CHAPTER 8

NAVIGATION THEORY AND EQUIPMENT

Basically, electronic navigation is a form of piloting. Piloting is that branch of navigation in which a ship's position is determined by referring to landmarks with known positions on the earth. These reference points may consist of the bearing and distance of a single object, cross bearings on two or more objects, or two bearings on the same object with an interval between them.

Position in electronic navigation is determined in practically the same way as in piloting. However, there is one important difference: the landmarks from which the ship's position is determined need not be visible from the ship. Instead, their bearings and ranges are obtained by electronic means (either radar or radio).

The advantages of piloting by electronic means are obvious. A ship's position may be electronically fixed in fog or thick weather that would make it impossible to obtain visual bearings. Moreover, an electronic fix may be based on stations located far beyond the range of clear-weather visibility.

This chapter will deal only with electronic navigation by:

1. Long Range Aid to Navigation (loran)
2. Omega (vlf radio-navigation)
3. Ship's Inertial Navigation System (SINS)
4. Navy Navigation Satellite System (NNSS)
5. Navstar Global Positioning System (Navstar GPS)
6. Tactical Air Navigation (TACAN)

LORAN SYSTEMS

Loran (LOng RAnge Navigation) is a long-distance radio navigation system used by ships at sea to obtain a position fix. The loran system is based on the difference in the time required for pulsed radio signals to arrive at the loran receiver from multiple synchronized omnidirectional transmitters ashore. This system also takes advantage of the constant velocity of propagation in order to use the time lapse between the arrival of two signals to measure differences in distance from the transmitting stations to the point of reception. The loran receiving set provides a direct reading, in microseconds, of the time difference in the arrival of loran-station signals. (Some sets automatically convert the readings to latitude and longitude.) When the time difference is measured between signals received from any two loran station pairs, a ship's line-of-position (lop) can be determined.

The loran system used to be comprised of two subsystems which differed in mode of operation. There was a basic loran A system and a more complex one, providing better accuracy at greater distances, designated the loran C system.

The loran A system has been shut down, and has been replaced as the Navy's primary navigation system by the newer systems mentioned at the beginning of this chapter. The remainder of this chapter presents information on these newer systems.

LORAN C

The loran C system is a pulsed system. Each master station has at least two slaves operating on the same pulse repetition rate (prr). Loran C uses one frequency for all transmitters: 100 kHz. Since this carrier frequency is low, the range of the loran C stations is greater. This allows the transmitting stations to be more widely separated, and permits position fixes at much greater distances from the transmitting stations.

Loran C offers more accuracy in time difference measurements. The 100-kHz rf waves that make up each pulse are superimposed as closely as possible for the time difference measurement.

Since readings on two station pairs can be made without receiver retuning, loran C time difference measurements may be made rapidly.

The loran C master pulse group consists of nine pulses spaced either 500 or 1000 microseconds apart except for the ninth pulse which is separated from the eighth pulse by 600 microseconds. The slave pulse group transmission is a group of eight pulses separated with the same spacing as the master station, 500 or 1000 microseconds. The loran C pulse groups are illustrated in figure 8-1.

Loran C has six basic prr's that are divided into two groups, single rate and double rate. The single rate has three basic prr's, 33-1/3, 25, and 20 Hz, that are designated H, L, and S, respectively. These rates produce pulse recurrence intervals of 30,000 microseconds for the H rate, 40,000 microseconds for the L rate, and 50,000 microseconds for the S rate, varying slightly for specific prr's.

The double rate is one-half the single rate, 16-2/3, 12-1/2, and 10 pulse groups per second, designated SH, SL, and SS, respectively. These rates produce pulse recurrence intervals of 60,000 microseconds for the SH, 80,000 microseconds for the SL, and 100,000 microseconds for the SS. Notice that these rates result in intervals double that of a single rate.

A typical loran C transmitter arrangement is the star chain shown in figure 8-2. In this configuration, four stations, a master (designated M) and three slaves (designated X, Y, and Z) transmit pulse groups. The transmissions of the slave stations are timed with respect to the master station to establish an accurate basis for the time measurements.

The master station starts the action by transmitting a pulse group of nine pulses. The pulse group transmission is received by the X, Y, and Z slave stations. After a predetermined delay, the X station transmits its pulse group. After a somewhat longer predetermined delay, the Y station transmits, and after another delay, the Z station transmits. These delays permit the signals to arrive at the loran C receiver in the M, X, Y, and Z sequence anywhere in the service area.

The results of these transmissions are three sets of lines of position (lop's), one set of each combination of master and slave. By measuring the difference in arrival time of the three slaves and the master, three lines of position may be located on the loran C chart. The intersection of the three lines of position produces a loran C fix.

On most modern ships, loran C is being supplanted by the newer Omega and NNSS installations. This is being accomplished either in new construction or, for older ships, during overhaul.

OMEGA NAVIGATION SYSTEM

The Omega system is an outgrowth of the loran A and loran C systems. When fully implemented, the system will include eight transmitting stations located around the earth to accommodate land vehicles, aircraft, ships, and submarines at moderate depths. Research relating to the nature of very low-frequency propagation has indicated the feasibility of a world-wide radio-navigation system in this

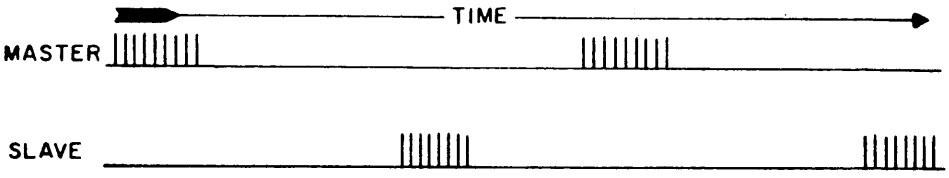

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Figure 8-1.—Loran C pulse groups.

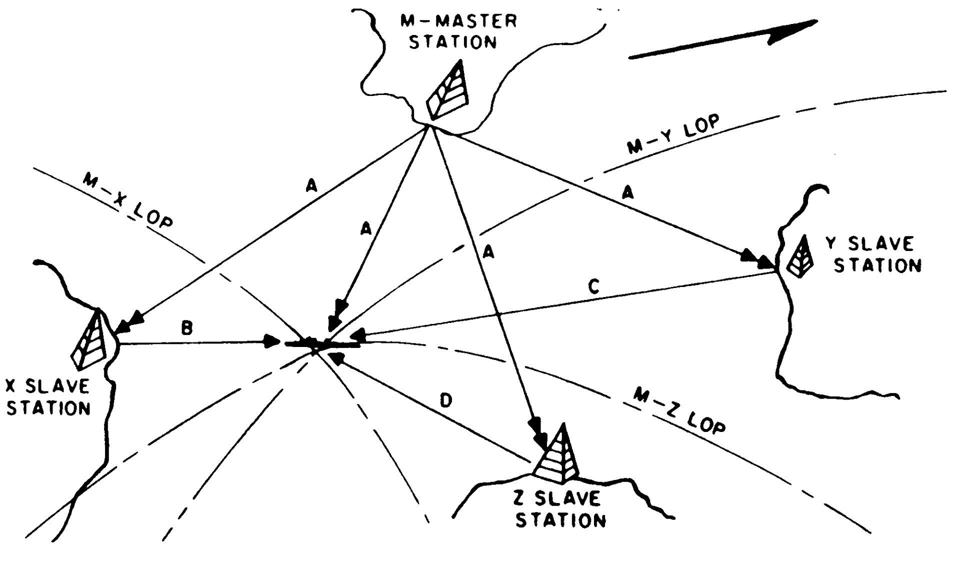

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Figure 8-2.—Loran C star chain transmitter arrangement.

frequency range. Based on these findings, the Omega system will provide position fixes over the globe with accuracy to within four NM with one to two NM as goals.

PRINCIPLES OF OPERATION

The Omega system relies on the characteristics of radio waves in general and specifically on the characteristics of radio waves in the very low frequency range.

In general, a given phase position of a radio wave occurs periodically as each 360° of cycle is repeated; thus, any phase angle will recur in intervals of wave duration. The rate of recurrence expressed in time is dependent on radio frequency; in distance, recurrence interval is directly related to wavelength. The latter phenomenon furnishes the basis for a hyperbolic system similar to that of loran. The Omega system, however, differs from the loran system in that measurement of phase relationship, rather than the time relationship between stations, is used to obtain a line of position. The system also employs a series of cesium-beam frequency standards for precise timing at each site, so that each station is effectively a master station and may be paired with one or more other stations to obtain a position fix. The time of the system is referred to as OMEGA time.

By locking Omega stations to an absolute time standard, phase is, in theory, maintained stationary throughout the transmitter's field of radiation (i.e., earth's surface). This constant phase over the earth's surface may be translated into hyperbolic lines. The lines for any two Omega stations produce a family of hyperbolas called isophase (constant phase) contours. Each contour represents a line of zero difference in phase angle between the paired station signals. Since zero phase difference between signals will occur every 180°, or half wavelength, measured differences within these "lanes" will be unique to a specific distance from either zero-phase contour line (fig. 8-3). This relationship will be constant along the length of any zero-phase delineated lane; therefore, a line-of-position within a lane may be established by measuring phase angle difference between paired stations.

Lane widths are determined by the frequency of transmission (fig. 8-4). The presently employed frequencies of 10.2 kHz, 11.33 kHz and 13.6 kHz have half wavelengths (distance between contours) of 8, 7 and 6 nautical miles respectively, along the baseline. Additionally, lane boundaries of 24 and 72 nautical miles may be derived by utilizing the ratios of the difference between 10.2 kHz and the other two frequencies. These broad 24- and 72-mile lanes may be used to resolve uncertainty in lane location.

Since the measured difference in phase angle can only produce a line of position within a known lane, it is essential to know in which lane the receiving station is located. This information is usually provided by counters or a graphic readout, associated with the receiver, which will count the number of lanes crossed. Lane identity, however, can also be resolved by taking advantage of the difference ratio in transmission frequencies in conjunction with another means of navigation, such as dead reckoning, celestial navigation or another electronic system. For example, when position is known to be within a broad 24-mile lane (dead reckoning to within ± 12 miles), ambiguity between 8-mile lanes may be resolved by comparing the 10.2 kHz and 13.6 kHz frequencies. By adjusting phase synchronization so that a contour of the higher frequency coincides with a contour of the lower frequency, the difference ratio of 1/3 (13.6 − 10.2/10.2 = 1/3) will result in every fourth contour of the 13.6-kHz signal (fig. 8-4). A comparison of the two phase relationships will identify the 10.2-kHz lane in which the receiving station is located. A similar procedure may be

