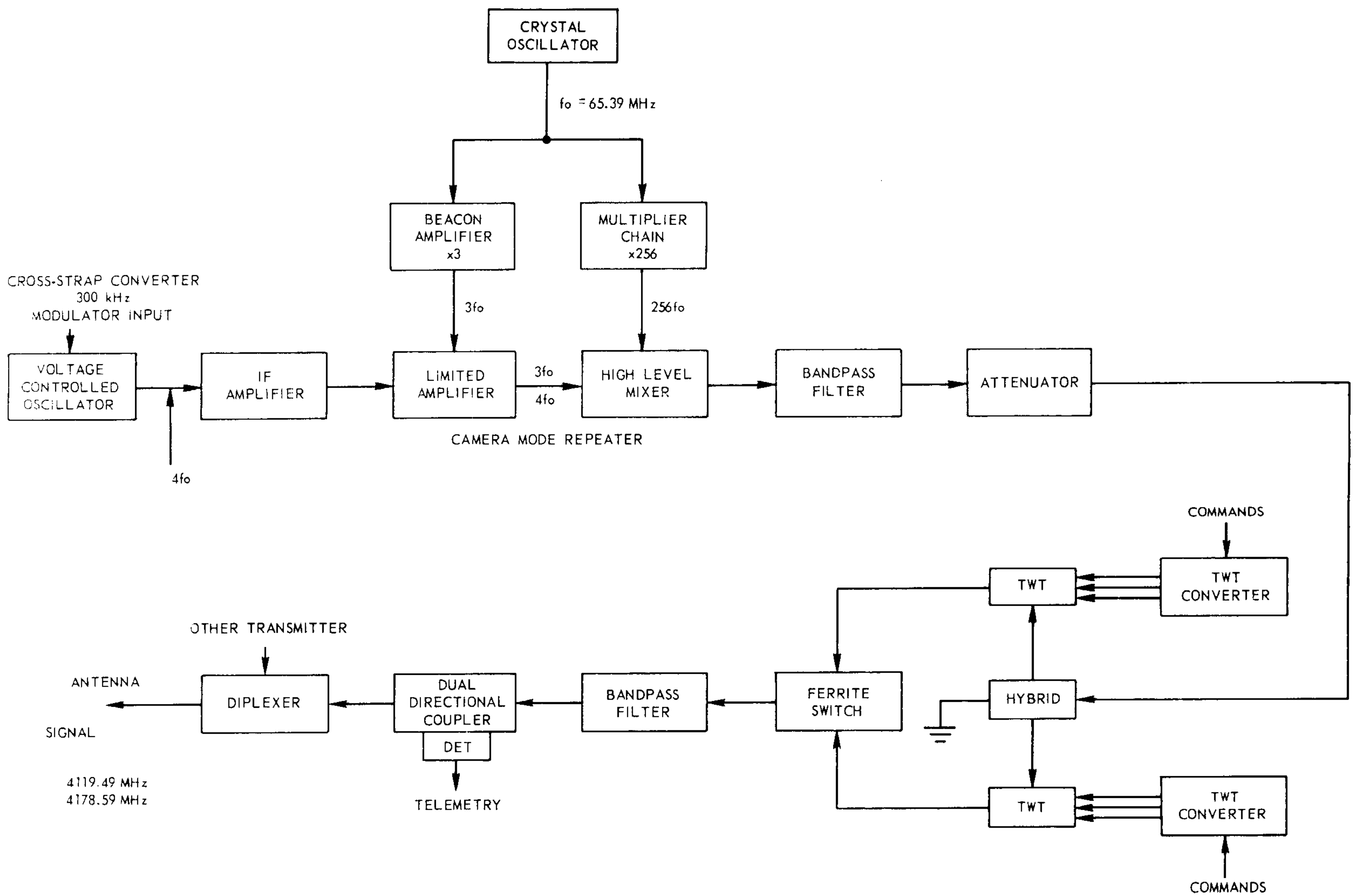


Figure 7. SHF Transponder Diagram (Camera Mode)

frequency is 65.39 MHz. The IF input signal level, derived from the VHF repeater, will be adjusted in amplitude so that the modulation index will be a minimum of 0.6 radians rms and a maximum of 1.2 radians peak. This will result in a carrier always being present in order to permit the use of a carrier-tracking phase-lock-loop at the Satellite Control Center. The FM output of the VCO is routed through the IF postamplifier to the limiter amplifier. The signal is limited to the proper level and coupled to the high level mixer where it is converted to the SHF transmitter frequency. It is then power-amplified by the TWT amplifier and coupled to the mechanically despun antenna which reinforces the signal in the direction of the earth.

3.2 Platform Electronics Package (PEP)

The PEP block diagram is shown in Figure 8. The operational sequence of the platform is determined by an on-board timer. Upon receipt of the proper platform address and upon the conclusion of the complete interrogation cycle the platform equipment is turned on and proceeds through the following normal sequence:

a. Transmit acquisition/reference (A/R) tone

b. Transmit meteorological sensor data

c. Transmit received Omega signals

d. Return to standby mode.

The PEP is capable of responding to four commands transmitted through the interrogation link as a part of the platform address. During the experiment, the commands will initiate the following actions:

1. Normal

2. Turn off entire system until next day/night transition

3. Transmit data only for entire three minute period

4. Abort balloon.

Command Number (1) has already been described. Command Number (2) is used to switch the PEP into a minimum power condition where the only system operating will be the light sensor electronics. This command will take effect immediately after the PEP completes a transmission sequence. If the

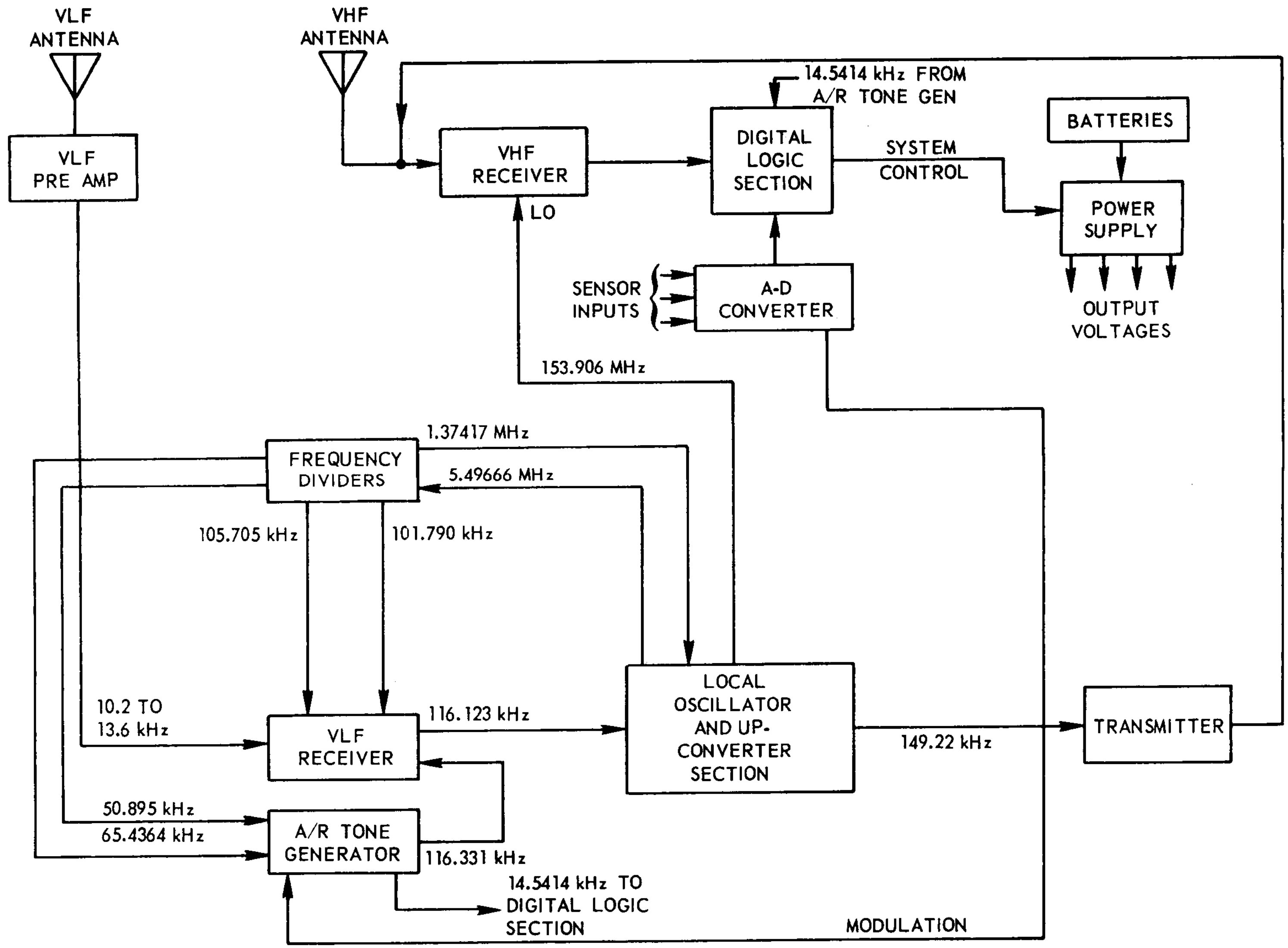


Figure 8. PEP Block Diagram

command is received during daylight, the PEP will revert to its minimum power condition until there is insufficient light to power the light sensor. At this time the VHF command receiver will be up-powered, and the PEP would again be ready to respond to interrogations. If this command is received during the night, the PEP will remain essentially off until daylight awakens it. Command Number (3) will be used for system link measurements and test purposes. Command Number (4) will be used for a balloon test and for resetting local monitoring equipment at remote sites.

The PEP has the capability of telemetering eight analog data channels. An analog-to-digital converter is incorporated to encode the sensor inputs into a seven level binary format. For this experiment, the data inputs will include the following:

a. Temperature inside the PEP

b. Temperature outside the PEP

c. +24 volt supply

d. +6 volt supply

e. -6 volt supply

f. For external monitoring equipment

g. For external monitoring equipment

h. For external monitoring equipment

The VHF receiver on board the PEP is operative at all times (except for day-night mode) and will receive the interrogation signals transmitted from the OCC through the satellite. The VHF receiver consists of a preselector, an RF amplifier with a 3.5 dB noise figure, mixer, IF amplifier, crystal filter, limiter-discriminator, and modulation sensing circuit. The receiver accepts a signal of 135.60 MHz that is FSK modulated with a deviation of ± 2.4 kHz. The discriminator detects the modulation while the modulation sensing circuit provides a dc signal to turn on the address decoder. Bit and word synchronization is established and 40 lines of address-command-parity are received. If the platform recognizes one of these addresses as its own it goes to "alert" but remains passive. When the interrogation carrier ceases to be transmitted by the OCC, a platform that has not been "alerted" reverts to standby mode; whereas, an "alerted" platform initiates its programmed transmission sequence by activating the timer. A sequence begins with transmission of the A/R tone at full PEP output power for approximately eleven seconds.

Meteorological data from the on-board sensors is then accepted by the A-D converter and the digitized data is phase modulated onto the A/R tone. The Omega signals are then passed through the VLF receiver. The VLF receiver accepts signals in a band from 10.2 through 13.6 kHz and compresses them to a bandwidth of 2 kHz. The mixing signals used in this process are derived from a temperature controlled crystal oscillator (TCXO) through a frequency divider. The frequency divider also provides signals to generate the A/R tone. The compressed VLF signal band, along with the A/R tone, is then up-converted to VHF at 149.22 MHz, amplified and retransmitted through the VHF antenna for a period of approximately 3 minutes.

Figure 9 illustrates the typical Omega data format with the frequencies shown for channel number twenty. The actual Omega signal levels will usually be below the VLF noise level when transmitted from the PEP. The 10.2 kHz,

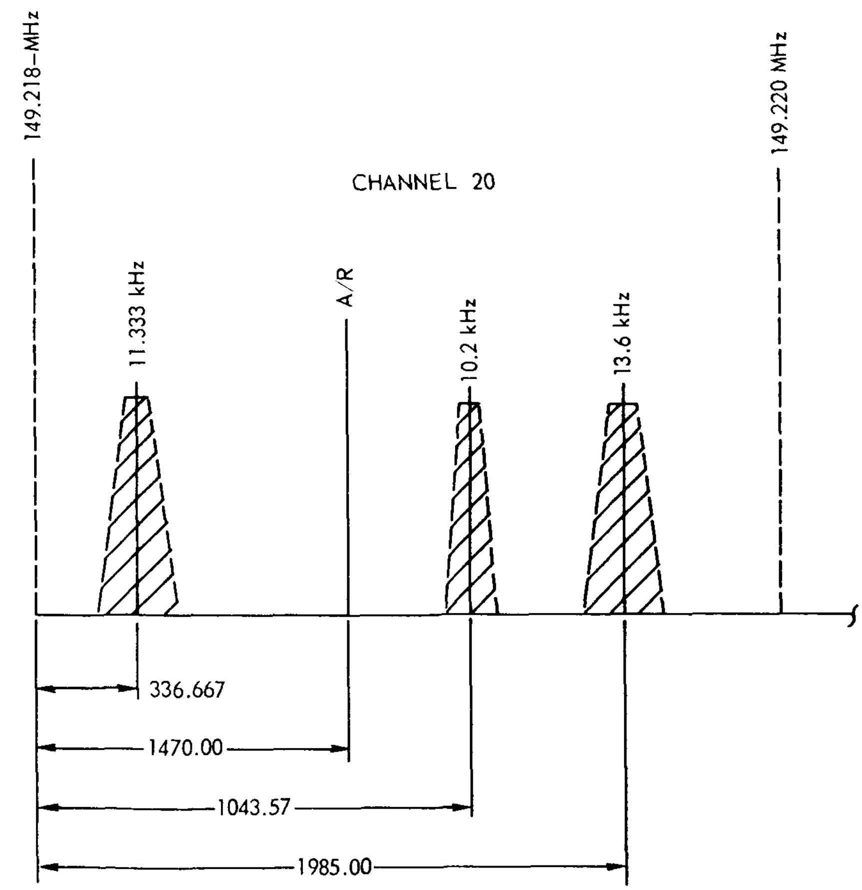


Figure 9. Typical PEP Data Spectrum

11.33 kHz and 13.6 kHz signals will be contained in noise bandwidths of 55 Hz, 140 Hz and 140 Hz respectively.

