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STUDY OF A NAVIGATION AND TRAFFIC CONTROL TECHNIQUE EMPLOYING SATELLITES

(Interim Report)

VOLUME I

SUMMARY

By David D. Otten

DECEMBER 1967

Prepared under Contract No. NAS 12-539 by

TRW SYSTEMS GROUP

One Space Park • Redondo Beach, California 90278

Electronics Research Center

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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STUDY OF A NAVIGATION AND TRAFFIC CONTROL TECHNIQUE EMPLOYING SATELLITES

Volume I. Summary
By David D. Otten

1. INTRODUCTION

In April 1967, the Electronics Research Center (ERC) of the National Aeronautics and Space Administration (NASA) awarded contract NAS12-539 to TRW Systems to perform a study and analysis of specific navigation and traffic control techniques employing satellites. The navigation and traffic control system was to be designed to provide:

- Atlantic coverage with the capability of eventual expansion to a worldwide network. The expansion should not impose additional operational or equipment requirements on the users. Gaps in polar coverage were permissible.
- A navigation technique accommodating passive (nontransponding) users.
- Service for the broadest possible range of users (i.e., large aircraft, such as SST and 707; general aviation; and marine craft).
- User hardware costs as a function of the performance obtained. In all cases, it was desirable that user hardware costs be significantly under the costs for similar capabilities using existing navigation techniques. (It was recognized from the outset that satellite and ground station costs would be modest relative to the total user hardware investment.)

With NASA's establishment of the contract objectives and the recognition that these represented the primary study goals, TRW structured its program around the most effective means of assuring that they would be successfully attained. However, during the formulation of specific study plans and modes of undertaking the various elements of effort, TRW perceived that some additional information would be useful to NASA even though not required by the contract and accordingly has provided it.

The broad objectives of the study conducted by TRW were to:

- Perform the conceptual design of a system (user hardware, satellites, and ground stations) meeting the above requirements.
- Conduct an error analysis of all modes of operation.
- Define critical test areas.
- Determine the rates and capacity of the system for traffic control.
- Assure the feasibility of and estimate the cost for hardware making up the navigation subsystem of the satellite and the ground station network.
- Perform the preliminary design and estimate the cost of user hardware for varying classes of users.

TRW Systems has accomplished all the study objectives related to navigation and presents a summary of the results in this volume. In addition, this report goes beyond the initial Work Statement by presenting detailed studies of modulation techniques for ranging, the preliminary design of the satellite and ground network, detailed equations for three classes of user, and an industry survey of the user-hardware state-of-the-art. Furthermore, since the aircraft antennas were deemed to be a very important design consideration, breadboards of several antenna designs were tested, and the test results have been included.

Sec. 2 of this volume briefly describes the overall system. Sec. 3 summarizes the system analysis covered in detail in vol. II. This analysis includes satellite tracking error analysis, navigation user error analysis, user equations, effects of perturbations on the satellite orbits and resultant stationkeeping requirements, and satellite eclipse considerations.

It was understood at the outset of the study that the modulation technique used for the ranging system would have a significant impact on user hardware costs as well as on the satellite design. Thus, detailed studies of this problem are summarized in sec. 4 of this volume and presented in app. B of vol. II.

Preliminary design and costing of all significant elements of the user hardware (antenna, receiver, preprocessor, computers, and displays) were performed and are summarized in sec. 5. Vol. III contains a thorough description of that work.

Studies were made of the satellite subsystem to be used for providing voice links to aircraft. Because numerous political and some technical decisions are required before a choice can be made between the use of VHF or L-bands, both bands were considered in the analysis presented in vol. IV.

The choice of L-band for a high-accuracy navigation system is more obvious. Thus, the satellite was designed to provide the navigation signal in the L-band region. This system is described in sec. 6 of this volume and covered in detail in vol. IV.

Ground stations are required to track satellites, receive telemetry data, compute satellite ephemeris, and transmit ephemeris and satellite oscillator time correction data to the satellites. The design information is summarized in sec. 7 of this volume and covered in further detail in vol. IV. The use of these data in the traffic control network is covered in sec. 8, and the test program considerations are discussed in sec. 9.