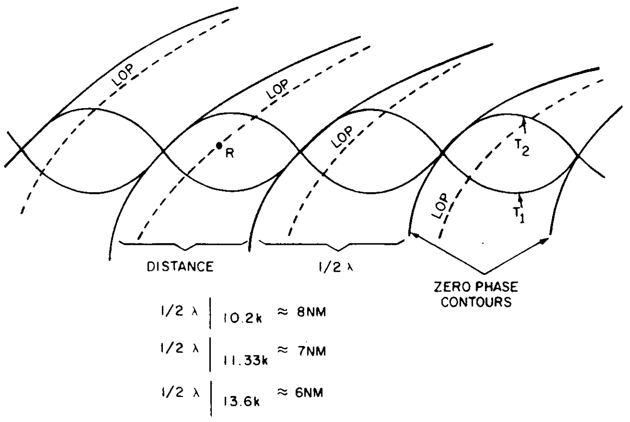

Figure 8-3.—Zero phase contours. **245.43**

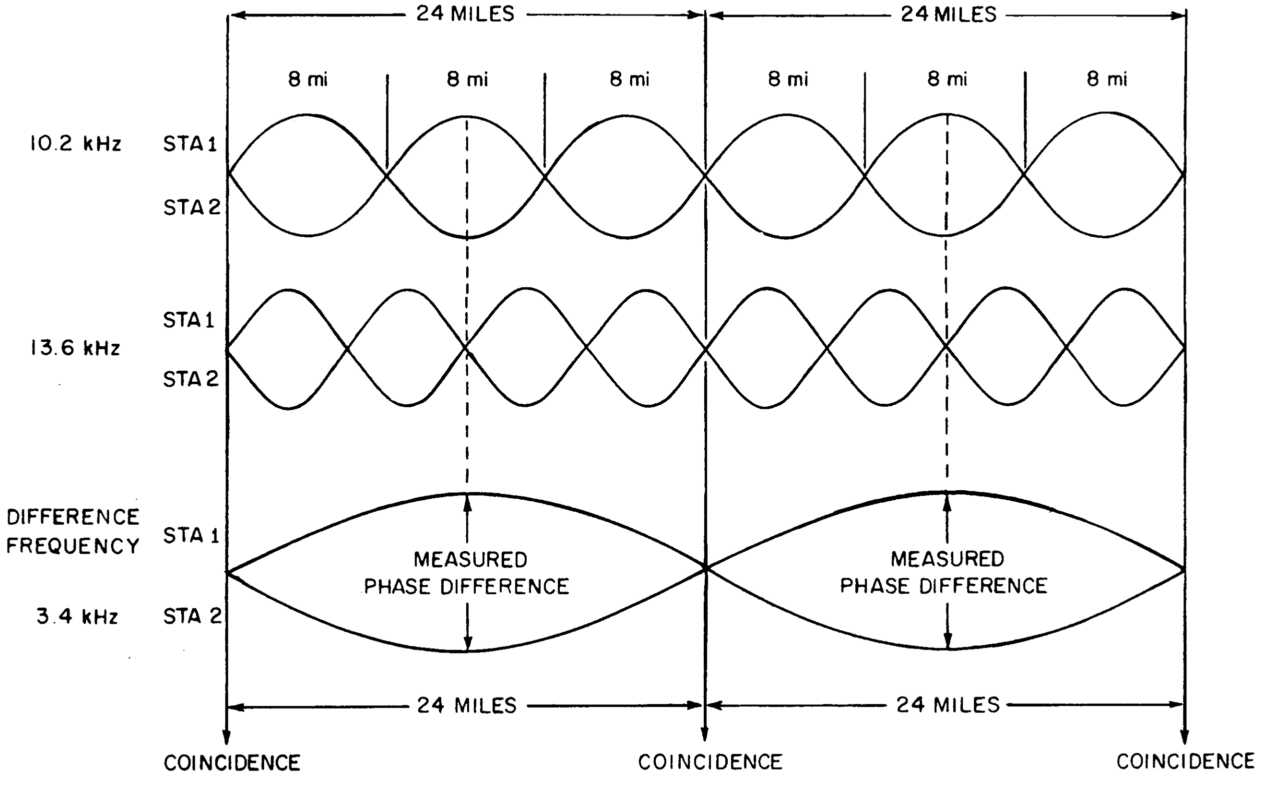

Figure 8-4.—Resolving lane ambiguity. **245.44**

used to resolve lane ambiguity within the broad 72-mile lane by employing the 11.3-kHz frequency.

A position fix is obtained by locating lines of position from additional pairs of transmitting stations. In figure 8-5 a position fix based on lines of position from three pairs of signals is shown.

Each station in the Omega system broadcasts a continuous-wave signal rather than a pulsed signal like that of loran. Because of the time separation between transmissions, the signal will have the appearance of being pulsed when seen on the cathode ray tube display of the receiver. This time separation is required, since each of the eight stations transmits on the same frequencies, and a means of identifying the sources of the signals being measured is needed. Examination of the broadcasting schedule of figure 8-6 shows a periodic pattern of interrupted

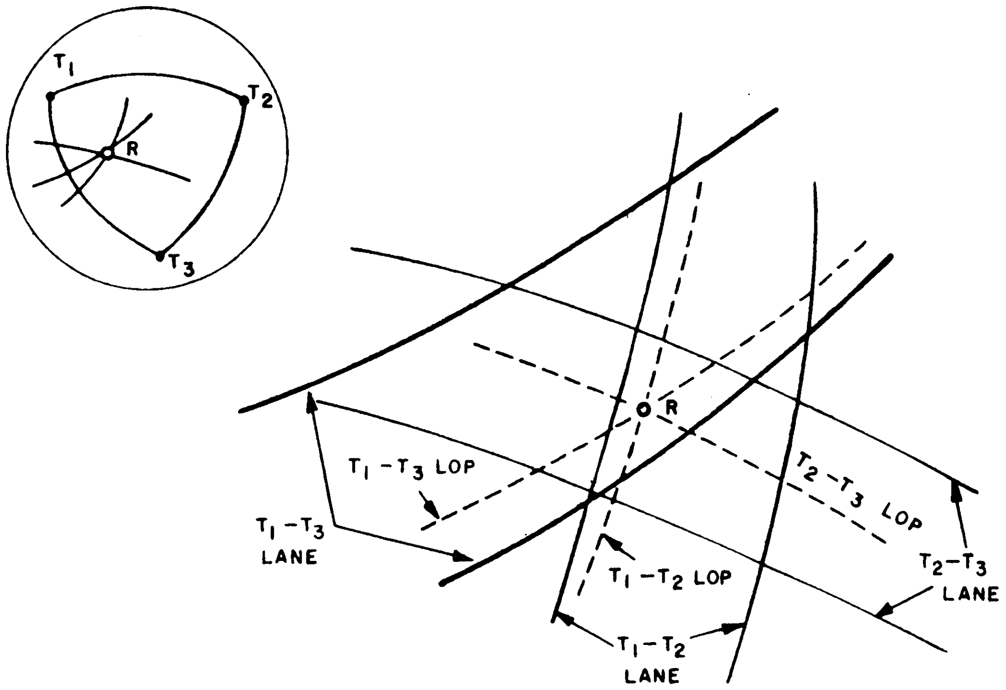

Figure 8-5.—Obtaining a position fix from three transmitting stations.

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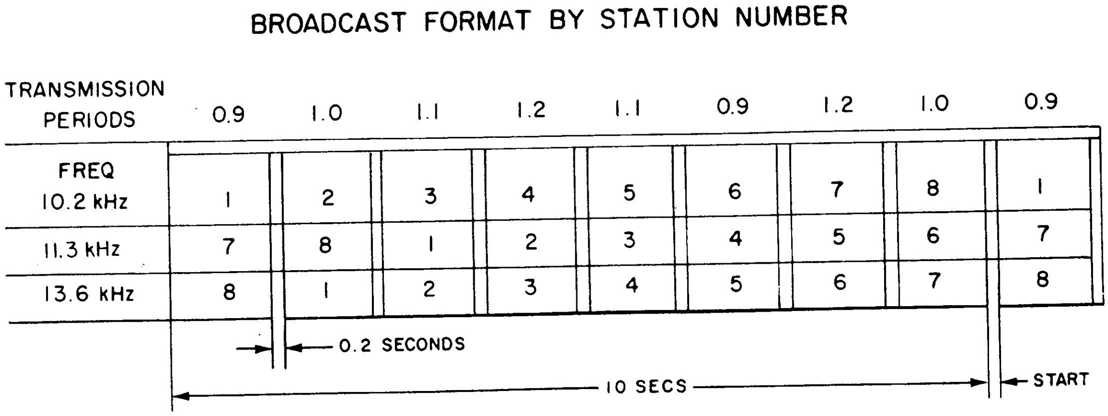

TRANSMISSION PERIODS	0.9	1.0	1.1	1.2	1.1	0.9	1.2	1.0	0.9
FREQ 10.2 kHz	1	2	3	4	5	6	7	8	1
11.3 kHz	7	8	1	2	3	4	5	6	7
13.6 kHz	8	1	2	3	4	5	6	7	8

Figure 8-6.—Broadcast format.

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transmissions repeating every 10 seconds. In this format, each station has a combined position/duration relationship that is unique. While stations 1 and 6, for example, are assigned the same signal duration on the 10.2-kHz frequency, their relative positions in the order of transmissions are different and ambiguity is eliminated. Because Omega time is synchronized with, but is not identical to, Greenwich Mean Time, the identification of stations received during any 10-second cycle is possible by utilizing a time reference from another source such as the time signals broadcast by major naval radio stations. Additionally, the relative nearness of stations will produce differing signal amplitudes when viewed on the receiver's cathode ray tube display. This will further aid in identifying the stations being measured.

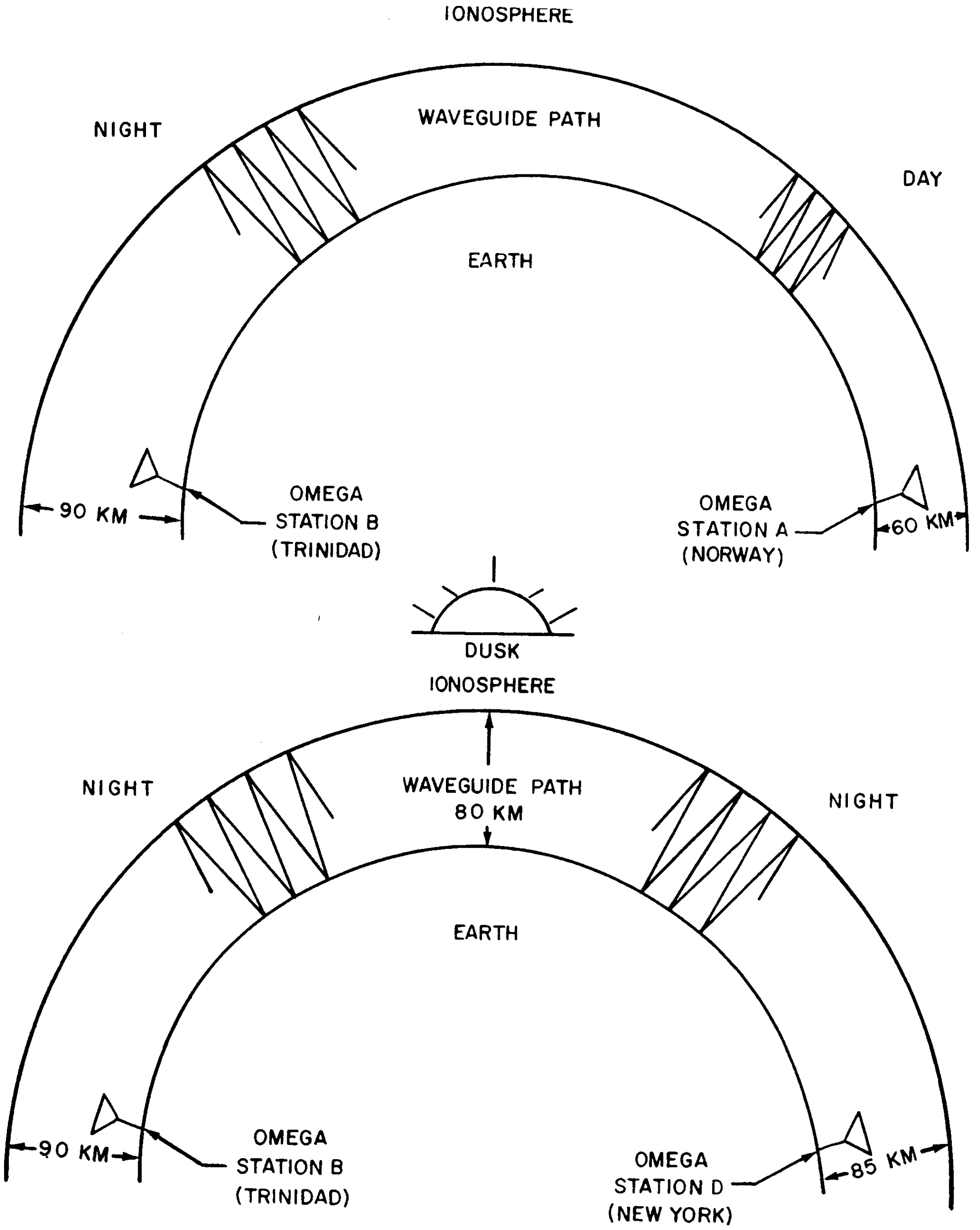

Figure 8-7.—Omega signal propagation. 245.47

OMEGA SIGNAL PROPAGATION

The Omega system is essentially a skywave system, with the surface of the earth and the ionosphere forming a waveguide through which the transmitted signals travel (fig. 8-7). The ionosphere is a cloud of free electrons whose lowest region lies at altitudes of 40 to 50 miles above the earth's surface. Very low frequency signals, such as those of Omega, are refracted by the ionosphere and also reflected by the earth. The velocity of phase propagation will be determined by ionospheric height, surface conductivity and, to some extent, the earth's magnetic field.

Variations in the height of the ionosphere (diurnal shifts) occur between night and day. The extent of these diurnal shifts can be as much as one percent and can cause daily changes in phase propagation velocity, which in turn will result in shifts of the isophase contours generated by any pair of Omega stations. Isophase contours form an electronic lattice which may be viewed as a grid slowly shifting back and forth over the earth's surface in a daily pattern following diurnal shifts of the ionosphere. Gradual changes to this pattern will occur as the ionosphere is affected by seasonal changes. The repetitive nature of this shifting lends a high degree of predictability to lattice movement. The United States Naval Oceanographic Office computes and publishes these predictions for each pair of transmitted signals in each geographic area of the earth's surface. Skywave correction factors are provided separately and must be applied to each of the receiver line-of-position readings to convert them to common Omega geographic map grids.

OMEGA RECEIVING SET AN/SRN-12

The Omega Receiving Set AN/SRN-12 (fig. 8-8) is a solid state, single frequency, phase-locked, superheterodyne receiver with whip antenna and coupler for the reception of Omega navigation signals. Incorporated in the set is the required timing, phase measuring, lane counting, and display equipment for determining lines of position (lop's). Four stations can be tuned simultaneously, thereby furnishing six lop's, any three of which may be displayed. Each lop is determined by a measurement of the phase difference of the signals received from any pair of transmitting stations. Two or three intersecting lines establish the receiver's position with an accuracy of within four NM with future accuracies expected to be greater. The selected lop's are displayed on the front panel. Skywave corrections (taken from U. S. Naval Oceanographic Office tables) are applied. Then corrected lop's are plotted for a position fix on an appropriate Omega chart (as shown in fig. 8-5).