Figure 10 illustrates the detailed block diagram of the PEP. Oscillator f_2 provides a temperature compensated frequency source of 1 part in 10^6 over six months. It is used to provide the local oscillator sources for up-converting and compressing the Omega spectrum, the A/R tone, and the basic PEP timing. Oscillator f_1 is preset to provide one of forty permissible transmission frequencies. To obtain maximum use of the available satellite transponder bandwidth (nominally 100 kHz wide on ATS/C), each platform is assigned a channel approximately 2.5 kHz wide within the transponder bandwidth (see Figure 11).

The transmitter consists of three stages: the driver, intermediate power amplifier, and the power amplifier. The driver operates Class A and the remaining two stages are operated very close to Class B. The design of the transmitter is optimized to provide maximum efficiency while still producing a minimum of intermodulation distortion. The average output power is 5 watts. Since the transmitter and VHF receiver are time sequenced in operation, a diplexer is not required; instead, a switched device protects the VHF receiver circuitry during the PEP transmissions.

In an operational system the balloon platforms travel freely around the earth, and take on a variety of look angles to the satellite depending on their relative position to the earth. For look angles to the satellite that are outside of the 3 dB antenna beamwidth, the following situations exist:

a. The antenna gain decreases;

b. The polarization ratio degrades so that the system transmission loss will increase (5 dB for axial ratio of 3 dB); and

c. The amplitude of the PEP transmitted signal can vary by 2 dB depending on the polarization orientation of the balloon antenna relative to the linear polarized satellite antenna.

For these reasons, an antenna with a hemispheric antenna pattern in conjunction with a circular polarized satellite would be required for an operational system. The gain of this antenna can be 0 dB with the maximum polarization loss reduced to an invariant 3 dB if the axial ratio of a circularly polarized satellite antenna can be maintained to 1.5 dB over its earth coverage beamwidth (20 degrees).

Since the experiment is restricted to the use of the ATS/C transponder frequencies and linearly polarized antenna configuration, two antennas will be used to economically simulate an all purpose operational antenna.

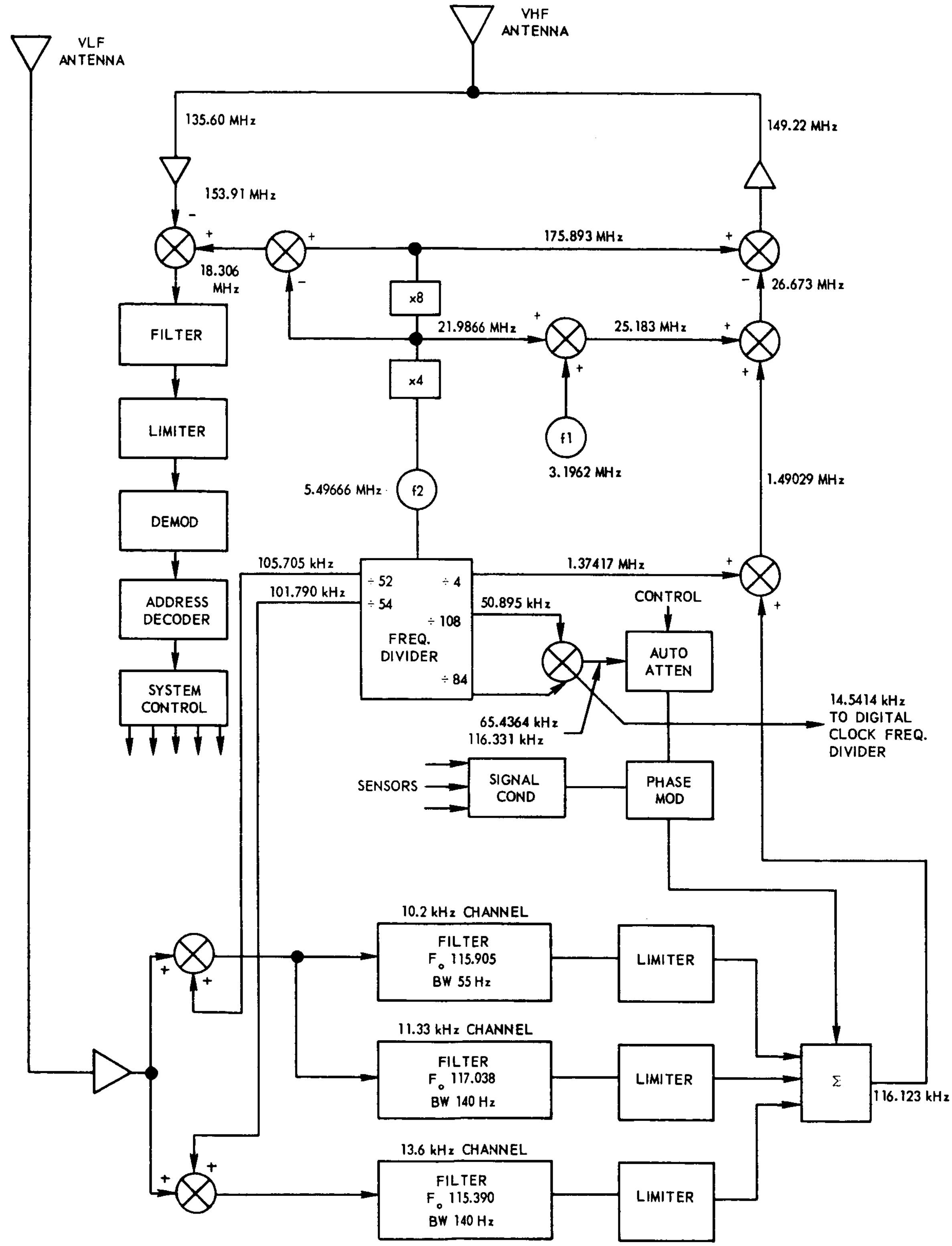


Figure 10. PEP Functional Diagram

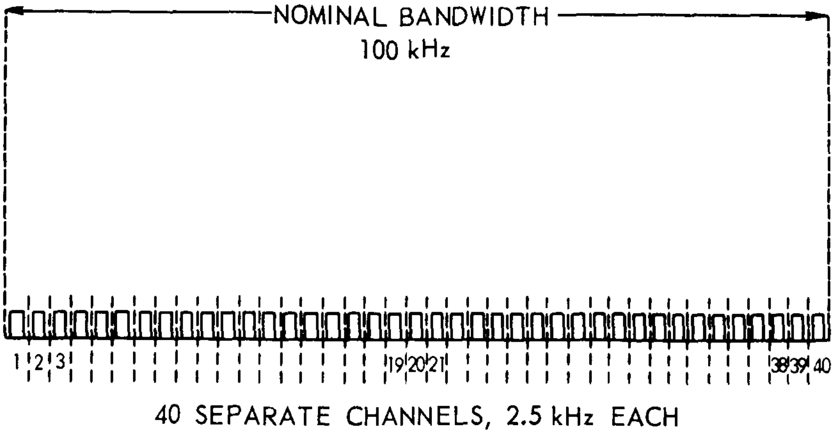


Figure 11. Satellite Transponder Channel Allocations

Either a loop-vee, or a crossed-dipole VHF antenna will be available for use with the PEP, depending on the satellite look angle from the deployment site. The loop-vee antenna has a 3 dB beamwidth coverage from 20 degrees to 50 degrees above the horizon and is right circularly polarized with an axial ratio of less than 3 dB over the half-power beamwidth. The crossed-dipole antenna is a 100 degree, 3 dB beamwidth (conical beam) and is circularly polarized with an axial ratio of less than 3 dB over the half-power beamwidth.

The approximate dimensions of the PEP are 12 inches × 12 inches × 5-1/2 inches with a weight of approximately 22 lb. A number of the packages at fixed sites will utilize a separate low voltage power supply. The approximate dimensions are 9 inches × 17 inches × 8 inches with a weight of approximately 22 lb. A small number of units will utilize batteries which will be approximately the same size and weight as the power supply.

The standby receiver primary power required for nominal battery voltages is 1.1 watts while the maximum primary power required to transmit is 35 watts.

3.3 OPLE Control Center (OCC)

The OCC performs six basic functions as follows:

a. Interrogation of the PEP's via the satellite

b. Simultaneous acquisition and continuous tracking of from one to four PEP's

c. Reception and demodulation of the meteorological data

d. Reception and processing of the Omega VLF signals to obtain the platform locations

e. Direct monitoring of the Omega stations in order to provide the required timing references, and

f. Simulation of full OPLE system operation by transmitting Gaussian white noise in unused PEP channels.

In addition to the prime functions of the OCC a self-check feature has been incorporated. The self-check signals, which consist of a simulated channel of sensor data, Omega signals and noise, can be used to verify the proper operation of the entire OCC.

A simplified block diagram of the OCC is shown in Figure 12. All of the processor-controlled timing signals utilized in the OCC are shown cross-hatched.

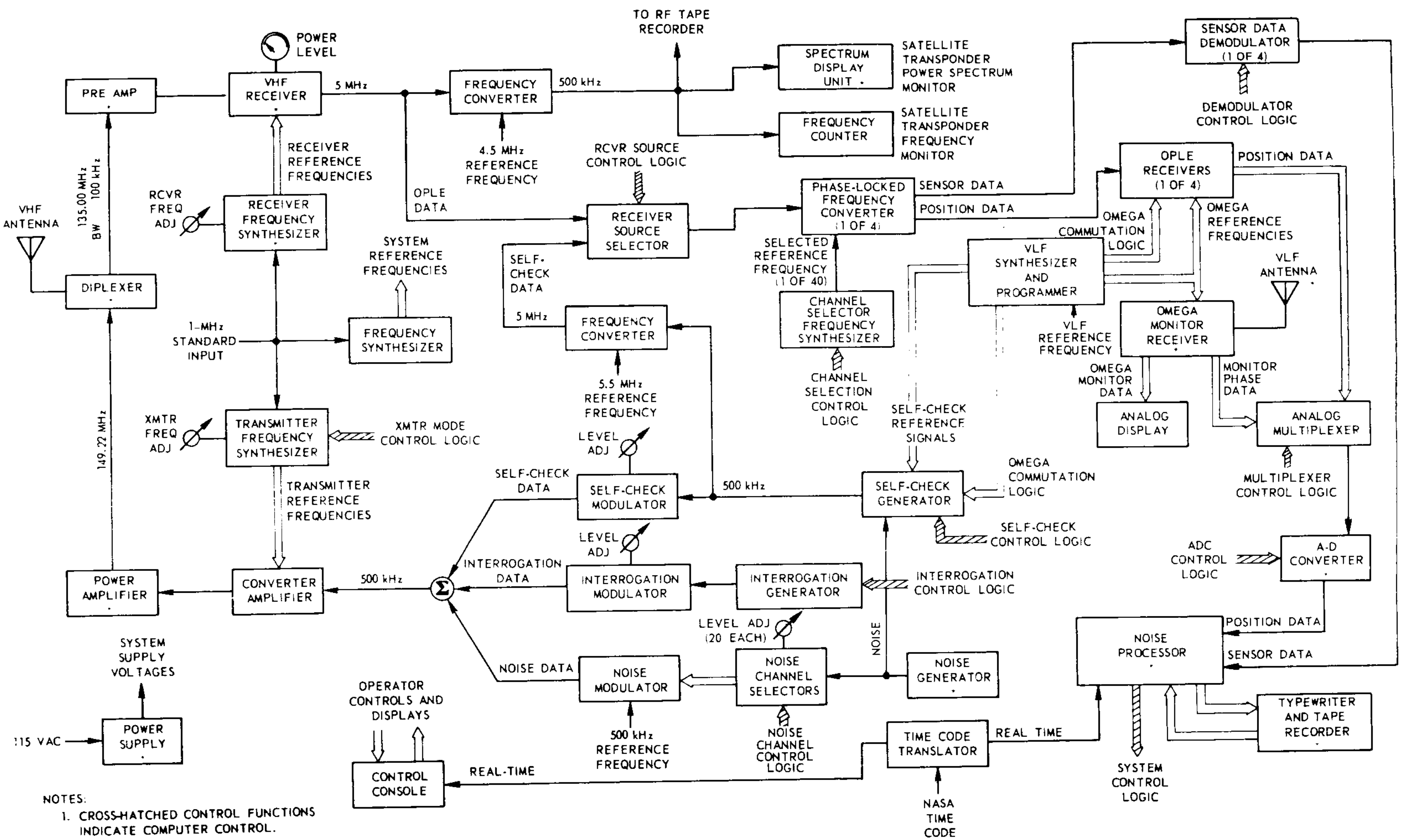
The following paragraphs discuss the detailed operation of the OCC.