The analyses and investigations described in these volumes emphasize the navigation considerations associated with the design of the system; and the resultant system configuration can be regarded as a breakthrough in navigation technology. Further study effort will be concentrated on the design of an onboard satellite capability for relaying traffic control information from aircraft to a central ground station. The results of that important investigation will be issued as an addendum to this report at a later date.

In addition to the system's role as a navigation and traffic control aid, the initial studies conducted by TRW point strongly to the possibility of using the design concept as a new starting point in the emergence of a low-cost, practical, collision-avoidance subsystem for aircraft. Clearly, this potential merits exploratory study.

The findings that are being submitted to NASA-ERC were the result of a strong team effort. Numerous technical experts at TRW Systems made major contributions to the study results contained in these volumes. While specific acknowledgments have been made on an individual basis in the introductions to vols. II, III, and IV, the following persons contributed directly to this summary volume:

D. A. Conrad	-	directed the system configuration studies (covered in detail in vol. III).
N. Estersohn	-	directed the user hardware studies (covered in detail in vol. III).
A. Garabedian	-	directed all work associated with the communications aspects of the system (as covered in detail in vols. II and IV).
D. D. Otten	-	provided overall study management, and directed the studies covered in vol. IV and the preparation of vol. I.
J. H. Craigie	-	was responsible for the traffic control study effort covered in vol. I.
A. J. Mallinckrodt	-	as a TRW consultant, made significant technical contributions to the system design from its inception.

And, finally, it is a pleasure to acknowledge our indebtedness to the editors from the Publications Department of TRW's Electronic Systems Division for their invaluable help in the processing of the preliminary and final manuscripts. The volume editors were: Jeanne McCallick, vol. II; Virginia Massey, vol. III; Marcia Eastwood, vol. IV; and John Dering, managing editor for all volumes and, with Sam Petralia, vol. I.

2. SYSTEM CONFIGURATION

The system concept to be described will be termed "NAVSTAR," a navigation and traffic control system which consists of a network of satellites (using synchronous inclined orbits) and ground stations. Each satellite radiates a precise navigation signal and its own assigned time slot. Since the satellite signals are accurately timed relative to each other, a NAVSTAR user can measure range difference between receipt of the ranging signals. If a user can view three satellites and knows his own altitude, he can calculate his latitude and longitude. Thus, the system is a hyperbolic radio-navigation technique, similar to a LORAN or OMEGA system, with orbiting rather than ground-based transmitters. The use of satellites for this service provides the following combination of advantages over the ground-based system:

- Coverage of vast areas of the earth at low cost (analogous to the similar advantage provided by communications satellites)
- Greatly increased accuracy
- Flexibility in choice of modulation technique
- Low-cost user hardware
- Minimum signal acquisition time and resulting high data rate
- Flexibility in choice of carrier. Thus, the signal will not be significantly affected by atmospheric or ionospheric anomalies.

Although only three satellites are required for Atlantic coverage, four satellites are suggested in order to provide "in orbit" redundancy. Thus, while failure of a single satellite will slightly reduce system accuracy, the network will remain operational. The satellite mean time before failure is 62 months, which means that it is extremely improbable that a second satellite would fail before replacement of the first could take place.

The interim Atlantic network consists of satellites 1, 2, 3, and 4 shown in Figure 1. Two orbit planes are used, each inclined 18.5° to the equator, with lines of nodes 157.5° apart. The ability to expand to a worldwide network is also indicated by the unnumbered satellites.