Controls and Indicators

The receiver controls and displays are contained in the bottom drawer of the set, which slides out to permit access for maintenance. Graphic recorders, which provide a visual record of the lines of position, and an oscilloscope that displays the Omega station signal patterns are contained in the upper drawer. The set also contains built-in test circuitry. The front panel of the set is shown in figure 8-8.

SHIP'S INERTIAL NAVIGATION SYSTEM

The Ship's Inertial Navigation System (SINS) is a navigation system that (after initial latitude, longitude, heading, and orientation conditions are set into the system) continuously computes the latitude and longitude of the ship by sensing acceleration. This method is in contrast to the loran and Omega system methods which fix the ship's position by measuring position relative to some known object.

Because SINS is completely independent of celestial, sight, and radio type navigational aids, the system has the advantage of security over other types of navigation systems. The advantages of an inertial navigation system include:

1. It is self contained.
2. It requires minimal outside information.
3. It cannot be jammed.

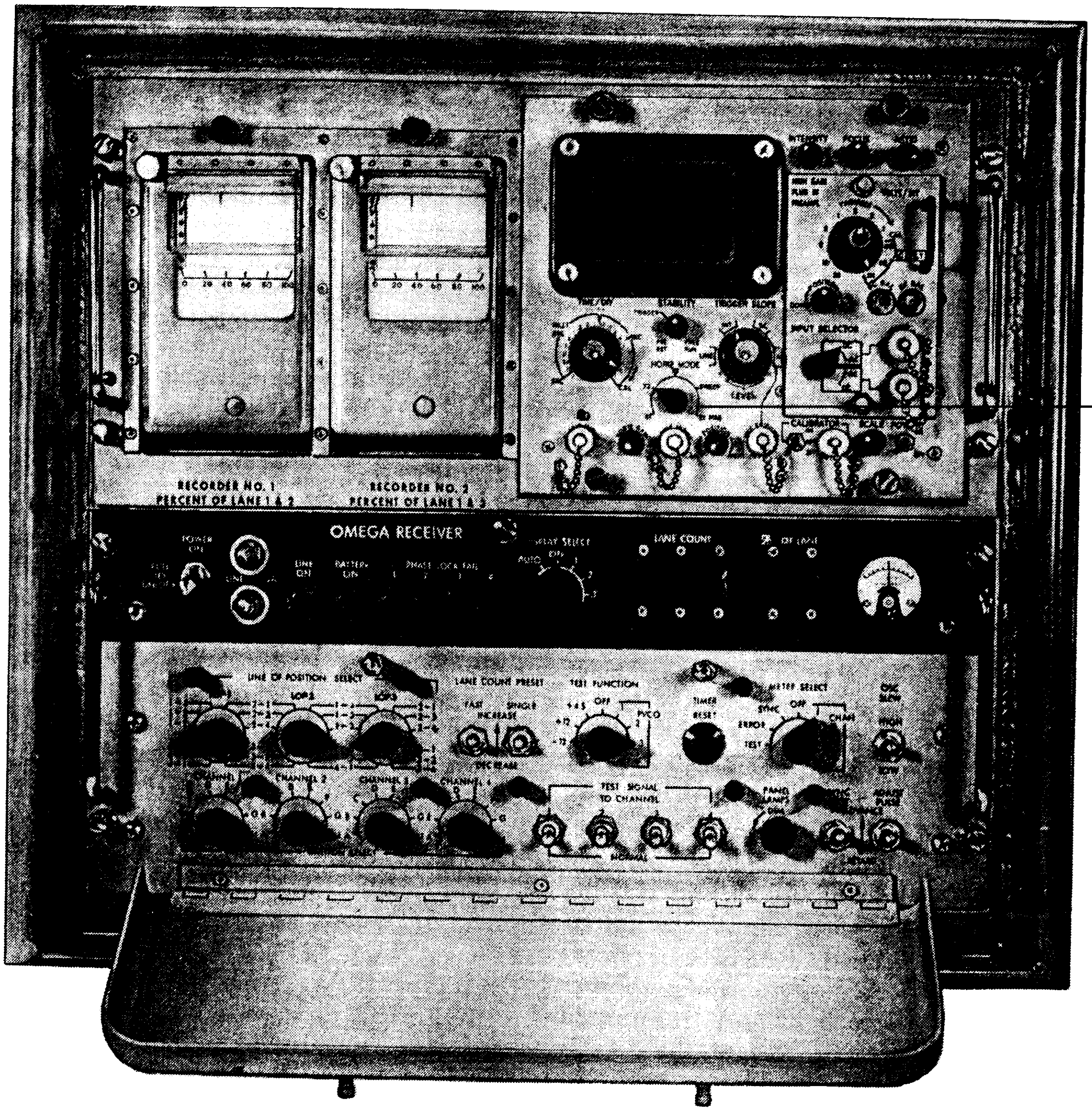

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Figure 8-8.—AN/SRN-12 front panel.

4. It is not affected by adverse weather conditions.
5. It does not radiate energy.
6. It is not detectable by enemy sensors.

The basic components of an inertial navigation system (fig. 8-9) are the accelerometers, gyroscopes, servosystems, and computers (not shown). An accelerometer is a device which measures changes in speed or direction along the axis in which it lies. Its output is usually in the form of a voltage proportional to the acceleration to which it is subjected. A set of two accelerometers (oriented North-South and East-West respectively) is mounted on a gyro-stabilized platform in order to keep them in a horizontal position despite changes in the ship's movements. The accelerometers are attached to

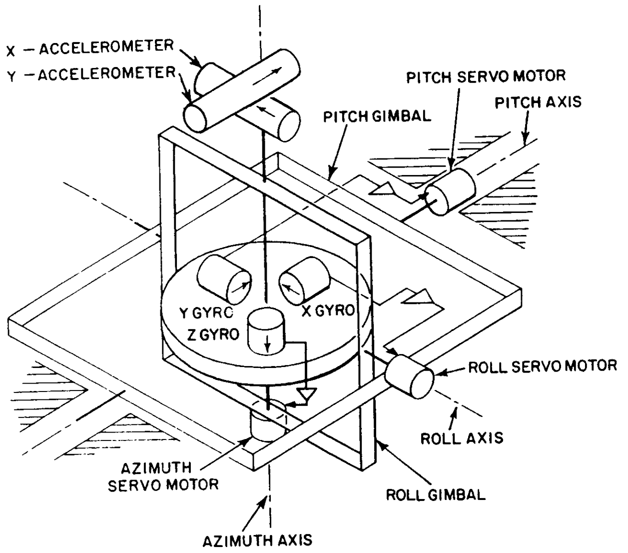

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Figure 8-9.—Stable platform with inertial components.

the platform by means of an equatorial mount (gimbal) whose vertical axis is aligned parallel to the earth's polar axis. This permits the N-S accelerometer to be aligned along a longitude meridian, while the E-W accelerometer is aligned along a latitude meridian.

A three-gyro-stabilized platform is maintained in the horizontal position regardless of pitch, roll, and yaw of the ship. When the ship's heading changes, the gyro signals will cause servosystem motors to operate to keep the platform stabilized. High-performance servosystems are needed to keep the platform stabilized to the required accuracy.

For relatively short periods of time, inertial navigation systems are extremely accurate. To maintain this accuracy over long periods of time, however, requires that the system be periodically updated (reset using a position obtained by some other navigational means: i.e., electronic, celestial or dead reckoning. A coverage of the basic principles of SINS is found in *Electronics Technician 3 & 2,* NAVEDTRA 10195 (Series), Volume 2.

There are several models of SINS on ships today. The Mk 3 Mod 6 system has been placed on SSN 637 class submarines and some aircraft carriers. The Mk 2 Mod 1 system is the configuration for many of the SSN 594 class submarines while the more recent AN/WSN-1 Dual Mini SINS (DMINS) has been installed on the SSN 688 class submarines.

The DMINS represents a considerable improvement in component size (lighter and smaller) and maintenance concept (replacement of entire units (cards) instead of individual part replacement). The DMINS is part of the Central Computer Complex which provides input/output and Central Processor Unit functions via the AN/UYK-7 computers.

The AN/WSN-5 SINS is slated for installation on various surface combatants. This newer unit is a "stand-alone" system (external digital processing resources not required for alignment, reset, calibration or navigational functions).

SATELLITE NAVIGATION SYSTEMS

Satellite navigation was thought feasible after observation of Russia's first artificial earth satellite, Sputnik I. Scientists listened to the beep generated by Sputnik as it passed by and noted the doppler-like shift in the received radio frequency signals. (The doppler effect is an apparent change in a received frequency because of relative motion between the transmitter and receiver. If the distance between the transmitter and receiver is decreasing, the received frequency is higher than that which is actually transmitted; if the distance is increasing, the received frequency is lower than that transmitted.) It was later demonstrated that accurate measurement of this doppler shift pattern would permit the determination of a satellite orbit. From this successfully proven technique it was further reasoned that, working from a known satellite orbit, the listener's own position on the surface of the earth could be determined by observing the doppler pattern. Following the first successful satellite launch in April 1960, the U. S. Navy Navigation Satellite System (NNSS) became an all-weather, highly accurate, fully operational navigation aid, which enables navigators to obtain accurate navigation fixes from the data collected during a single pass of an orbiting satellite.

This section describes the Navy Navigation Satellite System and discusses some of the principles of satellite navigation. The section also includes a brief discussion of Radio Navigation Sets AN/SRN-18 and AN/SRN-19.

NAVIGATION SYSTEM DESCRIPTION

The Navy Navigation Satellite System is a world-wide, all-weather system of high accuracy which enables navigators to obtain fixes approximately every two minutes, day and night. It consists of earth-orbiting satellites, tracking stations, injection stations, the U. S. Naval Observatory, a computing center, and shipboard navigational equipment, as shown in figure 8-10.

Four tracking stations, spaced to monitor five polar circling navigational satellites, are located in Hawaii, California, Minnesota, and Maine (one in each state). Their purpose is to determine accurately the present and future orbits of each satellite. These stations have radio receiving and data processing equipment which digitalize and send the orbital and time information via a control center to the computing center.

The tracking stations maintain highly stable oscillators which are continuously compared against a WWV transmitted frequency standard. In addition, the Naval Observatory sends a daily message which gives the error in the transmitted standard. The Naval Observatory error is then added to the data obtained from the frequency standard and corrections are made to the station oscillators. The station oscillators are used to drive station clocks which are compared with the time marks received from the satellite. This time data is transmitted by the tracking stations to the control center where the satellite clock error is calculated and the necessary time correction bits are added or deleted in the next injection message to the satellites.

The central computing center continuously accepts satellite data inputs from the four tracking stations and the Naval Observatory. Periodically, to obtain fixed orbital parameters for a satellite, the central computing center computes an orbit for each satellite that best fits the doppler curves obtained from all tracking stations. Then, using the computed orbital shape, the central computing center extrapolates the position of the satellite at each even two minutes in universal time for the 12 to 16 hours subsequent to data injection. These various data inputs are supplied to the injection stations via the control center, as are data on the nominal space of the orbits of the other three satellites, commands and time correction data for the satellite, and antenna-pointing orders for the injection station antennas.

The injection stations, after receiving and verifying the incoming message from the central computing center, store the message until it is needed for transmission to the satellite. As soon as the receiving equipment at the injection station receives and locks on the satellite's signals, the injection station reads the injection data and the commands from storage, then transmits them to the satellite. Transmission to the satellite is on a frequency different from those frequencies used by the satellite, and the bit rate is much higher; therefore, injection is completed in a matter of seconds. Once data injection is completed, the satellite continues to transmit at the normal two-minute intervals.

Satellites

The system satellites are launched as nearly as possible into circular polar orbits at altitudes of from 450 to 700 miles. Typically, a system satellite (fig. 8-11) is about the size of the large snare drum used in a marching band and weighs between 110 and 160 pounds. It is solar-powered with electrical energy collected by four solar cell vanes (blades) and stored in batteries within the satellite. A transmitting "lampshade" type directional antenna is mounted on its base, and receiving "rod" antennas are located at opposite ends of two solar blades. In orbit, the solar blades are extended to form an X with the payload in the center. A 100-foot spring steel boom, weighted at the end with a stabilization counterweight, is extended upward from the top of the spacecraft to keep the transmitting antenna always pointing at the target, earth.