3.3.1 Transmitter Operation

The signal processor selects one of two transmitting modes for the 149.22 MHz VHF transmitter. These are the Platform Electronic Packages (PEP) interrogation mode and the PEP simulation mode. In the PEP interrogation mode, programmed PEP addresses and commands are transmitted by the OCC. Noise data and/or self-check signals can be selected for transmission during the PEP data reception mode to simulate additional PEP data channels. A variable-frequency synthesizer provides the required transmitter reference frequency, and a power amplifier supplies the desired output power levels.

3.3.2 VHF Receiver

A 135.60 MHz VHF receiver accepts the PEP data transmissions and the PEP simulation data and provides a 5 MHz intermediate frequency output. The required receiver reference frequencies are provided by a variable frequency synthesizer. The 5 MHz VHF receiver output is converted to 500 kHz to provide inputs to the spectrum display unit and the frequency counter. In addition, the 5 MHz OPLE data is applied to a receiver source selector which selects either the OPLE data or the internally generated self-check data for processing by the OCC.



NOTES:
1. CROSS-HATCHED CONTROL FUNCTIONS INDICATE COMPUTER CONTROL.
2. COMMERCIAL EQUIPMENTS ARE DENOTED BY ASTERISKS (*).

Figure 12. OPLE Control Center Block Diagram

3.3.3 Channel Selectors

Four identical phase-locked frequency converters (channel selectors) select any four PEP data channels for processing, one for each OPLE receiver. The channel selector frequency synthesizer provides the 40 required reference frequencies, one for each of the 40 PEP data channels. In addition, a phase-locked-loop in each frequency converter tracks out any phase perturbations, caused by the PEP-Satellite-OCC link, in the incoming OPLE data. The phase-locked frequency converters provide detected meteorological data to the four sensor data demodulators and position data (Omega signals) to the four OPLE receivers.

3.3.4 Data Demodulators

The meteorological data is decoded by the sensor data demodulators and applied to the signal processor for formating. The position data (phase information) is processed by the OPLE receivers to obtain analog signals which represent the relative phases of the Omega signals.

3.3.5 Omega Monitor Receivers

The Omega monitor receiver accepts VLF signals that are received directly from the Omega transmitters and provides monitor data in two forms. One of these is Omega signal phase and/or amplitude information which is plotted directly on an analog recorder. The other is an analog representation of the relative Omega signal phases, which is identical in form to the OPLE receiver output data. The VLF synthesizer and programmer generates the self-check reference signals; the Omega commutation timing gates, and the Omega reference frequencies.

3.3.6 OPLE/Omega Signal Processing

The Omega signal outputs of the OCC channel selectors are applied through 40 Hz bandpass filters (which separate the individual Omega frequencies) to high gain amplifier/limiters. The constant-amplitude signals out of the amplifier/limiters are again applied to bandpass filters which remove the harmonics inserted by the limiters. Each of the resulting sinusoidal Omega signals is then applied to synchronous quadrature detectors. The outputs of the quadrature detectors represent the sine and cosine of the Omega signals. The sine and cosine signals are applied to simple resistor-capacitor integrators which have time constants of approximately one second. The analog sine and cosine outputs of the integrators are time division multiplexed and then digitized by an analog to digital convertor. The resulting binary signals are applied to a general purpose signal processor for further processing.

The signal processor averages the Omega signals over a three-minute period to obtain improved S/N ratios; at the same time phase errors due to time and frequency errors (Doppler shifts, platform oscillator instabilities, et cetera) are minimized. The Omega signals received by the OCC have four major sources of error. These are: (1) platform reference oscillator instability, (2) platform velocity relative to the satellite, (3) platform velocity relative to the Omega stations, and (4) random noise. The processor reduces the noise error by integrating each sample for approximately one second and then summing 18 of these samples. The three frequency perturbations are grouped into one offset frequency error that is assumed to be constant over the 180-second sampling period. The offset frequency error appears as velocity components in the phase angle measurements of the Omega tones when their phases are computed in the processor. This gives rise to two serious problems:

a. Unless this velocity component is nulled, phase measurements taken for a given Omega frequency when summed for improvement of S/N ratio will not add with equal phase angles,

b. For the purpose of hyperbolic lane resolution and triangular position location, phase measurements taken at different times will not correlate.

If the offset frequency is correctly calculated for one of the three Omega carrier signals, this value is used to determine a rough approximation for the offset frequency associated with the other two signals from the same Omega station. Once offset frequencies have been calculated for all signals, corrected phase measurements are calculated and recorded.

Appendix A outlines the techniques utilized, in the signal processor, for determining the offset frequency and correcting the Omega station phase measurements. Appendix B presents the calculated phase errors introduced by both input noise and the OCC processing method. These errors are tabulated in Table B-1.

The general-purpose signal processor not only provides the required position data processing, but also performs the system control functions, and formats the sensor data and position data for readout. Input/output information is communicated to the signal processor by means of a typewriter and magnetic tape recorder. Operator controls and the required displays are provided at the control console, and real-time signals are derived from the NASA time code input. The control console is capable of being operated by one operator and under normal conditions will initiate all control center sequences and monitor the overall operating status of the OPLE experiment.

3.4 System Transmission Links

Proper operation of the OPLE system is dependent upon the achievement of satisfactory signal-to-noise ratios in both the OCC to PEP link and the PEP to OCC link. During interrogation of the PEP by the OCC, the signal-to-noise ratio at the discriminator in each platform receiver determines the probability of bit error in the interrogation signal.

For the PEP to OCC link, the signal-to-noise ratio at the OCC receiver determines:

a. The ability of the phase-lock circuits to acquire and continuously track the (A/R) tone

b. The bit error rate on the PEP sensor data transmission

c. The accuracy of the Omega signal phase measurements.

The limiting portion of the overall system transmission link will be the PEP to OCC link. The following paragraphs discuss the system transmission links and include descriptions of the different modulation techniques used.

The interrogation link modulation and code characteristics are listed as follows:

Type of Code	Split phase (Manchester)
Bit Rate	48 bits/sec
Type of Modulation	FSK
Frequency deviation	±2.4 kHz
Worst case bit error probability	Better than 10^{-6}

The 149.22 MHz interrogation signal is down converted in the satellite transponder to 135.60 MHz. The VHF receiver on the PEP detects the modulation and turns on the PEP address decoder and starts the PEP clock. The individual PEP's remain on "alert" if they have received their correct address until all 40 platforms have been interrogated. After the interrogation carrier ceases, the interrogated platforms are up-powered and begin their transmission sequence.

The transmission link from the platform to the OCC, via the satellite, is comprised of three time multiplexed transmission modes listed as follows:

1. Transmission of an (A/R) tone for acquisition by the OCC phase-lock-loop

2. Transmission of meteorological data

3. Transmission of Omega position information

In both the data transmission mode and the Omega transmission mode, it is required that the A/R tone be in phase lock with a local reference signal at the OCC. To decrease the acquisition time a large loop bandwidth (150 Hz) is used, and all of the PEP transmitter power is provided for this transmission mode. The acquisition time is approximately 7 seconds. When lock is achieved, the time constant of the loop filter is automatically switched to change the loop bandwidth to 10 Hz for continuous tracking of the A/R tone when the PEP power is shared with the data signals.

During meteorological data transmission, the A/R tone is PSK modulated with the following characteristics:

Type of Code	Split phase Manchester
Bit rate	56 bits/sec
Modulation	PSK
Modulation index	$\pm 60°$

The effective bandwidth for the meteorological data demodulation is approximately 100 Hz.

The primary requirement of the platform to OCC Omega transmission link is that the added system noise be negligible compared to the PEP received VLF signal-to-noise ratio. The VLF Omega receiver's worst-case output will consist of a number of discrete tones whose total power will be small compared with the total VLF noise power. The minimum S/N that has been chosen for which the system will perform within specifications is O dB in a one Hz bandwidth. Figures 13 and 14 show the anticipated signal-to-noise ratios versus PEP receiver-Omega transmitter distances. Figure 13 is an approximate lower bound whereas Figure 14 is an approximate upper bound on an experimentally determined range of values (References 7 and 8).

Phase perturbations of any kind over the VHF links between the platform and the OCC are sources of error in position location. Because phase comparisons are made between Omega signals which are transmitted with up to 5 seconds separation, it is possible that the effective path length from the PEP to the OCC can change considerably between the two Omega transmissions. If this

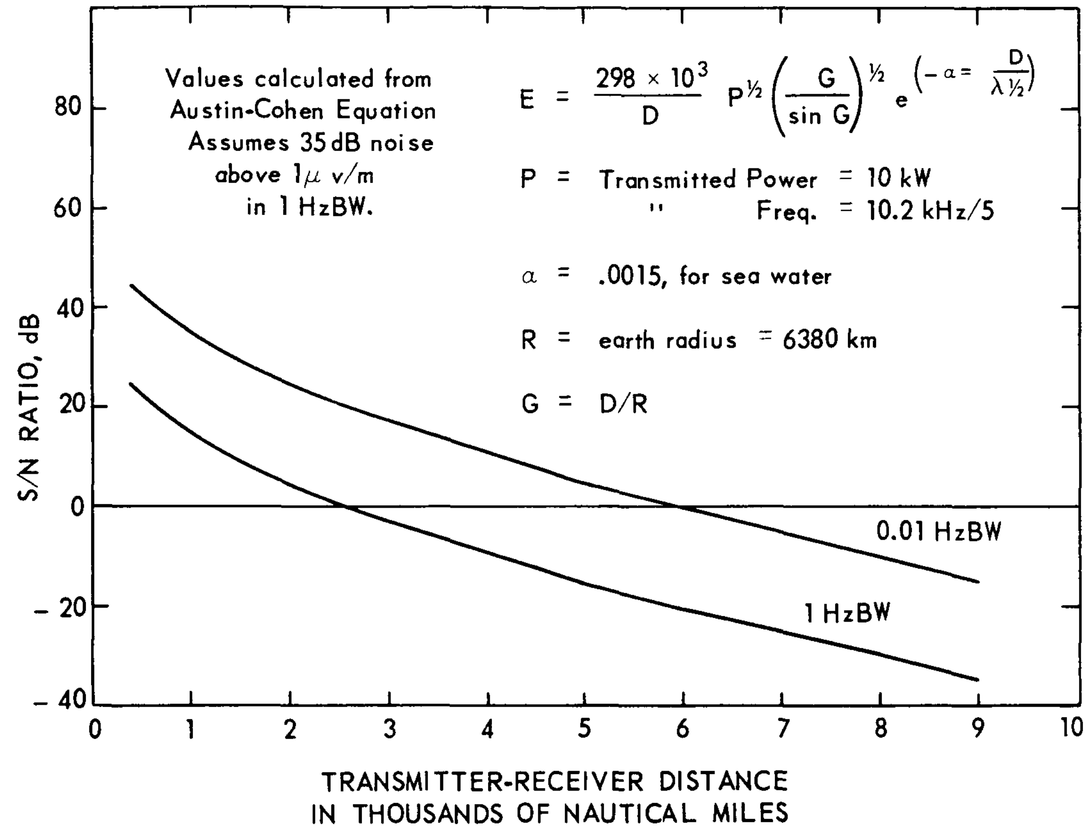


Figure 13. S/N Ratio vs Transmitter-Receiver Distance (D) for 10.2 kHz

happens, phase errors will occur when the two Omega signal phases are compared. To alleviate this problem, the A/R tone is continuously transmitted along with the Omega signals, which are fixed in frequency with respect to the A/R tone. At the OCC a local oscillator is phase-locked to the A/R tone to remove the phase perturbations encountered in the VHF link. Table 5 summarizes the typical received carrier-to-noise ratios expected for the transmission links.