Although successive models may differ, each system satellite basically contains the following:

1. Receiver equipment to accept injection data and operational commands from the ground

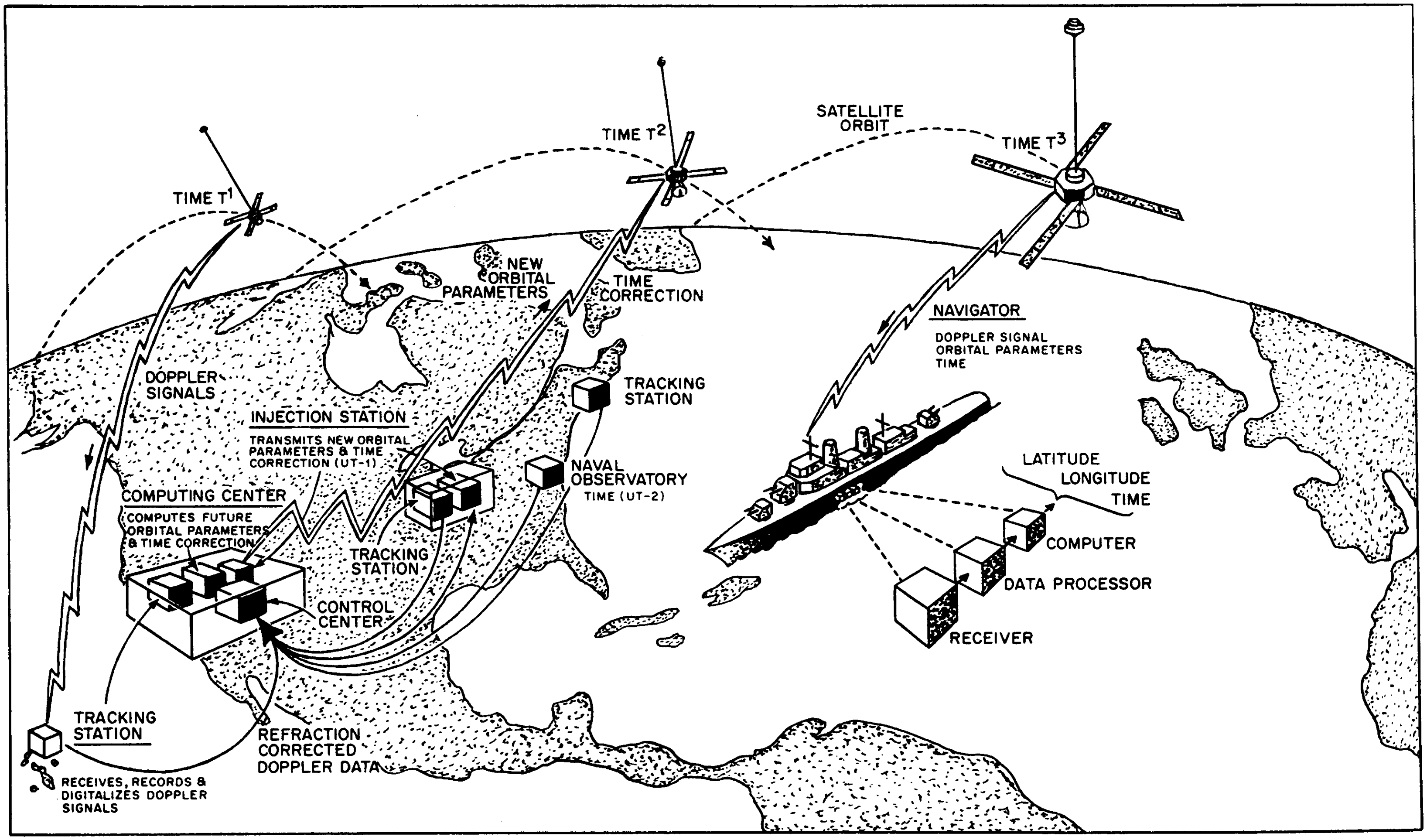

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Figure 8-10.—Navy navigation satellite system.

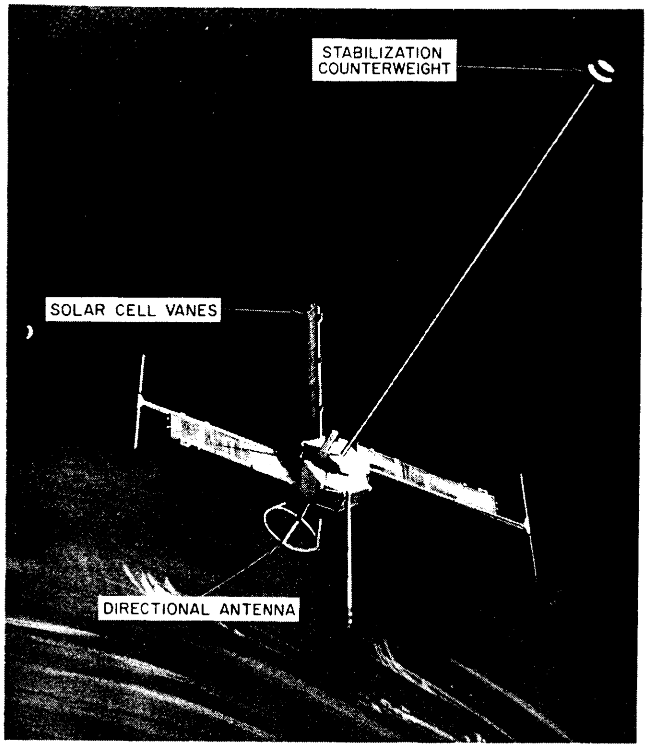

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Figure 8-11.—Navigation satellite.

2. A decoder for digitalizing the data, plus switching logic and memory banks for sorting and storing the digital data, and pulse control circuits to cause the data to be read out at specific times in the proper format

3. An encoder to translate the digital data to phase modulation

4. Ultrastable 5-MHz oscillators and 1.5-watt transmitters to broadcast the 150- and 400-MHz oscillator-regulated frequencies that carry the data to earth.

Any spot on earth rotates within range of a single circular polar-orbiting satellite at least twice a day. Therefore, a navigation satellite system is operable with one satellite. To provide more frequent availability, however, a constellation of satellites is used. For example, a constellation of five satellites criss-crossing at the poles in orbits that are equally separated as they cross the equator provides contact anywhere on earth on an almost hourly basis.

The satellites supply two important outputs to the fleet: the stable carrier frequencies that are generated by the satellites, and the data that they carry which is updated by the ground system at regular intervals. The data, phase modulated on the carrier signals, contains the current satellite time and the orbital parameters of the satellite. Each satellite is designed to receive, sort, and store data transmitted from the ground, and to retransmit this data at scheduled intervals as it circles the earth.

Each two-minute satellite broadcast typically contains "words" used for recognition and time synchronization, followed by a 400-Hz audible "beep" (or standard time marker) used by navigators to find their place in the broadcasts. The navigation data itself contains fixed and updated variable parameters describing the present orbit of the satellite. Essentially, each satellite is telling users which satellite it is, what time it is according to the satellite "clock," and the satellite's present location. With this information, the user's navigation set knows exactly where the satellite is, one of the necessary steps toward determining a precise navigational position.

While the user's navigation set is receiving data providing the satellite position, it is also measuring the doppler shift of the satellite signals and comparing them to determine where the navigation set is located in relation to the satellite. The navigation set associates the satellite outputs in real time, and prints out a fix in a short period of time. A description of the doppler principle involved is presented below:

System satellites placed in circular polar orbits from 450 to 700 miles in altitude yield optimum doppler measurability coupled with maximum coverage and long life. They circle the earth at a tangential velocity of about five miles per second. Stable oscillator frequencies radiating from a satellite coming toward the receiver (T_1, fig. 8-12) are first received at a higher frequency than transmitted, due to the velocity of the approaching satellite. The satellite's velocity produces accordion-like compression effects that squeeze the radio signals as the intervening distance shortens. As the satellite

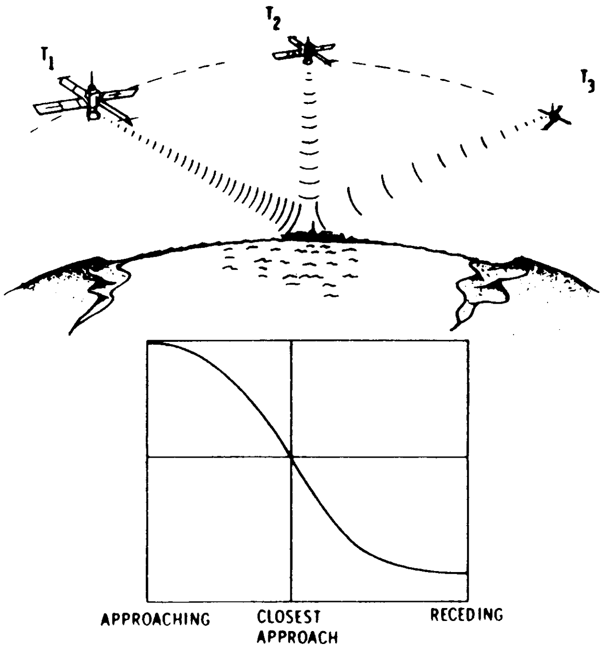

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Figure 8-12.—Doppler shift relative to satellite transmitted frequency.

nears its point of closest approach, these compression effects lessen rapidly, until, at the moment of closest approach (T_2), the cycle count of the received frequencies exactly matches that which is generated. As the satellite passes beyond this point and travels away from the receiver (T_3), expansion effects cause the received frequencies to drop below the generated frequencies proportional to the widening distance and the speed of the receding satellite.

Radio frequencies will yield an accurate cyclecount. By counting the cycles of the received signals at precise intervals, the amount of doppler shift can be measured. Measurement of doppler shift is complicated by the fact that satellite transmissions must pass through the earth's upper atmosphere on their way from space to receiver. Electrically charged particles in the ionospheric layer deflect satellite radio transmissions in much the same way that a prism refracts light. To solve this problem, system satellites are designed to broadcast simultaneously on two frequencies, each of which is refracted a different amount by the ionosphere. The receiver measures the difference in refraction between the two signals and supplies a signal to the computer. The computer uses this "refraction signal" as part of its computation in order to obtain more accurate fixes.

The time of zero doppler is the time of the satellite's closest approach to the receiver. The slope of the curve at that time is a measure of the slant range from the receiver to the satellite. Measurement of doppler shift against an offset frequency is the critical factor in an equation that establishes position on earth in relation to a satellite of known orbit. At a given instant, that particular curve can be acquired at only one point on earth in relation to that satellite. Given the orbital parameters of a satellite, (with each satellite constantly transmitting its position) and the doppler shift of the signal transmitted from that satellite, it is possible to obtain a navigational fix whenever and wherever the satellite passes within radio line-of-sight.

At least three doppler measurements from the satellite are necessary to determine a navigation fix. This normally requires three two-minute intervals. However, by using a "short count" computer program, a navigation fix can be obtained with less than three two-minute intervals. A "short count" mode on the digital processor unit of the navigation set allows doppler (and refraction correction) counts to be accumulated in intervals as short as 4.6 seconds.

Ground Network

Navigation satellites, being in comparatively near-earth orbits, do not follow fixed paths as do objects in deep space. The satellites, therefore, must be updated periodically. If the satellites were operating in deep space, their fixed orbits would be perfectly elliptical, therefore constant updates of these predictions would be unnecessary from the ground. However, since system satellites operate at altitudes of only 450 to 700 miles, they are subject to external forces that produce orbital irregularities, or perturbations. In other words, instead of traversing a smooth ellipse, system satellites tend to wriggle in orbit.

Some of the external causes for these perturbations are the fact that the earth is not a perfect sphere, but tends to be somewhat pear-shaped, with an unequal, off-center distribution of mass, producing a complex gravitational field. This field is made even more complex by the gravitational pull of the sun and moon, and the fact that the satellites are not operating in a perfect vacuum, but are subject to a certain amount of atmospheric drag that persists at orbital altitudes. Also contributing to orbital irregularities of the satellites are solar photon pressures, solar wind, and electrostatic and electromagnetic forces caused by the spacecraft's interaction with charged particles in space and the earth's magnetic field. Fortunately, all of the causes of these chronic irregularities are either sufficiently constant or so localized as to be reducible to formulas that can be programmed into orbital computations. In other words, the wriggles are predictable and can be compensated for.

Several ground stations are needed to determine that the data being transmitted by the satellite is correct. It is the task of these tracking stations to track the satellite and receive its data during a pass. The satellite data and the data describing the antenna positioning during the pass are sent to a computing center. The Navy Observatory maintains a listening station that receives the time information from the satellite. If a correction to the satellite time is required, such information is sent to the computing station. The computing center uses the track information from the tracking station to construct a mathematical model of the pass. This information is compared to the information received from the satellite. From these data, advance predictions of the satellite orbits may be made. Because the satellite memory is only capable of information storage for a maximum of 18 hours, the satellite must be fed new information periodically. A time period of 12 hours between upgrading has been selected as optimum.

Information that has been gathered and computed is sent to an injection station. This station will, during a pass, send new information to the satellite for retention in its memory (fig. 8-13). When the transmission is complete (a matter of about 15 seconds), the new information being transmitted by the satellite is checked by the injection station. If the new information is not as sent, a reinjection is attempted.

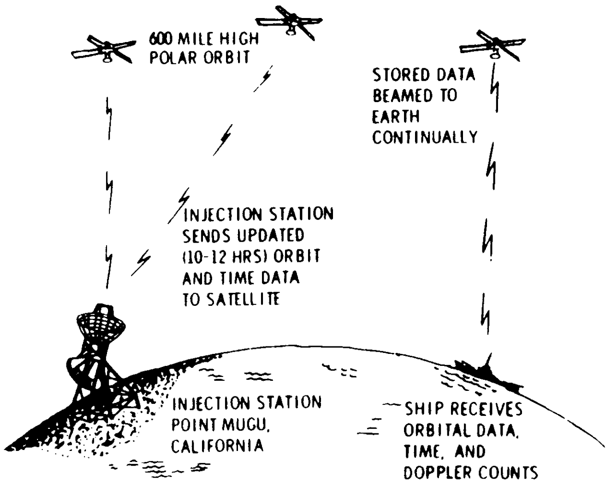

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Figure 8-13.—Updating navigation satellites.

AN/SRN-19(V)2 RADIO NAVIGATION SET FUNCTIONAL DESCRIPTION

The AN/SRN-19(V)2 is an automatic shipboard navigation set that provides a continuous display of the ship position. The ship position, which is maintained by dead reckoning on ship true speed and heading, is periodically corrected by satellite fixes.

Specifically, the navigation set can perform the following functions:

1. After each successful satellite pass, computes and displays present location of the ship to a nominal at-sea accuracy of 0.25 nautical mile
2. Dead reckons between satellite fixes
3. Computes and displays the great circle range and bearing from the present position to any location
4. Computes and displays the next expected rise time and elevation at closest approach of the previously tracked satellite
5. Displays time accurate to 1 second (in 5-second increments)
6. Displays speed and heading
7. Displays set and drift
8. Displays data on tracked satellite
9. Self tests itself and displays fault indication should a failure occur (self-test functions are limited to verification of the digital circuitry)

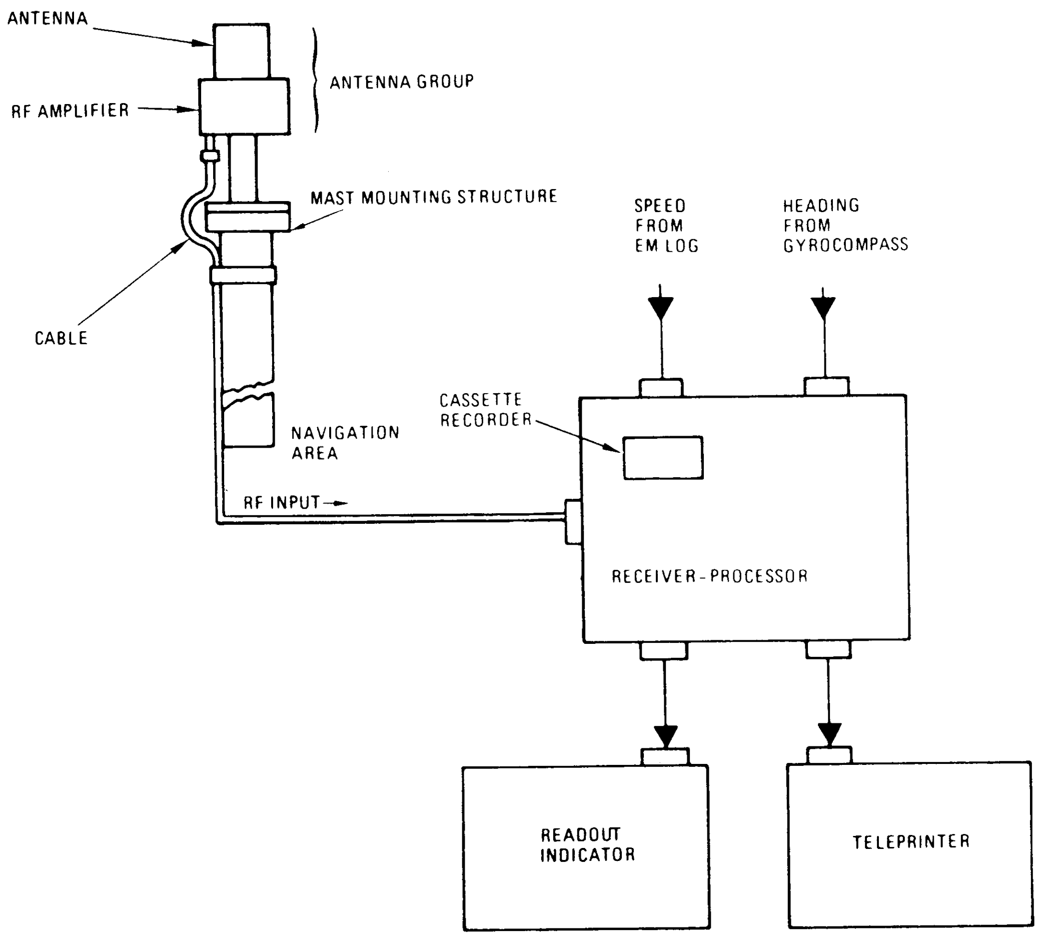

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Figure 8-14.—AN/SRN-19(V)2 Radio Navigation Set Simplified Block Diagram.

Major Components

The AN/SRN-19(V)2 Radio Navigation Set consists of the following major components (fig. 8-14):

- ANTENNA GROUP
- RECEIVER-PROCESSOR
- READOUT INDICATOR
- TELEPRINTER

ANTENNA GROUP.—The antenna group consists of the Antenna and RF Amplifier.

Antenna.—The antenna is a linear, vertically polarized type which receives rf signals transmitted by the satellite. The antenna pattern is omnidirectional in the horizontal plane. The vertical pattern varies approximately 11 dB from 10° to 70° above the horizontal plane.

RF Amplifier.—The rf amplifier provides initial amplification of the 400-MHz satellite signals from the antenna. The amplified signals are then connected via rf coaxial cable to the receiver for further amplification and processing.

RECEIVER-PROCESSOR.—The receiver-processor contains the electronics to process rf inputs from the rf amplifier, ship EM log, gyrocompass, and receiver-processor keyboard. The receiver-processor then performs the navigational computations and provides required outputs.

Receiver.—The functions of the receiver are to extract, amplify, and format message information from the rf signal transmitted by the satellite, and measure doppler shift of this same signal. The reconstructed doppler shift of the satellite signal results from relative motion between the receiver and the satellite. The message data obtained by demodulation of the rf carrier describes the satellite position at the time of transmission.

Data Processor.—The data processor processes inputs from the receiver, the ship EM log, gyrocompass (through converters), and the keyboard. The processor then performs computations and provides the desired outputs to the front panel display, readout indicator, teleprinter, and cassette recorder.

READOUT INDICATOR AND TELEPRINTER.—The readout indicator and the teleprinter provide visual outputs from the system.

RADIO NAVIGATION SET, AN/SRN-18

The AN/SRN-18 radio navigation set is comprised of units designed for shipboard operation in the vhf (150 MHz) and the uhf (400 MHz) ranges. It receives signals transmitted by the satellite, measures the doppler shift and the

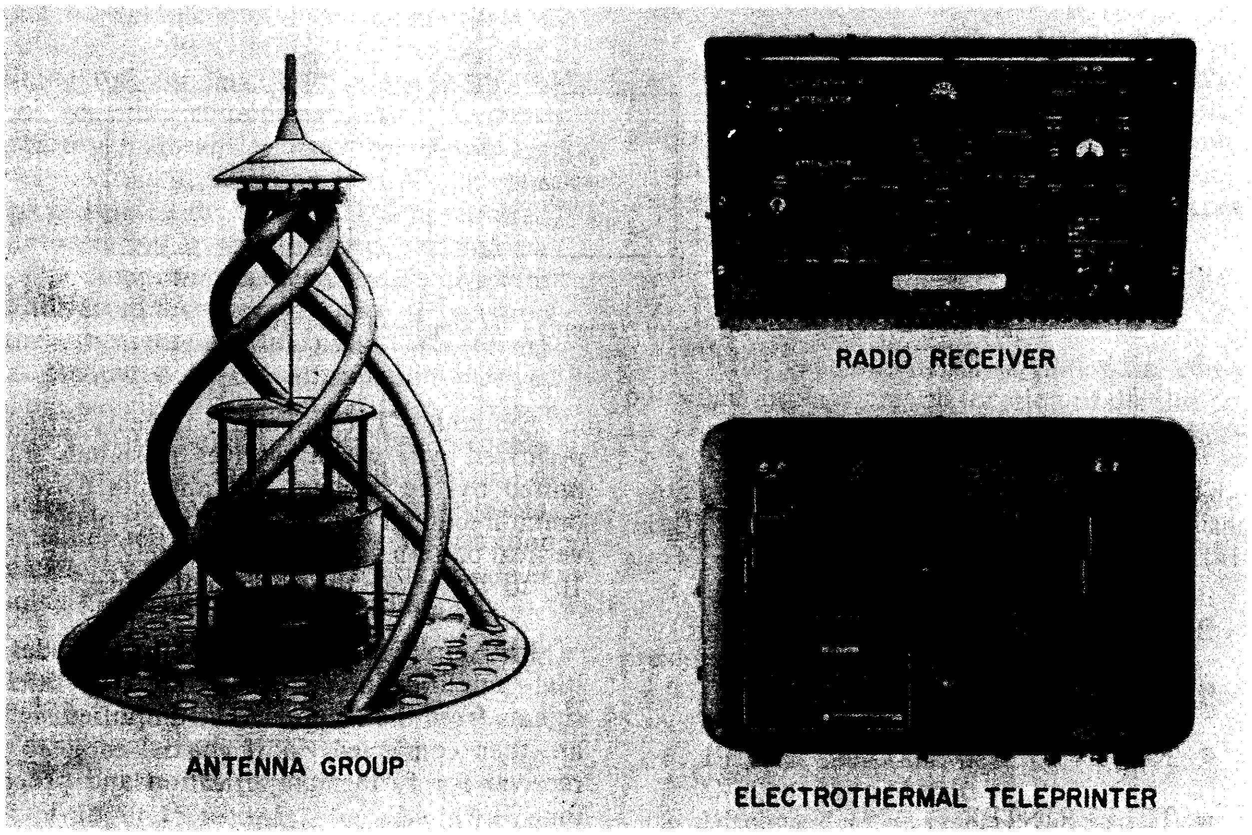

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Figure 8-15.—Radio Navigation Set, AN/SRN-18.

amount of refraction, decodes the satellite message, and organizes the data for navigational position fix computation.

The radio navigation set consists of three units (fig. 8-15):

1. Radio Receiver
2. Antenna Group
3. Electrothermal Teleprinter

A time-base unit (frequency standard AN/URQ-10, or equivalent, or time standard) is required to provide a stable time base for the precision timing circuits within the radio navigation set. (Frequency standard AN/URQ-10 is described in detail in technical manual NAVSHIPS 0967-LP-053-7010). The time base unit is mounted external to the radio navigation set. The standard should provide a 5-MHz reference signal which is stable to approximately 5 parts in 10^{-11} per 120-second period.

Radio Receiver

The radio receiver is the major unit of the radio navigation set. This unit consists of two phase-lock tracking receivers, a small digital processing unit (dpu), a power supply, and a signal generator.

Amplified 150-MHz and 400-MHz outputs from the antenna, via the antenna group, are applied as inputs to a low-noise, dual-channel, phase-lock tracking receiver in the radio receiver. The receiver contains channel isolation and image filters. A precision 5-MHz standard frequency must be provided to this unit from a separate frequency standard (AN/URQ-10). These equipments operate in conjunction to extract information from the incoming frequencies, measure the doppler frequency shift and refraction count, decode the information content of the phase modulation, and provide this decoded information to the digital processing unit (dpu) for processing. The information extracted from the 150-MHz and 400-MHz signals will determine the ship's geographic position.

The dpu is made up of logic elements that reduce the outputs of the receiver to a form suitable for navigational computations. The dpu or the digital data processing function provides for:

1. Data buffering and time-multiplexing control of satellite orbit data

2. Doppler shift count data, ionospheric refraction data, and satellite message data sent to a computer in real time

The dpu provides outputs to an external computer and converts the information into suitable formats for data recording and data computation equipment.

A self-test function is performed by a signal generator which is mounted in the radio receiver. The self-test function allows the operator to test the radio navigation set at both 400 MHz and 150 MHz by providing simulated satellite signals to the input of the preamplifiers of the antenna group. There are two test modes of operation, the sensitivity mode and the doppler mode. In the sensitivity mode, a calibrated power level is sent through the preamplifiers to the phase-lock tracking receiver for a test of its sensitivity. In the doppler mode, a known offset frequency with satellite type phase modulation of known content is sent through the receiver components to test its doppler counting circuits and message demodulation ability.

Antenna Group and Electrothermal Printer

The antenna group and electrothermal printer serve the same functions as described for the AN/SRN-19. The differences are the use of dual frequencies and the type of data printed out.