3.5 System Timing

The system timing after interrogation is controlled by the platform clock. The timing sequence for the interrogation link is shown in Figure 15 and the timing sequence for the PEP transmissions after cessation of the interrogation modulation is shown in Figure 16. The sequence of events for the entire system is as follows:

a. The (OCC) operator programs the general purpose signal processor to interrogate selected platforms at a particular time. At this time the

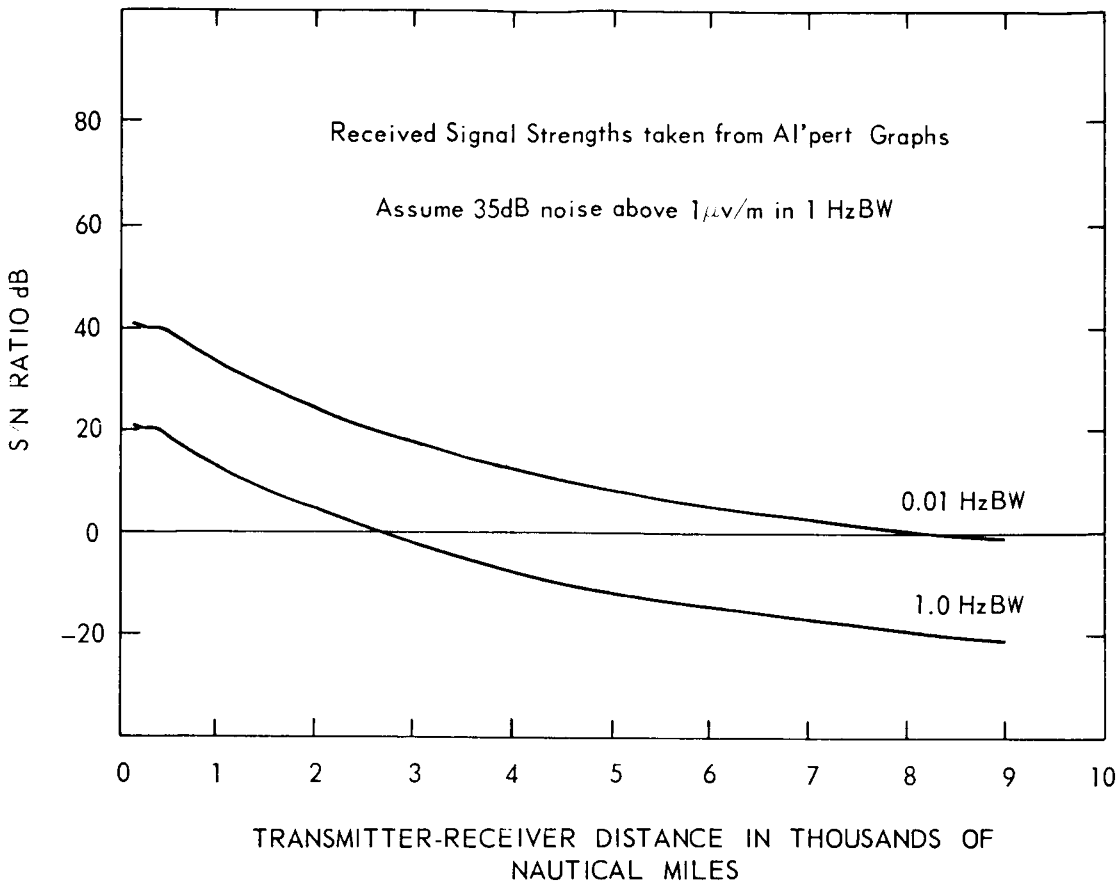


Figure 14. S/N Ratio vs Transmitter-Receiver Distance for 10.2 kHz

OCC sequentially transmits the unique address codes assigned to the selected platforms. A total of 45 lines of interrogation format are transmitted at 16 bits per line. The total interrogation time is 15 seconds.

b. The satellite transponder receives the interrogation data, side steps to the transmitter frequency, and relays the interrogation to all OPLE platforms.

c. The PEP VHF receiver receives the carrier at 135.60 MHz.

d. The PEP VHF discriminator detects the modulation and rectifies the detected signal. The resultant DC voltage turns on the address decoder. Three lines of bit sync (1 second) are made available in the interrogation format for this function.

TABLE 5

Platform-Satellite-Ground Station 2.5 kHz Bandwidth Location and Data Channel		Ground Station-Satellite-Platform Interrogation Channel	
Uplink 149.22 MHz	Nominal	Uplink 149.22 MHz	Nominal
Radiated Power 5W minimum	7.0 dBW	Transmitter Power (40 watts)	16.0 dBW
Platform Antenna Gain	2.0	Ground Station Cable Losses	3.0
Polarization and Tracking Losses	4.0	Ground Station Antenna Gain	13.0
Path Losses	167.9	Path Losses	167.7
Satellite Antenna Gain	8.0	Polarization Losses	4.0
Satellite Cable Losses	1.3	Satellite Antenna Gain	8.0
Satellite Receiver Noise Power (2.5 kHz)	164.1 dBW	Satellite Cable Losses	1.3
Received Carrier-to-Noise Ratio	+7.9 dB	Satellite Receiver Noise Power (100 kHz)	-148.1 dBW
		Received Carrier-to-Noise Ratio	9.1 dB
Downlink 135.6 MHz		Downlink 135.6 MHz	
40 watts total 1.0 watt/channel		Transmitter Power	16.0 dBW
Transmitter Power	7.0 dBW	Satellite Cable Losses	1.8
Satellite Cable Losses	1.8	Satellite Antenna Gain	8.0
Satellite Antenna Gain	8.0	Path Losses	167.1
Path Losses	166.9	Polarization Losses	4.0
Polarization Losses	4.0	Platform Antenna Gain	2.0
Ground Station Antenna Gain	13.0	Platform Cable Losses	1.0
Ground Station Cable Losses	2.5	Platform Receiver Noise (7.5 kHz)	160.6 dBW
Ground Station Receiver Noise (2.5 kHz)	154.2 dBW	Received Carrier-to-Noise Ratio	+12.7 dB
Received Carrier-to-Noise Ratio	+7.0 db		

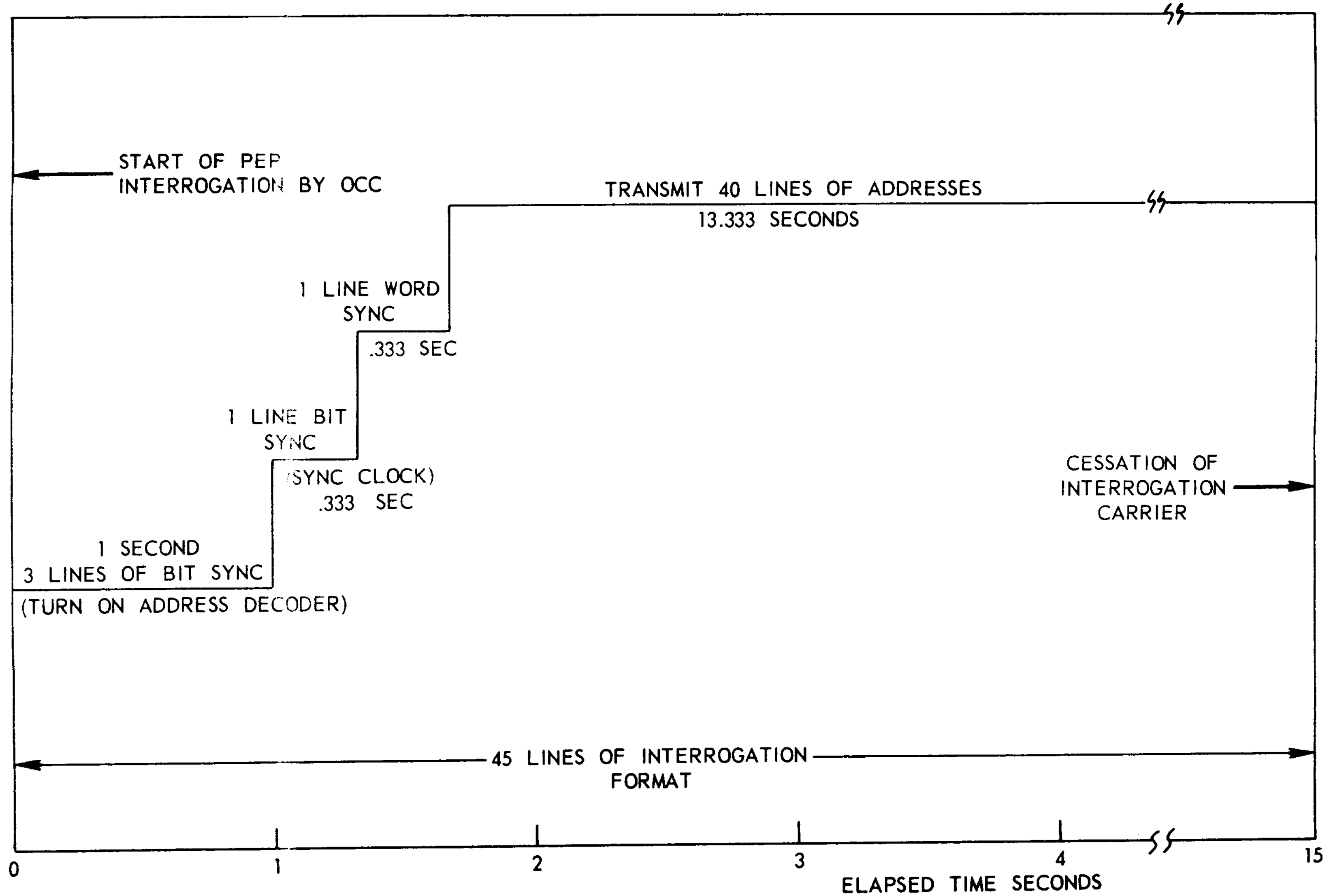


Figure 15. Interrogation Timing Diagram

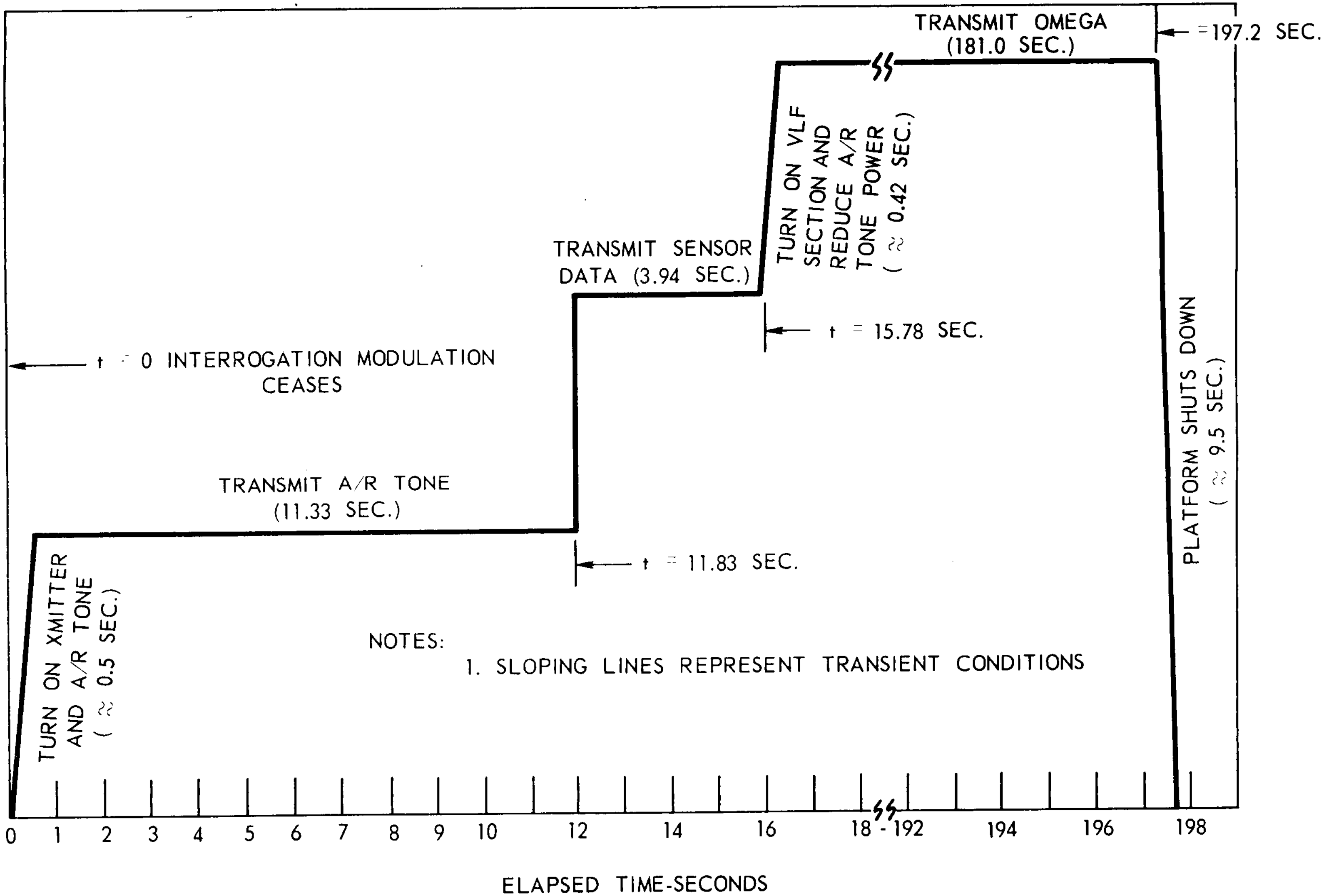


Figure 16. PEP Timing Diagram

e. A fourth line of bit sync is received and utilized to synchronize the PEP clock.

f. A line of word sync is received.

g. 40 lines of address-command-parity are reviewed, taking approximately 13 seconds. If the platform recognizes one of the addresses it goes to "alert" but remains passive.

h. The interrogation carrier ceases to be transmitted by the ground station (this represents t_o on the PEP timing diagram).

i. The cessation of modulation causes the dc voltage from the modulation sensor to decay. When threshold is reached, the platform timing clock will begin operation. The accuracy of the clock is 1 part in 10^6, however, the initial turn-on has a tolerance of ±40 milliseconds. Simultaneously with the start of the clock, power supplies are turned on to begin transmitting the A/R tone for a period of 250 milliseconds. Thus, the A/R tone will be at full power approximately 0.5 second after $t = 0$.

j. The A/R tone will be transmitted at full power for approximately 11 seconds. Just A/R tone transmission will end at time $t = 11.8$ seconds. Sensor data modulation begins at this time.

k. Sensor data is transmitted for 3.9 seconds and ceases at time $t = 15.8$ seconds.

l. At this time A/R tone level is reduced to 0.5 watts and the Omega signals are turned on. The transition time will not exceed 420 milliseconds.

m. Omega signals are transmitted for no less than 181 seconds until time $t = 197.2$ seconds.

n. The platform then reverts to standby, with only the VHF receiver on.

o. At time $t = 197.7$ seconds platform interrogation may again begin.

4. PLATFORM DEPLOYMENT

There will be twelve platform equipments fabricated and deployed for the ATS/C experiment. Seven of these will be located at widely spaced fixed sites to evaluate VLF propagation parameters, VHF communication links and unattented equipment performance. There will also be five mobile equipments located to evaluate (in addition to the above) differential location accuracy, velocity measurements through sequential interrogations, Doppler effects, and multipath effects.

Four of the fixed sites are NASA operated tracking stations which will provide good voice communications with GSFC and allow ease of installation. The Network Engineering and Operations Division of GSFC will assist in the installation and housing of these units.

The investigators will directly deploy three units. The first unit is the engineering model PEP and it will be permanently rack mounted in the OCC to provide a standard reference for system operational checks. The second unit will be deployed in the vicinity of GSFC and moved periodically to determine the resolution of the system for fixed intervals during the experiment. The third unit will be van mounted to evaluate VHF and VLF communications under fixed and moving conditions. The VLF reception through these units will be compared with the VLF monitoring station at GSFC and with Omega receivers located adjacent to several of the PEP's.

The Environmental Science Services Administration (ESSA) will assist in the deployment of four units. The first unit will be a fixed ground platform located in the North Central region of the United States. The site will be located at St. Cloud, Minnesota, a weather station which can provide a good weather history of the area to correlate with the reception of Omega signals. The second unit will be located at Torbay, Newfoundland, also a weather station, operated by the Meteorological Service of Canada. The third unit will be located aboard a United States Coast and Geodetic Survey ship. The fourth unit will be located on a balloon and launched from the National Center for Atmospheric Research's center at Palestine, Texas during favorable wind conditions to evaluate the use of OPLE for a horizontal balloon sounding system.

The Federal Aviation Agency (FAA) will install a PEP aboard an aircraft suitably equipped with VLF and VHF antennas. This aircraft will fly along a prescribed flight path of known location to provide geographical correlation with the PEP equipment.

The following is a list of the tentative experimental platform locations:

a. Winkfield, England (NASA) STADAN Site

   This is the most north-easterly location from the sub-satellite point. The very low antenna elevation angle will provide a test of the VHF communications link.

b. <u>Grand Canary Island, Spain</u> (NASA) Manned Space Flight Network

This site is surrounded by water providing multipath and fade conditions to evaluate the VHF communications link as well as providing comparison VLF data with the Bermuda site.

c. <u>Bermuda, United Kingdom</u> (NASA) Manned Space Flight Network

This site is in a favorable position to receive all Omega signals which will be compared with the signals received by the U.S. Navy OMEGA monitoring station presently located there.

d. <u>Quito, Ecuador</u> (NASA) STADAN Site

This site will provide near sub-satellite point communications, and is the most southernly site for evaluation of the VLF link.

e. <u>GSFC Fixed Differential</u>

This will be a local unit near GSFC to determine system resolution and differential accuracy.

f. <u>GSFC Mobile</u>

This unit will be used to evaluate static and dynamic system parameters under controlled conditions. This van will also be equipped with an Omega monitoring receiver and will be used to monitor the Omega reception in the St. Cloud, Minnesota and Palestine, Texas sites.

g. <u>GSFC OCC</u>

This unit will be used to routinely check the complete system communications links, and provide a basis of comparison with the GSFC fixed differential unit.

h. <u>St. Cloud, Minnesota</u> (ESSA)

This land locked site will be receiving Omega communications from Aldra, Norway over the Greenland Ice Cap. This link will be compared with the reception at Torbay, Newfoundland which is not shadowed by Greenland.

i. Torbay, Newfoundland (ESSA)

This site will receive Omega signals from Aldra and Trinidad over a water path, and Forestport, New York over a land path. These VLF links will be compared with the reception at St. Cloud, Minnesota.

j. Ship (ESSA)

This unit located on the USC & GSS Discoverer, will provide information concerning VHF performance and VLF propagation characteristics over a wide latitude on a moving platform on the ocean.

k. Balloon (ESSA)

This unit launched from Palestine, Texas will provide information to determine optimum interrogation time intervals for moving balloons.

l. Airplane (FAA)

This unit located aboard an aircraft and flown in the vicinity of Atlantic City, New Jersey will provide controlled flight data to be correlated with the balloon flight. Doppler shifts and signal multipath over land and sea will also be evaluated.

5. SYSTEM TESTS

An operational test plan is being prepared for the OPLE experiment. This plan is designed to demonstrate the full capability of the OPLE system to perform its basic objectives. These objectives in order of their importance are (1) the interrogation and position determination of a single remote platform, (2) the simultaneous interrogation and position determination of up to four remote platforms, (3) the investigation of system performance with moving vehicles including van, ship, aircraft, and possible balloon and buoy platforms and (4) the investigation of differential OPLE measurement techniques. The operational test plan is designed to cover six months of testing. It includes four phases with each succeeding phase providing for more intensive and comprehensive tests than the previous phase. However, certain basic tests will be continued throughout the test period in order to obtain the necessary amount of long term data and to establish confidence in the overall operation of the OPLE system.

The first test phase consists of a group of basic engineering tests to be called the Engineering Test Plan. This phase of the test will last for approximately fifteen days and is designed to provide confidence in the overall adequacy of the system. The tests will be in the form of an operational performance checkout of the basic components of the experiment. The primary objective of this test phase will be to demonstrate the capability to locate one remote platform with a reasonable degree of accuracy (±2 n.mi.) on a reliable basis.

The second test phase is designed to acquire data on the multiple access capability of the experiment. Up to four remote platforms will be simultaneously interrogated on a routine basis. The primary objective of this phase is to demonstrate the capability of simultaneously locating with a reasonable degree of accuracy (±2 n.mi.) up to four remote platforms.

The third phase of tests is designed to measure the error contributions of each portion of the system as well as the total system error. The primary objective of this phase of the test program is to determine the errors inherent in the system and to assess the magnitude of the contribution of each portion of the system.

The fourth phase of tests is designed to provide long term routine data on the operation of the experiment. The primary purpose of this phase is to determine the overall capability and reliability of the experimental system including a simulation of up to forty platforms.

The test plan incorporates communication link evaluation tests which will determine the characteristics of the various transmission links used by the OPLE experiment. This includes measurements of the VLF propagation parameters which effect the performance of the OPLE system such as the VLF propagation velocity as affected by diurnal and seasonal changes, the nature of the band limited VLF noise spectrum and its affect on the accuracy of the OMEGA phase measurements, the VLF signal strength at various distances and directions from the Omega transmitting stations, and the relative phase measurement accuracy obtainable between two platforms as a function of platform separation distance. Sufficient data will be collected to support a complete statistical analysis of the VLF parameters including absolute accuracy, relative accuracy, and ambiguity resolution. Measurements of the VHF link to determine frequency and phase stability, noise characteristics, multipath propagation, cross-channel interference and other VHF parameters pertinent to the OPLE system performance are included. Data will be collected to permit a statistical analysis of the VHF parameters and to determine the degree that each one affects the OPLE system performance. Successive tests will be conducted at different times of the day to investigate the satellite VHF link characteristics. The effect of atmospheric and other disturbances (rain, clouds, fog, lightning, etc.) will be investigated to the extent permitted by the existing conditions at the time of conducting the experiment. Measurements will be made of the received signal strength, dynamic range, signal-to-noise ratio, fade characteristics, phase modulation and noise frequency modulation, frequency translation and stability, intermodulation distortion, and/or other parameters as applicable for the type of source signal.

The test plan also includes measurements of the SHF link to determine its performance parameters and to compare it with the performance of the VHF link.

6. MANAGEMENT

The Goddard Space Flight Center of the National Aeronautics and Space Administration will conduct the scientific investigation of the Omega Position Location Equipment Experiment and is producing the necessary equipments to demonstrate operational feasibility.

Responsibility for the investigation is assigned to the Application Experiments Branch of the Systems Division, Goddard Space Flight Center. Mr. A. E. Jones is Chief of the Division and Mr. R. H. Pickard is Head of the Application Experiments Branch.

Contractors are being utilized to develop and fabricate the various equipments necessary for the experiment. Administrative support is being provided through Dr. Michael J. Vaccaro, Assistant Director, Office of Administration.

The Principal Investigator is Mr. Charles Laughlin, Assistant Branch Head of the Application Experiments Branch. He is responsible for defining the overall goals of the experiment and assuring that the various equipments are technically capable of meeting these goals.

The co-investigator is Mr. Gay E. Hilton, Systems Engineer in the Application Experiments Branch. He is responsible for the specification and implementation of the OCC equipments to be built by the contractors. He will also be responsible for the Data Acquisition and Data Reductions efforts.

Mr. Harold Horiuchi of the Applications Experiments Branch is the OPLE Project Manager. He is responsible for the overall implementation of the OPLE experiment, including contract management and coordinating the efforts of the various groups participating in the experiment.

Mr. Richard Lavigne, Systems Engineer, Applications Experiments Branch, is the technical officer for the Platform Electronics Package contract and will be responsible for the field deployment of the experimental platforms.

Mr. M. Aleksandrov, Applications Experiment Branch, is responsible for the installation and operation of the GSFC Fixed Differential System Platform.

The Tracking and Data Systems Directorate is responsible for the operation of the OPLE Control Center at GSFC and for supporting the deployment of the platform packages at the STADAN and MSFN stations. The T and DS Directorate is also supporting the data analysis requirements of the experiment. Mr. C. A. Schroeder is responsible for the overall T and DS support for the experiment with assistance from the following:

Mr. B. Truedell, OPLE Tracking and Data Systems Manager
Mr. A. Chi, OPLE Tracking Scientist
Mr. J. Maley, OPLE Control Center Manager
Mr. R. Granata, Technical Officer, OCC Contract
Mr. W. Alford, Data Processing Engineer
Mr. V. Turner, Communications Engineer
Mr. D. Grove, Coordinator, STADAN Station Platform Deployment
Mr. D. Bonnell, Coordinator, MSFN Station Platform Deployment.

Agencies and personnel cooperating in the OPLE experiment are:

Mr. Holmes Moore of the National Environmental Satellite Center is directing the overall ESSA cooperative efforts and liaison with the Meteorological Service of Canada.

Platform installation aboard the USC & GSS Discoverer will be under the direction of Captain Raymond Stone of the Coast and Geodetic Survey, ESSA.

The balloon platform tests will be conducted under the direction of Mr. Vincent Lally of the National Center for Atmospheric Research.

Aircraft Platform Tests will be coordinated by Mr. Allan B. Moody, Long Distance Navigation Branch, F.A.A.

REFERENCES

1. "The Feasibility of a Global Observation and Analysis Experiment," Publication 1290, National Academy of Sciences National Research Council, Washington, D. C., 1966.

2. "Omega, A World-Wide Navigational System," System Specification and Implementation. Prepared by the Omega Implementation Committee for the U.S. Navy Department, Bureau of Ships, and submitted through the Office of Naval Research. Published for the Committee by Pickard and Burns Electronics, 103, Fourth Avenue, Waltham 54, Massachusetts.

3. "Omega Navigation Capability Based on Previous Monitoring and Present Prediction Ability," by E. R. Swanson, 5 June 1964. Navy Electronics Laboratory, San Diego, California Report 1226.

4. "Rendezvous Accuracy of the Omega Navigation System," by J. W. Brogden, A. N. Duckworth and J. J. O'Neill, 17 November 1964. Radio Division of Navy Research Laboratory, Washington, D. C. NRL Memorandum Report 1573.

5. "Meteorological Experiment Using the Omega Systems for Position Location," October 1965, GSFC Report No. X-731-65-416.

6. "Description of Experimental Omega Position Location Equipment (OPLE)," January 1966, GSFC Report No. X-731-66-20.

7. Al'pert, Ya. L., "Radio Wave Propagation and the Ionosphere," pp. 256-258, Consultants Bureau Enterprises, Inc., 1963, Authorized translation from the Russian, USSR Academy of Sciences Press, Institute of Terrestial Magnetism, the Ionosphere, and Propagation of Radio Waves, 1960.

8. "Electromagnetic Field Strength Measurements at 10.2 Kilocycles Per Second," by E. R. Swanson, 17 September 1964. Navy Electronics Laboratory, San Diego, California Report 1239.

ACKNOWLEDGEMENT

The possibility of using the Omega Navigation System for the location of meteorological platforms was first brought to the authors' attention by Dr. John W. Townsend, Jr. of the Goddard Space Flight Center in January 1965. He referred the authors to Mr. H. S. Moore of the National Environmental Satellite Center who was performing a preliminary system definition of the GHOSTS and SCOMO concepts in which the Omega System was considered the best means for balloon location.

The authors gratefully acknowledge the assistance and support of many governmental and private individuals and organizations who have been of great help during the formative stages of the OPLE concept.

APPENDIX A

OCC PROCESSING OF THE OMEGA SIGNALS

The OPLE Control Center utilizes an open loop offset-frequency estimating technique to eliminate the need for a highly stable frequency source on the platform (the actual requirement being 1×10^{-6} for six months). The offset-frequency error introduced into the platform transmission is proportional to the PEP local oscillator stability and the doppler frequency shifts between the platform and both the satellite and the Omega stations.