NAVSTAR SYSTEM

The Navstar Global Positioning System (Navstar GPS) is an anti-jam precise ranging system that will enable instant, simultaneous determination of position and velocity. The system will use twenty-four satellites and should be fully deployed by the mid-1980's.

TACTICAL AIR NAVIGATION

TACAN (tactical air navigation) is a radio air-navigation system of the polar coordinate type which provides an aircraft with distance measuring equipment (DME) and bearing information. Usually, a meter in the aircraft indicates, in nautical miles, the distance of the aircraft from the surface beacon. Another meter will indicate direction of flight in degrees-of-bearing with respect to the geographic location of the surface beacon (fig. 8-16). When bearing and distance from a specific geographic point are known, position can be fixed by the pilot. The identification signal transmitted by the surface beacon enables the pilot to identify from which beacon information is being received, thus allowing the geographic location to be plotted.

TACAN PRINCIPLES

Basic principles of TACAN are discussed briefly in the following paragraphs.

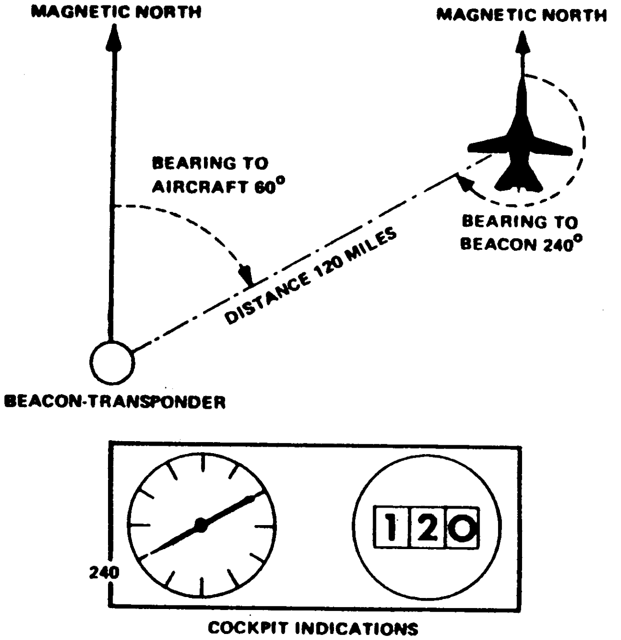

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Figure 8-16.—Aircraft indications.

The distance measuring concept used in TACAN equipment is an outgrowth of radar-ranging techniques, i.e., determining distance by measuring the round-trip travel time of pulsed rf energy. The return signal (echo) of the radiated energy is dependent on natural reflection of the radio waves. However, TACAN beacon-transponder facilities, located at specific geographic positions, generate artifical replies rather than depending upon natural reflection. The airborne equipment generates timed interrogation pulse pairs that are received by the surface TACAN system and decoded. After a 50 μsec delay, the transponder responds with a reply (fig. 8-17). The round trip time is then converted to distance from the TACAN facility by the airborne DME. The frequency and identification code provides the geographic location.

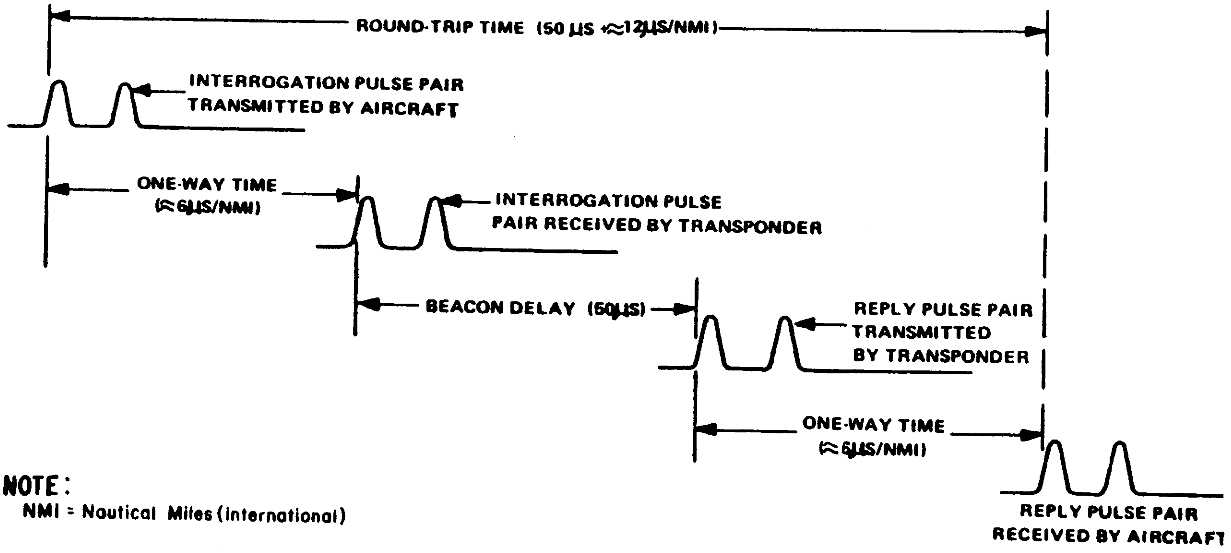
TACAN Pulse Pairs

All TACAN pulse signals, generated by either the airborne or ground equipment, are pulse pairs (fig. 8-18) spaced 12 μsec apart (for all "X" channels). The transponder utilizes a twin-pulse decoder to pass only pulse pairs with the proper spacing. The purpose of the twin-pulse technique is to increase average power radiated, and to make the TACAN system less susceptible to false signal interference. Once the interrogation is decoded by the receiver, an encoder will generate the necessary pulse pair required for the transponder's reply.

Constant Transponder Duty-Cycle

In principal, the TACAN transponder need only reply to aircraft interrogations to supply the necessary distance data. However, the total pulse output of the transmitter would constantly vary according to the number of interrogating aircraft. In order for azimuth information to be supplied, the average power supplied to the antenna must be relatively uniform over time. To accomplish this, the transponder is operated on the constant-duty-cycle principle.

In this method of operation the receiver has automatic gain and squitter (noise-generated output) controls which maintain the receiver at a



NOTE:
NMI = Nautical Miles (International)

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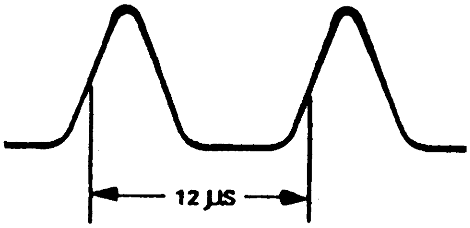
Figure 8-17.—Distance measurement round-trip travel time.



PULSE WIDTH = 3.5 ± 0.5 µS
PULSE RISE TIME = 2.5 ± 0.5 µS
PULSE FALL TIME = 2.5 ± 0.5 µS

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Figure 8-18.—TACAN pulse pair.

constant pulse output (fig. 8-19). If few interrogations are being received, the squitter and gain of the receiver will increase and add noise-generated pulses until the constant pulse output is obtained. If more interrogating aircraft come into range, the gain and squitter will decrease to maintain constant pulse output. If more than 100 aircraft interrogate, typically only the strongest 100 will generate replies from the transponder.

Beacon-Transponder Identification Code

To provide aircraft with positive identification of the replying transponder, an identification feature is necessary. To meet this need, an identification code is transmitted at approximately one-half minute intervals. This is accomplished by momentarily interrupting the transponder distance data and squitter-generated output and substituting pulse groups spaced at a 1350-pps rate. Each pulse group contains two sets of 12 µsec pulse pairs spaced 100 µsec apart. The duration of the identification pulse groups varies to represent Morse-coded characters. The duration for a dot is 0.125 second, and for a dash 0.375 second. (See fig. 8-19.)

15-Hz Bearing Information

The timing of the transmitted pulses is used for supplying distance information to the aircraft. This leaves amplitude modulation as another medium for the transponder to convey information to aircraft. The TACAN beacon-transponder modulates the strength of the pulse to convey bearing information by producing a

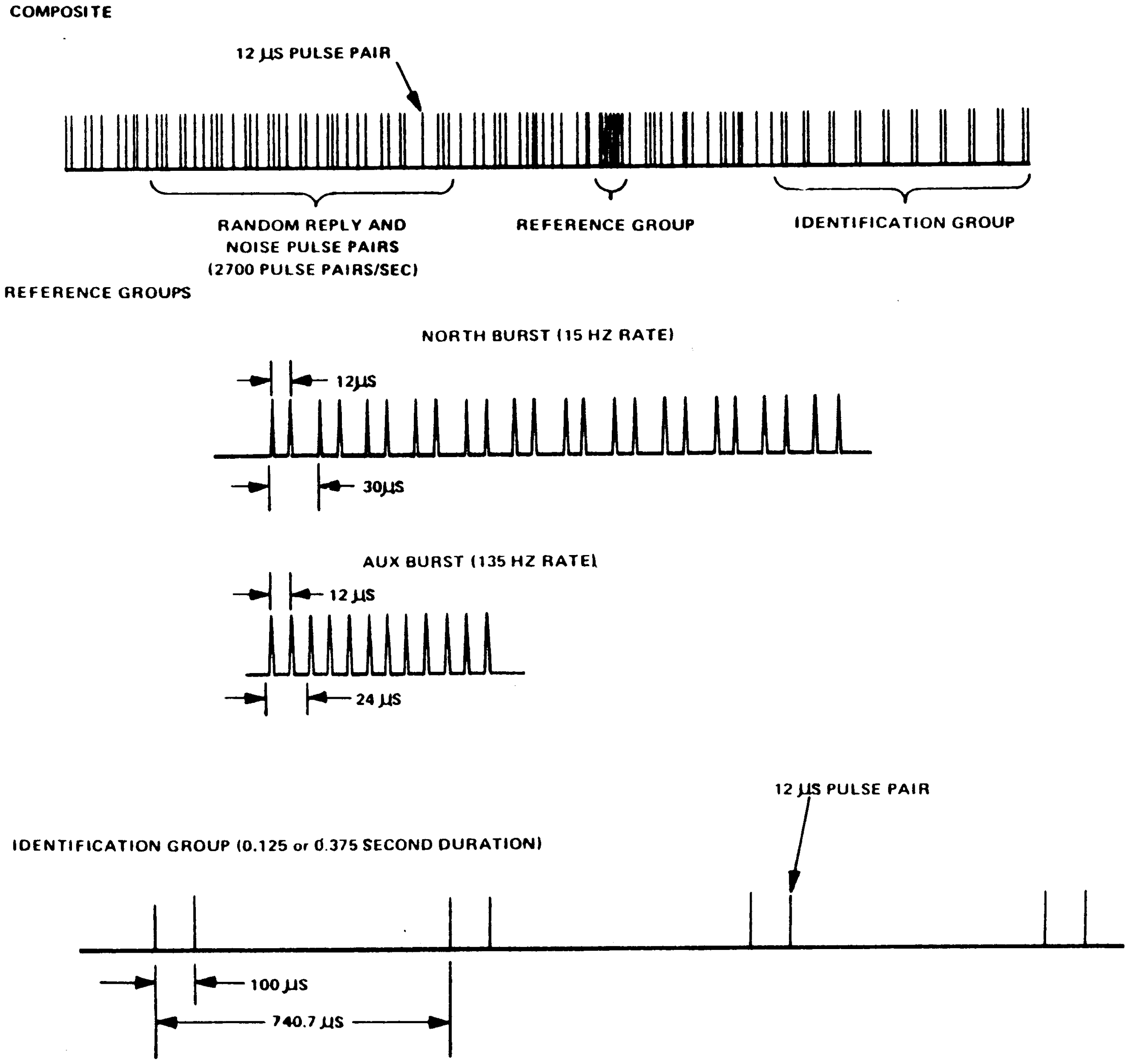

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Figure 8-19.—Transponder output pulse train.

specified directional-radiation pattern rotated around a vertical axis. This signal, when properly referenced, identifies the aircraft direction from the TACAN facility. This, and distance data, give a two-point fix for specific aircraft location.