The Omega signal is corrected for frequency errors by a two-step process. The first step employs a trial and error method which applies a series of anticipated corrections and then selects the optimum correction value. This reduces the offset over the 180-second period from several cycles to a value less than 270 degrees. This is a rough approximation for the true frequency and is further processed in the second step to obtain a fine value of frequency offset. The fine correction for the 10.2 kHz Omega frequency is multiplied by a constant and used as the rough approximation of the frequency offset for the 11.33 kHz and 13.6 kHz signals that are transmitted from the same Omega station.

The value of the correction factor can be determined by calculating the maximum frequency offset due to worst-case conditions. The upper and lower limit of the trial offset coorection factors is established by the maximum frequency offset, and the number of samples attempted is determined by the output resolution requirements.

The frequency offset, w_d, for the 10.2-kHz Omega frequency can be expressed as follows: (Similar expressions result for the 11.33 and 13.6 kHz signals).

$$w_d = f_{10.2\ kc} = 10^{-6}\ (17.5\ V_p + 0.73\ V_s + 10{,}626\ O_s) \qquad \text{(A-1)}$$

where

f = total offset frequency in Hz at the indicated carrier frequency

V_p = component of platform velocity in knots toward the Omega transmitter

V_s = relative platform velocity in knots toward the satellite

O_s = stability of platform oscillator in parts per million

Substituting the worst-case conditions, $V_p = V_s = 200$ knots and $O_s = 1 \times 10^{-6}$, into the offset equation results in a maximum offset frequency (w_d) max of ± 0.0143 Hz.

For a 180-second sampling period, this corresponds to a rotation of ± 2.57 Hz.

Aside from the values of trial offsets attempted, the system sampling rate imposes a limit on the maximum correctable frequency offset. For each Omega signal, 18 samples 10 seconds apart are taken over a period of 180-seconds. Since unambiguous results are reached if a sine wave is sampled at least twice per cycle, the system upper limit for maximum frequency correction is established by this sampling rate. For 18 samples, nine cycles of frequency offset can be corrected without ambiguity.

The offset correction values applied must be large enough to correct for 0.0143 Hz. Therefore, the maximum correction value applied (w_c) max must be equal to or greater than (w_d) max.

(w_c) max $\geq w_d$ max,

(w_c) max $\geq \pm 0.0143$ Hz,

than let (w_c) max $= \pm 0.02$ Hz.

For this value of frequency offset, a range of combinations of O_s and V_p can be determined (for the case where $V_p = V_s$) that will not exceed the processor capability. By substituting 0.02 into the offset equation and solving for V_p as a function of O_s the following expression results.

$$V_p \simeq 1100 - 580\, O_s \qquad \text{(A-2)}$$

This equation is plotted in Figure A-1. The cross-hatched area shows the range that O_s and V_p can assume without exceeding the signal processor capability.

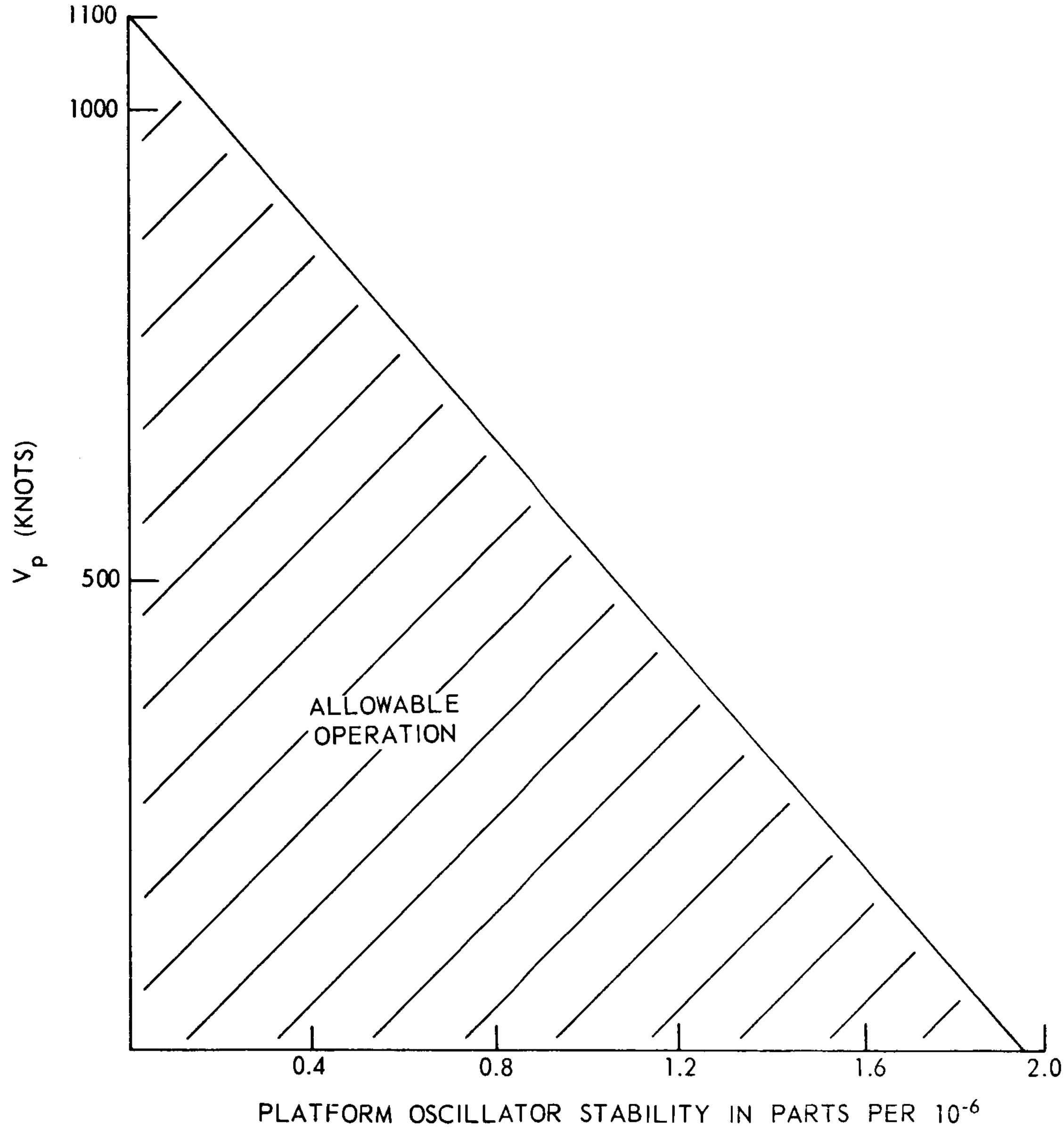


Figure A-1. Platform Velocity versus PEP Oscillator Stability

During the first processing step of the Omega phase data, the X and Y components (Sine and Cosine) of the 18 Omega data samples are summed for each trial value of frequency offset. The equations for X and Y are as follows:

$$X_i = S_i \cos(\phi_i + w_d t + w_c t) + N_i \cos \theta_i \quad \text{(A-3)}$$

$$Y_i = S_i \cos(\phi_i + w_d t + w_c t) + N_i \sin \theta_i \quad \text{(A-4)}$$

where

ϕ_i = Omega signal phase angle

θ_i = Noise vector phase angle

w_d = Total offset frequency

w_c = Offset frequency correction

S_i = Signal amplitude

N_i = Noise vector amplitude

i = 1, 2, 3, . . . , 18.

The 18 X's and 18 Y'x are summed for each total value of w_c, the vector sums are added, and the relative magnitudes of the total signal vectors are inspected. The w_c value corresponding to the largest signal vector is the rough approximation for the frequency offset. Figure A-2 illustrates the 18 signal vectors summed without applying the frequency correction factor, w_c. The total rotation in the diagram is less than 360 degrees for ease of illustration, although it can be several cycles over a 180-second sampling period. Figure A-3 illustrates the resultant vector with a particular value of frequency correction, w_c.

For each value of w_c attempted, the new X and Y components are summed and the chord length R, R_1, R_2 . . . are calculated and inspected for a maximum. From Figure A-4 the ratio of chord length to arc length (b/c) as a function of sector angle (α) for an ideal circle is:

$$b/c = \frac{2R \sin \alpha/2}{\frac{2\pi R\alpha}{360^\circ}} = \frac{115^\circ \sin\frac{\alpha}{2}}{\alpha} \quad \text{(A-5)}$$

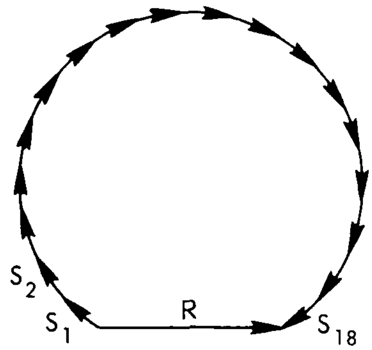


Figure A-2. Signal Vector Summation Without Frequency Offset Correction

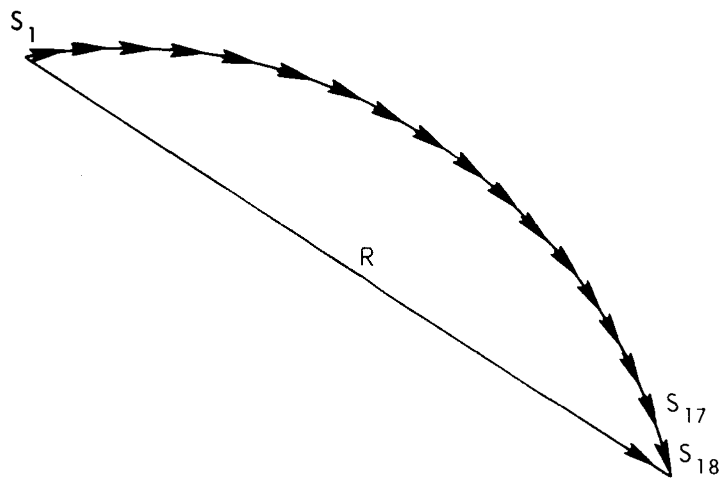
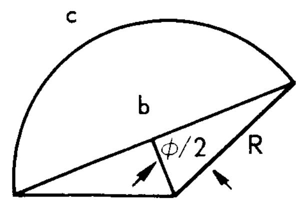


Figure A-3. Residual Frequency Offset

The ratio b/c is of the (sin x)/x form and is plotted as a function of α in Figure A-5. The two sidelobes on the curve show relative values of chord length that will be measured if the total rotation is greater than ± 360 degrees. In the description of the second step of the process, which follows, it can be seen that the theoretical noiseless resolution capability is less than 360 degrees. That is, the frequency correction must be estimated to within ± 360 degrees, and to avoid ambiguity, sample points must be no more than 600 degrees apart for the ideal case.



The chord length (b) is: $b = 2R \sin \phi/2$

The length of arc (c) is: $c = \dfrac{2\pi R \phi}{360°}$

Figure A-4. Sector Showing Chord and Arc

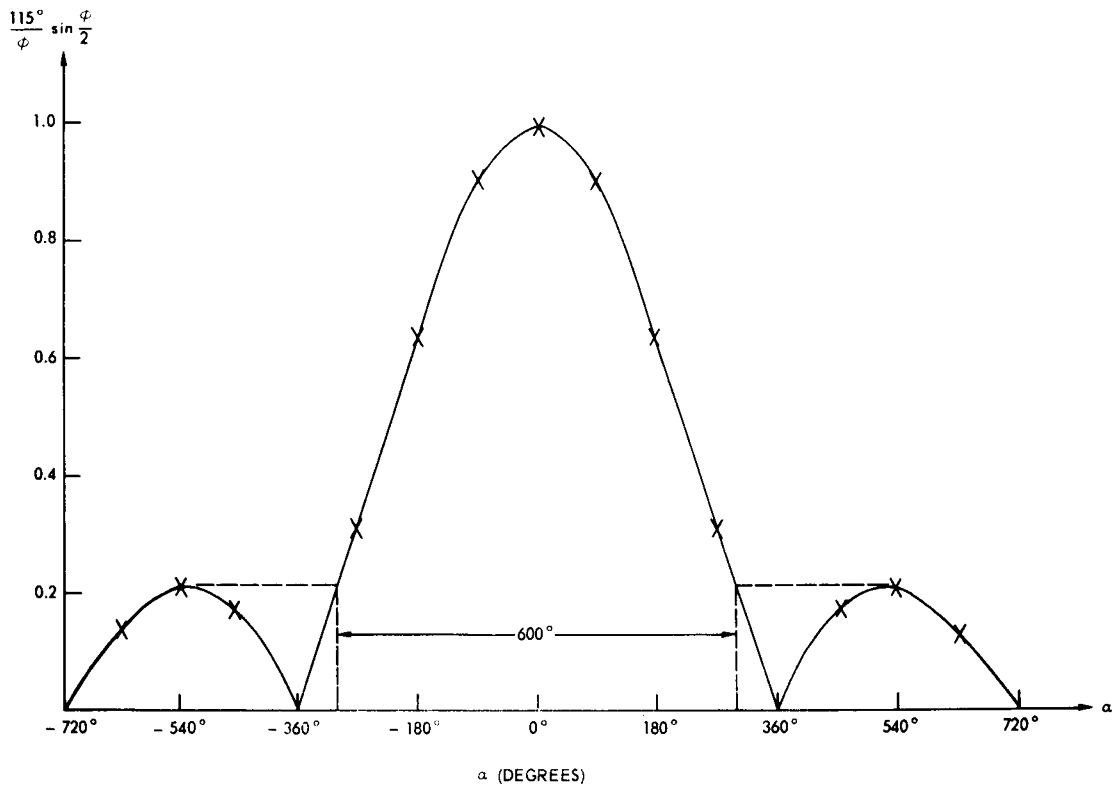


Figure A-5. Plot of $\dfrac{\sin X}{X}$

In the presence of noise, the sample distance for clearly resolving ambiguity within one cycle is 240 degrees. For samples 240 degrees apart, the maximum residual rotation going into steps is ±240 degrees.