The rf energy from the transmitter is fed to a stationary central element in the antenna that has no directivity in the horizontal plane. A vertical, parasitic element is rotated around the central element at 15 revolutions per second. The distance between the central element and parasitic element is established to obtain a cardioid radiation pattern (fig. 8-20). To an aircraft at a specific location, the distance-data pulses would contain a 15-Hz amplitude-modulated

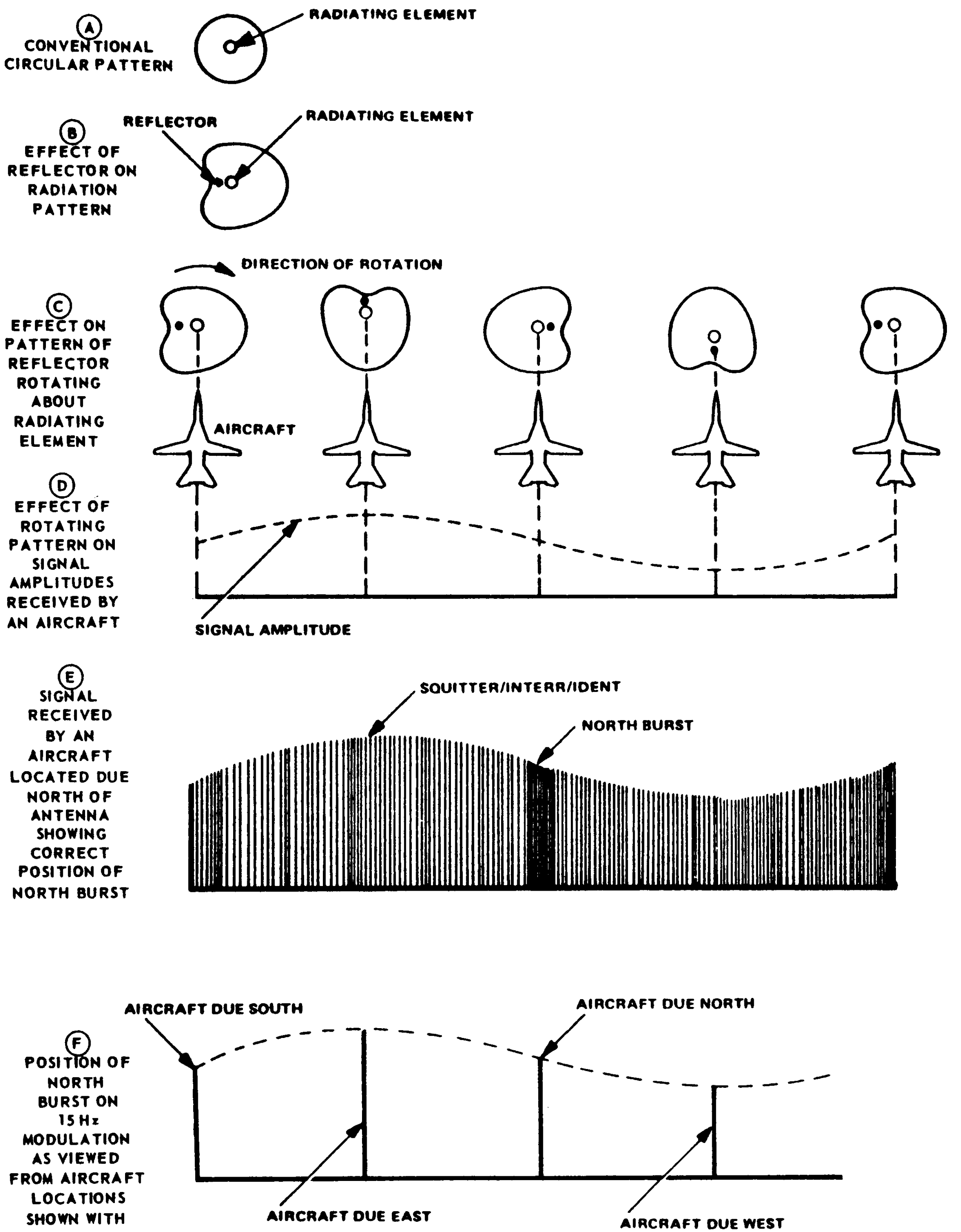

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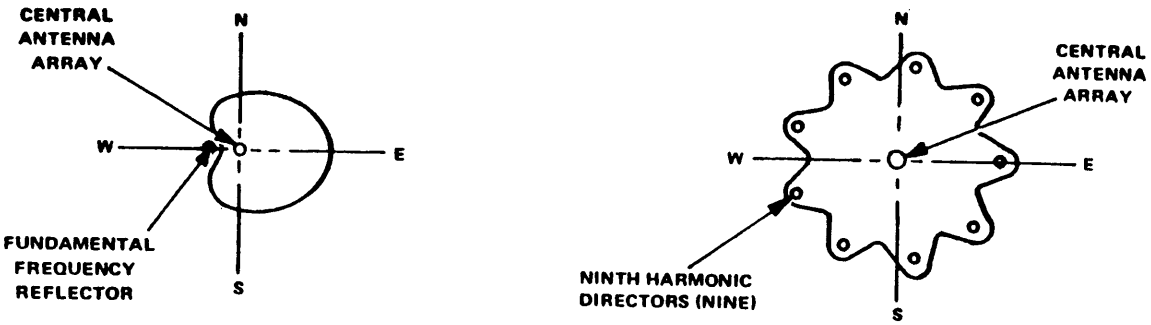
Figure 8-20.—Development of radio beacon radiation (15 Hz only).

signal due to the rotation of the cardioid radiation pattern.

Bearing information can now be obtained by comparing the 15-Hz modulated signal with a 15-Hz reference burst signal received from the ground facility. The phase relationship between the 15-Hz modulated signal and the 15-Hz reference burst signal will be dependent upon the location of the aircraft in the cardioid pattern. The 15-Hz reference burst signals are transmitted when the maximum signal of the rotating cardioid pattern aims due east (fig. 8-20C and E). The reference signals are distinguished from the distance data by transmitting a burst of 12 pulse-pairs (12 μsec apart) spaced exactly 30 μsec apart (fig. 8-19). This group of 12 pulse pairs is commonly referred to as the north or main reference burst.

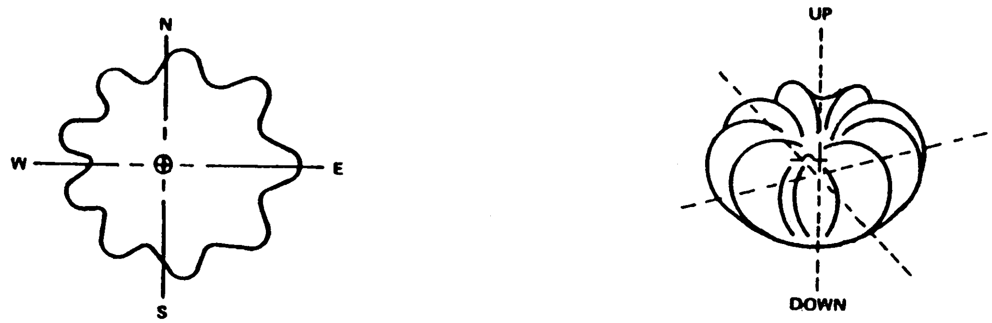
135-Hz Bearing Information

Errors in the single parasitic element system arise from imperfection of the phase-measuring circuits and radio propagation effect known as site error. The errors are significantly reduced by adding to the antenna a group of nine parasitic elements mounted 40 degrees apart (fig. 8-21). These nine parasitic elements rotate around the central elements with the single element and modify the antenna cardioid radiation pattern. Although the cardioid pattern is still predominant, it is altered by superimposed ripples (fig. 8-21). The maxima of these ripples, or minor lobes, are spaced 40 degrees apart. The aircraft now receives the 15 Hz with a 135-Hz ripple amplitude modulated on the distance data pulses (fig. 8-22).



Ⓐ HORIZONTAL PATTERN OF 15 Hz (Fundamental Frequency) MODULATION

Ⓑ HORIZONTAL PATTERN OF 135 Hz (Ninth Harmonic) MODULATION



Ⓒ HORIZONTAL PATTERN COMBINATION OF FUNDAMENTAL & NINTH HARMONIC MODULATION

Ⓓ THREE DIMENSIONAL ANTENNA RADIATION PATTERN

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Figure 8-21.—Development of composite radiation pattern.

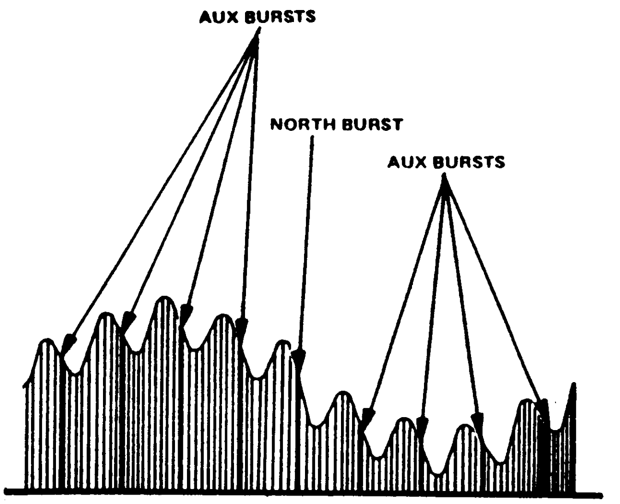

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Figure 8-22.—Radio beacon radiated 15 Hz and 135 Hz pattern showing auxiliary and north reference burst as viewed from an aircraft located due north of beacon.

To furnish a suitable reference for measuring the phase of the 135-Hz component of the envelope wave, the transponder is designed to transmit a coded 135-Hz reference burst similar to that explained for the 15-Hz reference. The 135-Hz reference burst is a precisely timed group of six pulse pairs (12 μsec apart) spaced exactly 24 μsec apart (fig. 8-19). In one rotation of the parasitic elements, eight 135-Hz reference bursts are transmitted. The ninth group transmitted is the 15-Hz reference group. Each group is separated by 40 degrees of rotation. The 135-Hz reference group is commonly referred to as the auxiliary or aux reference burst.

The composite TACAN signal is composed of 2700 interrogation replies and noise pulse pairs per second, plus 180 north burst pulse pairs per second, plus 720 auxiliary burst pulse pairs per second for a total of 3600 pulse pairs per second or 7200 pulses per second.

TACAN Signal Priorities

Priorities have been established for transmission of the various types of TACAN signals. These priorities are as follows:

1. Reference Bursts
2. Identification Group
3. Replies to Interrogations
4. Squitter

Therefore, the identification group, replies, or squitter will be momentarily interrupted for the transmission of either the main or auxiliary reference group. The transmission of replies or squitter will be interrupted every 37.5 seconds during the transmission of an identification code dot or dash.

Characteristics of Radio Beacon Signals

All signals transmitted by the radio beacon consist of pulse pairs with 12-μsec spacing between the two pulses of the pair. The number of pulse pairs per second and the spacings between pulse pairs (i.e., the spacing between the leading edge of the first pulse of the first pulse pair, and the leading edge of the first pulse of the next pair) depend upon, and are a characteristic of, that particular signal element. However, it is the spacing of 12 μsec between the pulses of a pair that provides the aircraft with a means of distinguishing between the signal pulses from the radio beacon and any other pulses that may be present at the received radio frequency. The characteristics of the signal elements transmitted by the radio beacon are given below:

1. North Reference Burst—consists of 12 pulse pairs with 12-μsec spacing between pulses of a pair, and 30-μsec spacing between pulse pairs occurring 15 times per second.
2. Auxiliary Reference Burst—consists of six pulse pairs with 12-μsec spacing between pulses of a pair, and 24-μsec between pulse pairs occurring 120 times per second at the rate of 135 Hz.
3. Identification Code—consists of a train of 2,700 pulse pairs per second with 12-μsec spacing between pulses of a pair occurring at a 1,350-Hz double-pulsed rate (100 μsec between double-pulsed pairs). The tone pulses are phase-locked to the reference bursts.
4. Distance Measuring Interrogations—consist of pulse pairs with 12-μsec spacing between pulses of a pair. The spacing between pulse pairs depends upon the pulse repetition rate peculiar to the interrogating aircraft.

5. Squitter Pulses—consist of pulse pairs with 12-μsec spacing between pulses of a pair. The number of pulse pairs per second depend upon the number of interrogations being received by the beacon, but with a minimum spacing of 40 μsec (60 μsec for some equipment) between pulse pairs.

TACAN EQUIPMENT

There are a number of different types of TACAN equipment aboard ship that perform the same function, although they are physically different in appearance. The AN/URN-20B(V)1, and AN/URN-25 represent the old and new TACAN radio sets in the fleet today. In the new antenna configurations the parasitic elements have been replaced by electronic components.

Radio Set AN/URN-20B(V)1

The single Radio Set AN/URN-20B(V)1, (fig. 8-23) and dual Radio Set AN/URN-20B(V)2 are TACAN air navigation aids intended for ship or shore installation. The functions performed by the single and dual sets are identical. The dual set, however, includes two transponder groups, one additional monitor, and three additional line voltage regulators. Also, the local control units, interconnecting wiring, and the test monitor control (TMC) rf components are different from that of the single set. The additional equipment in the dual set makes it possible to maintain operation of the TACAN set in case of failure of one transponder group.

The radio set is capable of being operated in either the "X" or "Y" mode of operation. In the X mode the set transmits both distance measuring and bearing information. In the Y mode, only distance measuring information can be transmitted. (Evaluation results of on-going tests of an equipment field change may make transmission of all information feasible.)

Capabilities and Limitations

In the X mode of operation, the radio set transmits on one of 126 discrete channel frequencies (which are 1 MHz apart) within the ranges from 962 to 1024 MHz and from 1151 to 1213 MHz. In the Y mode of operation, the set transmits on one of 126 discrete channel frequencies (which are 1 MHz apart) within the range from 1025 to 1150 MHz. The radio set receiver, operating in the 1025 to 1150 MHz range for both the X and Y modes, is always 63 MHz displaced from the transmitter frequency.

The radio set can provide individual distance measuring service for up to 100 interrogating aircraft simultaneously. Of the 3600 pulse pairs per second transmitted by the radio set, 900 pulse pairs contain the bearing information; the remaining 2700 pulse pairs are either random noise pulses, identity pulses, or replies to interrogations from the aircraft. Once every 37.5 seconds, the interrogation replies and random noise pulses are interrupted for the transmission of identity pulses.

The radio set has a receiver sensitivity of −92 dBm or better and a nominal peak power output of 10 kilowatts at the transponder cabinet output. (Power output may be limited to less than peak by directives.) Since the bearing and identification signals are delivered spontaneously and not in response to interrogations, an unlimited number of properly equipped aircraft can derive this information from the radio set over a line-of-sight range up to 300 nautical miles.

AN/URN-25 RADIO SET

The AN/URN-25 is a newer TACAN Beacon set which replaces the AN/URN-20B(V)1 sets on many ships. It is smaller and has been improved for modern shipboard use.

AN/SRN-15 BEACON-TRANSPONDER SET

The AN/SRN-15 Beacon-Transponder Set (fig. 8-24) is a lightweight, low cube, highly reliable system specifically designed for use as a shipboard air (helicopter) navigation system for ARN-52 or ARN-84 equipped aircraft only.

The system provides radio navigation information (omnidirectional azimuth, distance and identification information) to as many as 100 aircraft simultaneously. The azimuth portion of the system measures the phase angle between two radiated signals and provides information on the magnetic azimuth relative to the

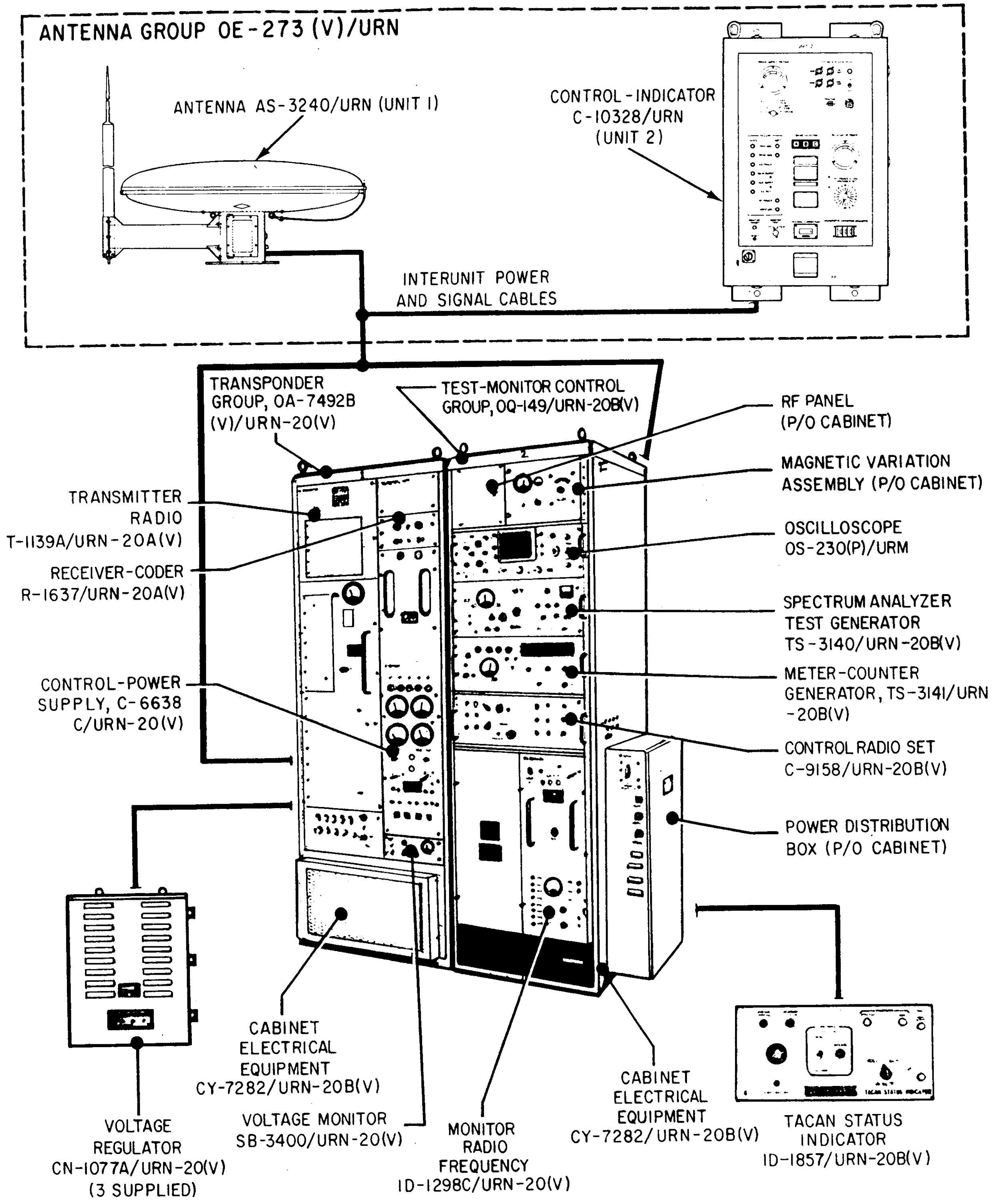

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Figure 8-23.—Radio Set AN/URN-20B(V)1 (single radio set).

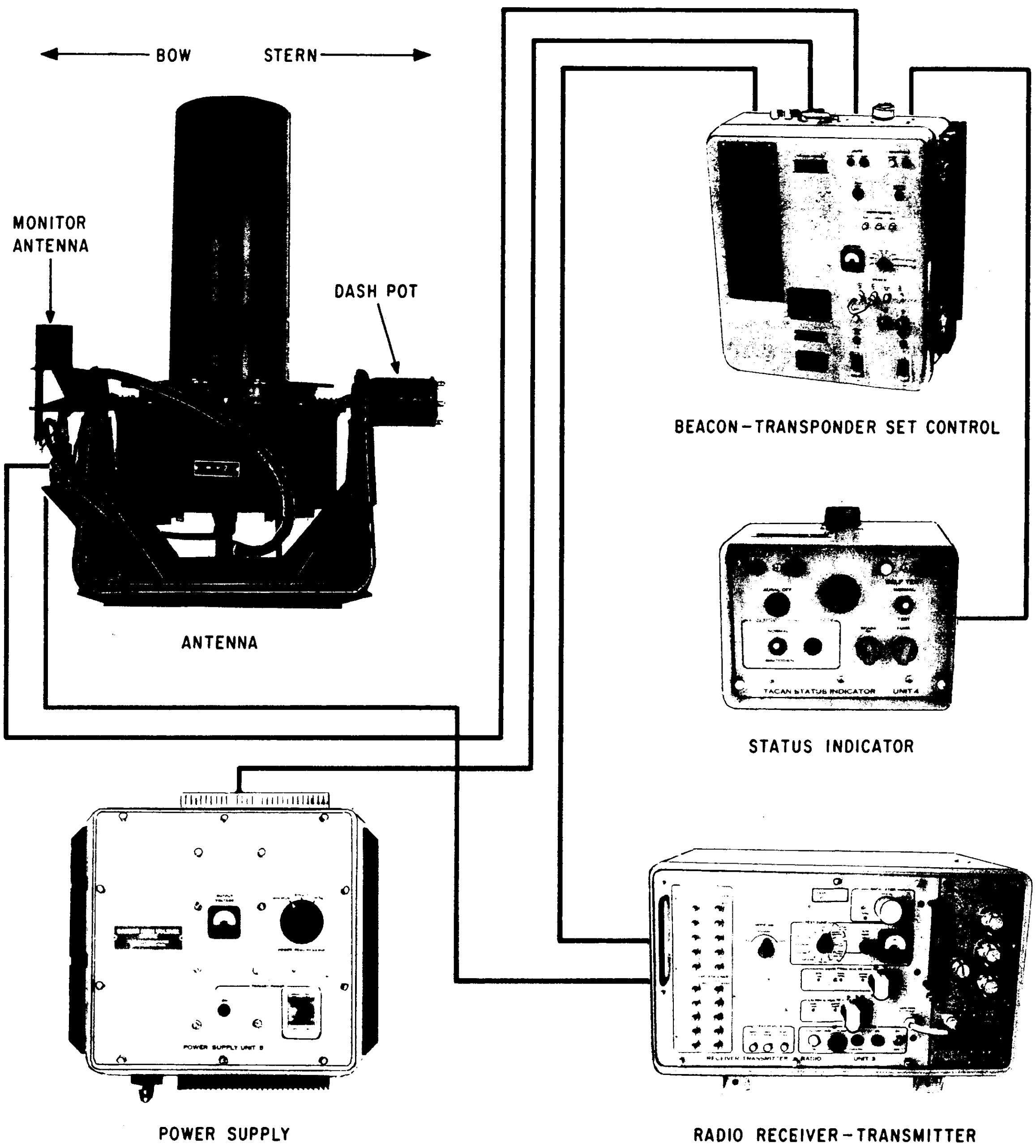

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Figure 8-24.—AN/SRN-15 System Configuration.

station. The distance portion continuously measures the time interval between an interrogating signal transmitted by the aircraft equipment and a "reply" transmitted by the ship's station, and converts the time interval into distance. The identity portion is a Morse code identification message, produced by the radio receiver-transmitter unit every 37.5 seconds.

The description of the equipment which comprises the AN/SRN-15 Beacon-Transponder Set is contained in the following subparagraphs.

Control Beacon-Transponder Set

The beacon-transponder set control (hereafter referred to as control unit) provides for distribution of power and signal sources among the various other units of the system. It contains the drive circuitry for antenna azimuth stabilization, and generates the required three-phase 60-Hz power for application to the antenna spin motor, monitors system operation (controls the status of the system, processes status information to the status indicator, and responds to rf silence commands from the status indicator). The set also contains the azimuth servosystem which electronically positions the antenna trigger pick-off to a fixed position with respect to magnetic north, independent of the ship's heading.

Antenna

The antenna contains two functionally separate antenna systems. One antenna system processes bearing, distance, and station identification signals and is referred to hereafter as the main antenna. The other antenna is the monitor antenna. The monitor antenna provides a sampling of the system-radiated rf pattern for system self-test.

The main antenna consists of a central radiating array, 15-Hz parasitic element assembly, trigger pulse generating assembly and a spin motor. The antenna is vertically polarized and is capable of operation over the following low band range: 962 through 1024 MHz in the transmission band, and 1025 through 1087 MHz in the receiving band.

The monitor antenna is a quarter-wave stub type. It has a nominal impedance of 50 ohms and a voltage standing wave ratio (vswr) of 3.0 to 1 maximum over the 962 to 1024 MHz frequency band, and will provide an adequate signal throughout the transmit band of 962-1024 MHz without relocation.

The antenna assembly is supported by a yoke mounting device which will permit the assembly to (by gravity stabilization) maintain a relative upright position within ship roll limits of 40° on each side of the center stable point.

Receiver-Transmitter, Radio

The radio receiver-transmitter (hereafter referred to as RT) detects and decodes weak interrogations at one frequency and generates high-power replies at another frequency. Combined with this transponding operation is the function of maintaining a constant average transmit power. Random squitter transmissions are automatically inserted between the reply transmissions in a great enough quantity that the average output power level is held constant. This ensures that the amplitude modulation of the broadcasted DAME (Distance Azimuth Measuring Equipment) pulse train is attributable strictly to antenna rotation and not RT output variations. The RT also produces a Morse code identification message every 37.5 seconds.

The RT is functionally separated into four sections: the receiver section, the identity logic section, the control and transmitter section, and the power supply section.

Status Indicator

The status indicator provides indication of system status and allows for rf silencing from a remote site. Visual indication of the following conditions is provided: TRANSPONDER STANDBY, TRANSPONDER ON, SYSTEM ALARM, SYSTEM NORMAL, and EMERGENCY SHUTDOWN. The EMERGENCY SHUTDOWN indicator is located in proximity to the EMERGENCY SHUTDOWN switch whose operation causes rf silencing of the station. This switch and indicator are bracketed within borders marked on the panel. When the EMERGENCY SHUTDOWN switch is actuated, the rf silence condition cannot be defeated by operation of controls at the remote site. The station can be returned to ON status only by actuating a reset switch at the local site after the EMERGENCY SHUTDOWN switch is placed in the normal position. Visual indication is provided to confirm normal (system ON-AIR and system not alarmed) system operation, system alarm status, and rf silence condition. A spring-loaded, two-position, toggle switch is incorporated to permit self-check of indicator lamps and audio alarm. This unit receives its power source from the control unit, and requires connection only to that unit.