The function of the second step in the Omega data processing sequence is to calculate a correction factor to apply to the rough approximation, w_c, that was calculated in the first step.

The signal process or operations for the second processing step are discussed below and two examples are illustrated graphically in Figure A-6 for various values of offset phase angle. The sign convention is such that counterclockwise rotation of a vector increases the positive value of its angle, ϕ. The sequence that is used in calculating the correction phase ($\phi_c = w_c t$) is:

1. Determine the phase of the first nine readings (ϕ_{1-9}) by using the equation:

$$\phi_{1-9} = \tan^{-1} \sum_{i=1}^{9} \frac{X_i}{Y_i} \qquad \text{(A-6)}$$

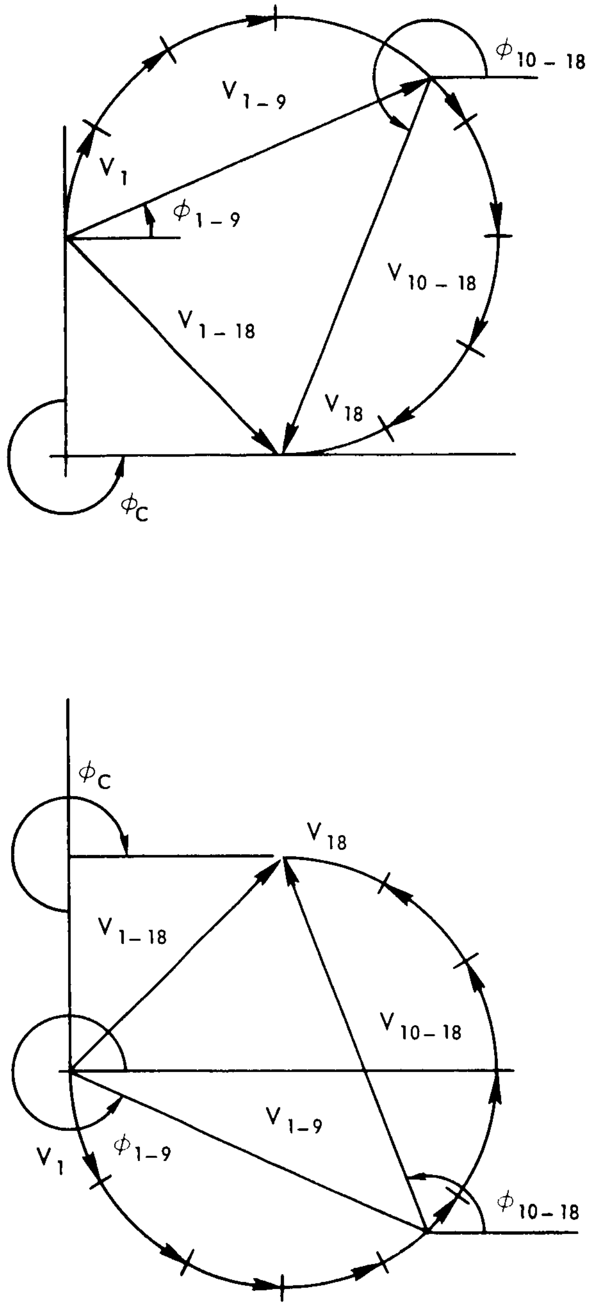
2. Determine the phase of the second nine readings (ϕ_{10-18}) by using the equation:

$$\phi_{10-18} = \tan^{-1} \sum_{i=10}^{18} \frac{X_i}{Y_i} \qquad \text{(A-7)}$$

3. Subtract the phase of the second nine reading (ϕ_{10-18}) from the phase of the first nine readings (ϕ_{1-9}).

4. Examine the value of ($\phi_{1-9} - \phi_{10-18}$). If the phase difference is less than -180 degrees, subtract +360 degrees. If the phase difference is between -180 degrees and +180 degrees, use the phase difference as is.

5. Divide the resulting phase difference by 90 seconds times 360 degrees and add the answer to the coarse value of offset frequency that was obtained in the first step. The resulting sum is the total offset frequency, w_c.



(a) ϕ_c Loss Then $-\,180^\circ$

$$\begin{array}{rl} \phi_{1-9} & = 22.5^\circ \\ -\phi_{10-18} & = -\,247.5^\circ \\ \hline \phi_{1-9} - \phi_{10-18} & = -\,225^\circ \end{array}$$

This value is less than $-\,180^\circ$

$\therefore \phi_c = 2(-\,225^\circ + 360^\circ)$
$= 270^\circ$

(b) ϕ_c Greater than $+\,180^\circ$

$$\begin{array}{rl} \phi_{1-9} & = 337.5^\circ \\ -\phi_{10-18} & = -\,112.5^\circ \\ \hline \phi_{1-9} - \phi_{10-18} & = 225^\circ \end{array}$$

This value is greater than $+\,180^\circ$

$\therefore \phi_c = 2(225^\circ - 360^\circ)$
$= -\,270^\circ$

Figure A-6. Example of Second Processing Step

Applying this value for doppler offset into the X and Y equations and summing the components yields the corrected phase angle (ϕ) between the reference frequency and one Omega station for a platform.

$$\phi = \tan^{-1} \frac{\sum_{i=1}^{18} X_i}{\sum_{i=1}^{18} Y_i} \tag{A-8}$$

Let ϕ_A and ϕ_B be the phase angles between a common reference frequency and the Omega stations A and B. The differential phase between two Omega stations is determined by the difference of the two phase angles $\phi_A - \phi_B$.

APPENDIX B

ESTIMATE OF OCC SIGNAL PROCESSING ERRORS

In this Appendix, the random phase and offset frequency errors introduced by both input noise and the OCC signal processing method are calculated and tabulated. Only the random phase errors are considered in the calculations. The effect of time invariant phase errors will be zero when two Omega station phases are compared by computing a phase difference.

The calculated phase errors from different sources are assumed to be independent and of Gaussian distribution with a mean of zero. The rms or one-sigma value of error from each source is tabulated in Table B-1 for VLF S/N ratios of -6 dB, 0 dB, +6 dB, and +12 dB in a 1 Hz bandwidth. The total rms error introduced by the signal processor at a 0 dB S/N ratio for the Omega carrier signals is noted to be 11.1 degrees. The total rms errors are calculated by taking the square root of the sum-of-the-squares of the individual errors.

TABLE B-1

OCC SIGNAL PROCESSING ERRORS

Error Source	Error Magnitude in Degrees and Values of S/N Ratio in a 1 Hz Bandwidth			
	+12 dB	+6 dB	0 dB	-6 dB
VLF Noise	2.7	5.3	10.5	20.4
Offset frequency inaccuracy	0.3	0.5	1.0	1.9
Analog-to-digital converter	0.7	0.7	1.4	1.4
Omega receiver	1.4	1.4	1.4	1.4
Phase-lock loop	3.0	3.0	3.0	3.0
Digital processor	1.0	1.0	1.0	1.0
Total rms error (degrees)	4.5	6.4	11.1	20.6

The following paragraphs discuss the calculations used to determine the sources of error presented in Table B-1.

B.1 PHASE ANGLE ERROR DUE TO VLF NOISE

The rms value of noise-induced phase error is calculated for several values of S/N ratio and for both 9- and 18-measurement samples. The error after nine samples contributes to the offset frequency error as calculated during the second processing step, while that for 18 samples is applied to the total phase error of each Omega signal. Factors which determine the magnitude of the noise-induced error are the S/N ratio, the number of samples, and the total uncorrected rotation of the signal vector occurring during the sampling periods.

The equation for the rms value of the phase error ($\epsilon_{\theta N}$) is developed by considering the phase measurement vectors shown on Figure B-1. The signal vector without noise is V_s, which is composed of the sum of vectors V_1 through V_m rotated through uncorrected angle ϕ caused by the frequency error.

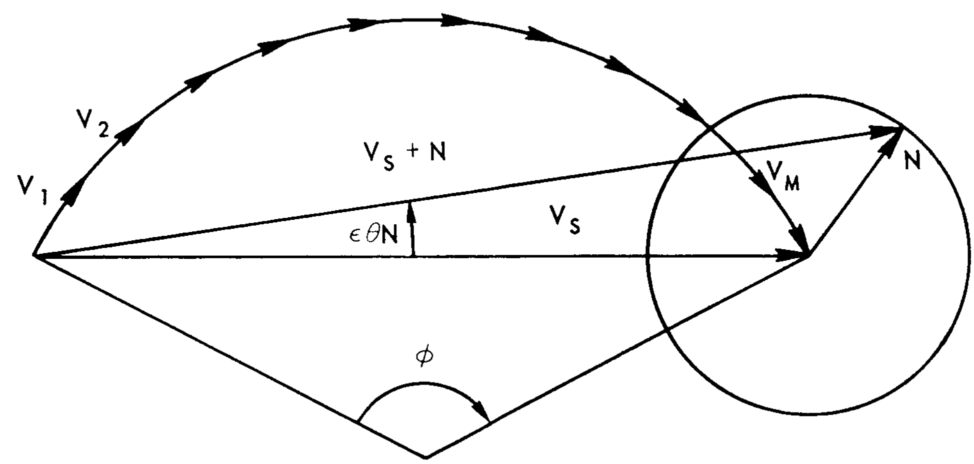


Figure B-1. Phase Measurement Vectors

The length of the resultant vector V_s, related to the length of the arc defined by vectors V_1 through V_m, can be shown to be a factor (F) given by

$$F = \frac{115°}{\phi} \sin \frac{\phi}{2} \qquad \text{(B-1)}$$

where ϕ is the vector rotation between V_1 and V_m. It is clear that the resultant value of V_s for the summation of M unity vectors is simply MF. This resultant signal vector (V_s) is modified by adding a composite noise vector N. Noise vector N has a normally distributed value of amplitude at an equally probable random phase angle. The rms noise amplitude associated with each unity-signal vector (V_1) is 1/S by definition, where S is the signal-to-noise ratio expressed in volts. Then, the composite rms magnitude of M noise vectors can be expressed as N = M/S. This composite noise vector has a random phase angle with respect to the signal vector, so that the rms value of the quadrature component is the noise vector magnitude divided by two. The rms value of the phase error ($\epsilon_{\theta N}$) is:

$$
\begin{aligned}
\epsilon_{\theta N} &= \tan^{-1} \frac{N}{\sqrt{2}} \div V_s \\
&= \tan^{-1} \frac{\sqrt{M}}{S\sqrt{2}} \div MF \qquad \text{(B-2)} \\
&= \tan^{-1} \frac{1}{FS\sqrt{2M}}.
\end{aligned}
$$

The resultant noise-induced phase errors are plotted in Figure B-2 for both nine and 18 samples as a function of signal-to-noise ratio. An uncorrected vector rotation value of 90 degrees is assumed in both cases. The rms value of phase angle error at 0 dB S/N ratio is noted to be 10.5 degrees for 18 samples and 14.7 degrees for nine samples.

The following discussions show that the assumed uncorrected vector rotation of 90 degrees approximates the 1.3-sigma variance for both nine and 18 samples, and is therefore a conservative assumption. The measurement of phase angle from nine samples is used during the second processing step to determine a more accurate value of offset frequency. Therefore, the uncorrected rotation for this phase angle measurement is a result of inaccuracies introduced during the first processing step.

For the first processing step, sequential trail values of offset frequency with increments of 0.00371 Hz are used to approximate the value of offset frequency. A residual phase rotation, randomly distributed between +120 and -120 degrees, is generated after 18 samples, or between +60 and -60 degrees after nine samples. In addition, a noise-induced rotation uncertainty must be added to this value of uncorrected rotation. At 0 dB S/N ratio, the total uncorrected phase rotation for nine samples is less than 90 degrees. The actual

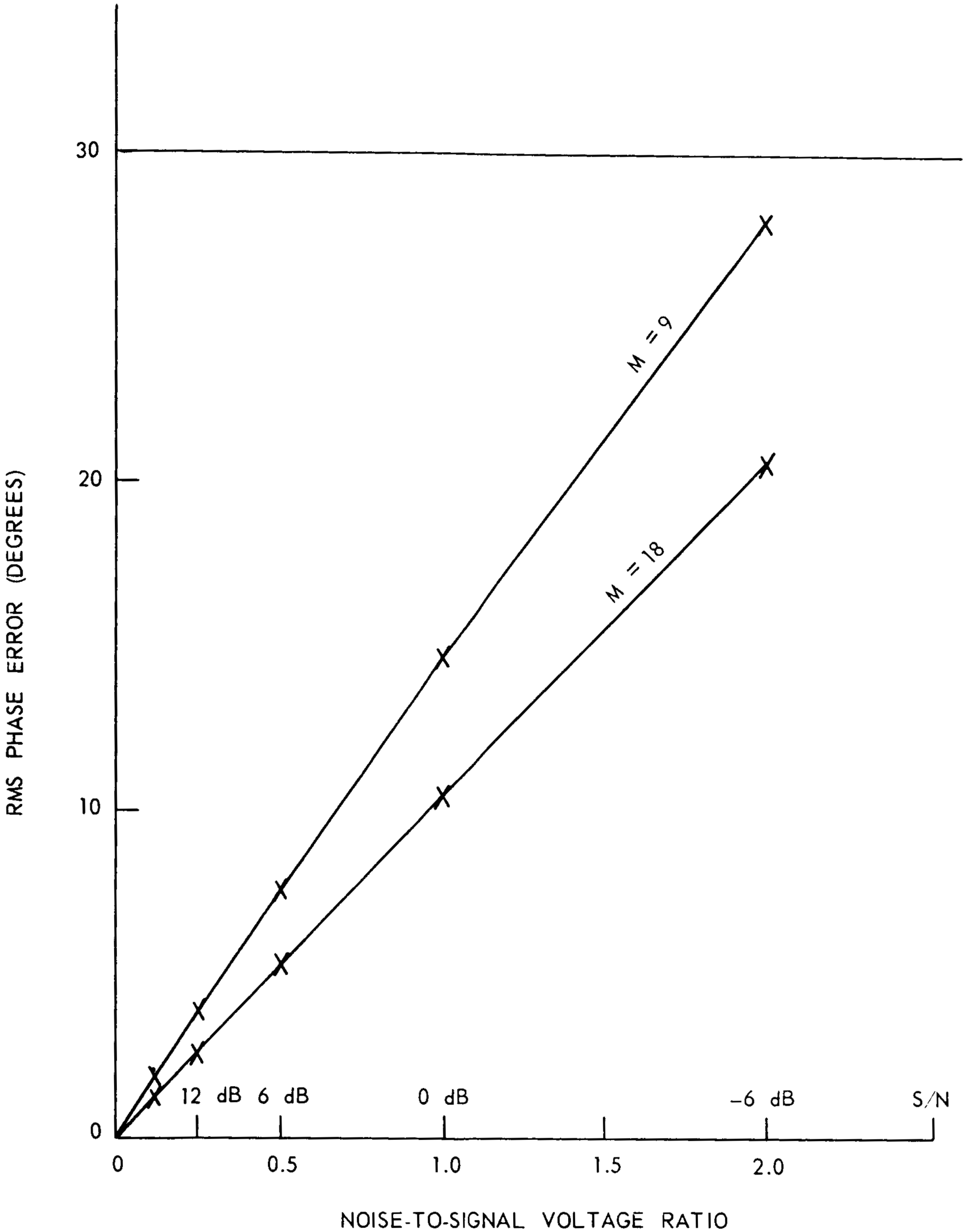


Figure B-2. Noise-Induced Phase Angle Errors versus S/N Ratio for M Samples consequence of exceeding this 90-degree value of uncorrected phase rotation is to slightly increase the rms value of phase error; conversely, for values less than 90 degrees, the value of error will be slightly reduced.

For the case of 18 samples, which is used in determining the final value of phase angle, the uncorrected offset error results from calculating an offset correction in processing the second step. This correction is twice the difference between the phase angle of the first nine samples and the phase angles of the second nine samples. Since the errors of both nine-sample groups are independent and are calculated at a 0 dB S/N ratio to be 14.7 degrees rms for each nine-sample group, the total rms uncorrected phase shift becomes (14.7 degrees)(2)($\sqrt{2}$) = 41.6 degrees. The 2.2-sigma value of this error is then 90 degrees. Thus, 98 percent of the inputs will be less than the assumed value of 90 degrees.

B.2 PHASE TIME SHIFT ERROR DUE TO OFFSET FREQUENCY INACCURACY

The computed value of offset frequency for each of the Omega carrier frequencies contains some error which is a function of VLF noise. The magnitude of this error is determined by considering the second step of the correction process, which applies a correction factor to the best trial value of offset frequency selected by the first step of the process. The phase rotation factor applied by the second step is twice the angle of rotation correction between the total vector for the first and last nine samples. These vector values are computed from phase measurements and therefore contain errors. Because the phase angle errors for these two vectors are Gaussian distributed and uncorrelated, the total rotation correction phase error over the 180-second period becomes $2\sqrt{2}\ \epsilon\theta_n$, where $\epsilon\theta_n$ is the phase angle error due to VLF noise after nine samples. This is expressed as offset frequency error ($\epsilon\Delta f$) by the equation:

$$\epsilon\Delta f = \frac{2\sqrt{2}\ \epsilon\theta_n}{(360°)\ (180\ \text{seconds})} \qquad \text{(B-3)}$$

$$= 0.00064\ \text{Hz for 0 dB S/N}$$

The primary effect of this offset frequency is to introduce a phase angle error when the phase angle measurements of the various Omega signals are time-shifted to determine the phase difference between a pair of Omega stations. The maximum amount of time shift required is ± 4.4 seconds because all Omega stations have relative transmission starting times between 0 and 8.8 seconds. Therefore, the rms value of phase error due to the error in computed offset frequency ($\epsilon\theta_f$) is no greater than

$$\begin{aligned} \epsilon\theta_f &= \epsilon\Delta f \times 4.4 \text{ seconds} \times 360^\circ \\ &= 0.069\ \epsilon\theta_n \text{ degrees.} \end{aligned} \tag{B-4}$$

The resultant phase time-shift error is plotted as rms amplitude for various signal-to-noise ratios in Figure B-3. The rms error value for a 0 dB S/N ratio is noted to be 1 degree, and at a +6 dB S/N ratio, it is 0.5 degrees.

B.3 ANALOG-TO-DIGITAL CONVERTER (ADC) ERROR

The digital output of the ADC contains seven data bits plus a sign bit. The design accuracy of the ADC is 0.1 percent with a corresponding error of approximately one-tenth the value represented by the least significant bit in the digital output. This digital output also contains a quantizing error with square-law distribution between -1/2 and +1/2, the value represented by the least significant bit. The effect of these errors on the phase angle measurement is not considered.

The value of the output from the seven-bit ADC is scaled so that the maximum possible Omega input signal will produce a full-scale output of the seven bits. This value is ensured by applying hard limiting to the signal-with-noise in the OPLE receiver. This limiting is done on a signal with a 40 Hz bandwidth. The bandwidth is then reduced to 1 Hz by the action of the integrator. This reduction of bandwidth after limiting reduces the signal by 17 dB for the case of 0 dB S/N ratio in a 1 Hz bandwidth. Thus, the maximum output of the ADC under the condition of 0 dB S/N ratio is four data bits. Letting these four bits represent a value of 16, and considering a summation over 18 samples, the maximum value of the summation of either the X or Y components is seen to be 288 (16×18). The total converter error (rms) for each X or Y reading is assumed to be 0.6 in value. Then, the error in the summation of 18 X and 18 Y values becomes 0.6×18, or 2.54. The values of phase error ($\epsilon\theta_{ADC}$) due to the analog-to-digital converter are then calculated for several values of phase angle by adding the error to the X component and subtracting it from the Y component, as shown in Table B-2. The maximum value of rms phase error for the carriers is noted to be 0.7 degrees, occurring over a wide range of phase angles. For signals that have a -6 dB S/N ratio, the phase error becomes 1.4 degrees.

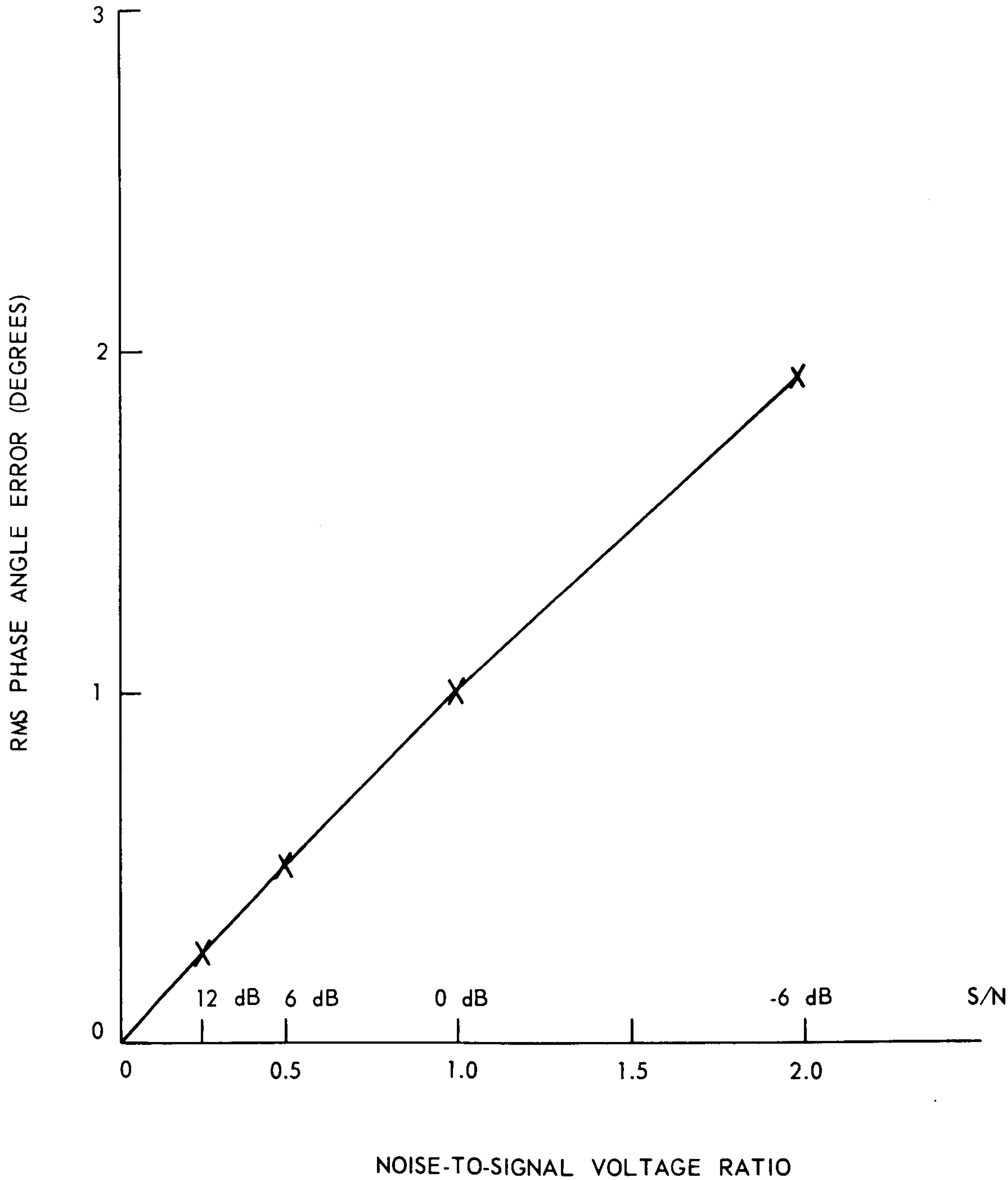


Figure B-3. Time Shift Phase Angle Error versus S/N Ratio in a 1 Hz Bandwidth

TABLE B-2

ANALOG-TO-DIGITAL CONVERTER PHASE ERRORS

θ	288 sin θ	$+\epsilon$	288 cos θ	$-\epsilon$	$\tan^{-1} X+\epsilon/X-\epsilon$	θ_{ADC}
0	0	2.54	288	287.46	0.5	0.5
22.5	110.22	112.76	266.08	263.54	23.2	0.7
45	203.64	206.18	203.64	201.10	45.7	[illegible]
67.5	266.08	268.62	110.22	107.68	68.2	0.7
90	288	290.54	0	-2.54	90.5	0.5

B.4 VLF RECEIVER ERRORS

The Omega VLF receivers introduce two sources of error. The first is a normal distribution of phase shift by the various filters at different signal levels. The rms value of this phase error is one degree. The second source of error in the VLF receiver is due to nonlinearity and offset in each output integrator circuit. The rms value of this error is equivalent to one bit of the ADV output. The corresponding phase error is calculated as discussed in the previous paragraph, giving a maximum value of

$$\theta = 45 - \tan^{-1} \frac{288 + 1}{287 - 1}$$

$$= 0.3 \text{ degrees.}$$

Thus, the total rms phase error for the Omega receiver ($\epsilon\theta_R$) is

$$\epsilon\theta_R = \sqrt{1^2 + (0.3)^2} = 1.4 \text{ degrees.}$$

B.5 PHASE-LOCK LOOP TRACKING ERRORS

The function of the phase-lock loops is to track the A/R tones transmitted by the platforms. The accuracy of this process depends on the bandwidth of the phase-lock loop, the magnitude in frequency of an input transient, and the VHF path S/N ratio. The design values are (1) a loop bandwidth of 20 Hz, (2) a one Hz transient in frequency, and (3) a VHF link S/N ratio of 10 dB. Derating the S/N ratio of 7.5 dB, the total rms phase error ($\epsilon \theta_L$) for the phase-lock loop becomes three degrees.

B.6 DIGITAL PROCESSING ERROR

The digital processing of the Omega phase data results in errors due to truncations, approximations of sine and cosine functions, etc. The value of this total digital processing error has not presently been determined since it is a function of the final computer program, which has not been written. However, the error magnitude can be limited since 16 bits are available in the computer for the processing of seven-bit inputs. An rms value of one degree is assumed for this error.