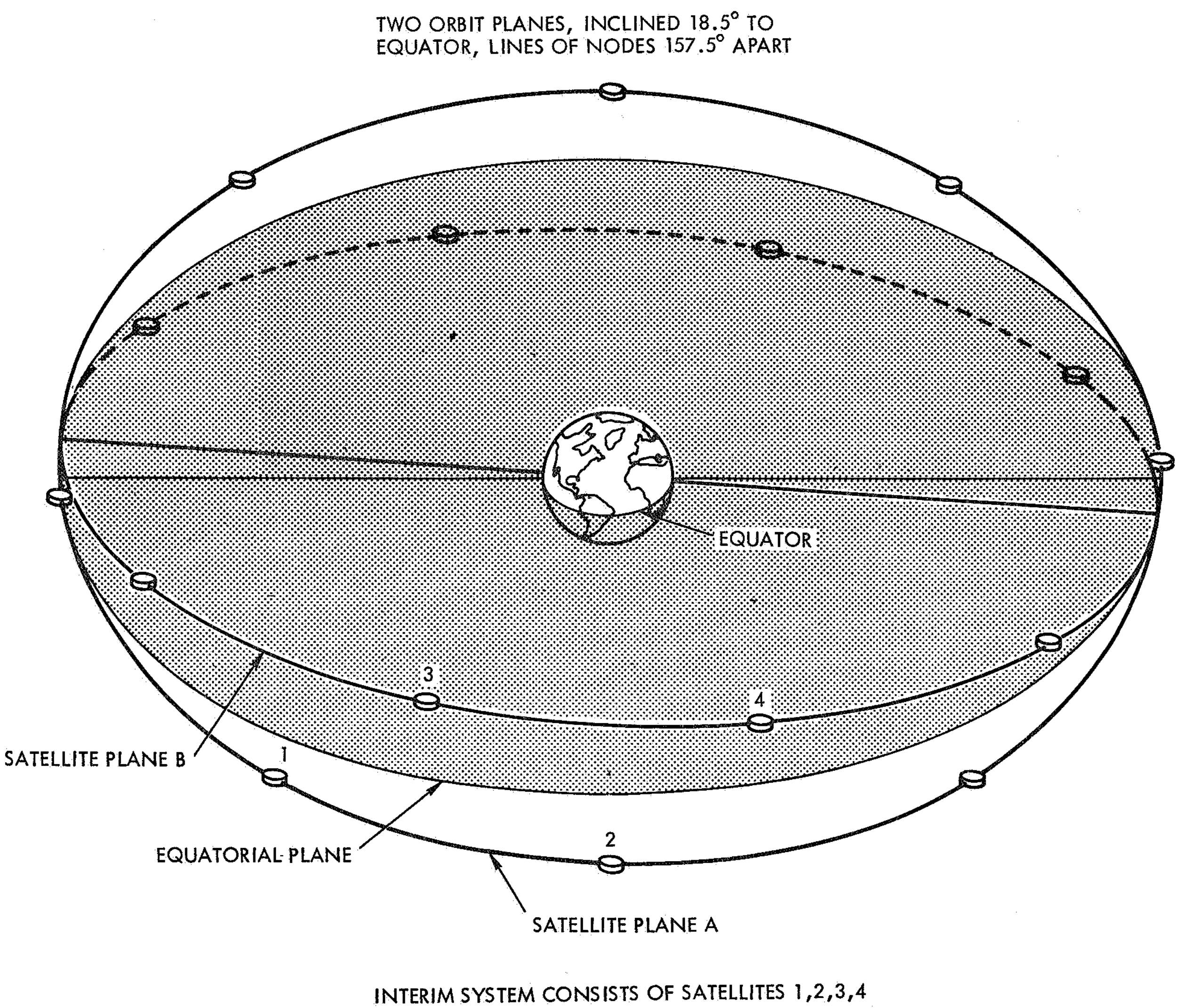

Figure 1. Satellite Geometry

Figure 2 portrays the Atlantic NAVSTAR Information Network and depicts the operations and functions of the system elements. Each satellite repeatedly transmits a ranging signal and data (ephemeris, satellite identification, and satellite oscillator time corrections) in its assigned time slot on an L-band signal carrier. In addition, each satellite contains a transponder to relay satellite tracking data from two remote tracking stations to a central ground station. This relay link uses L-band uplink and downlink carriers, and the carriers are assigned L-band frequencies which will not interfere with reception of the satellite navigation signal by system users and ground stations.

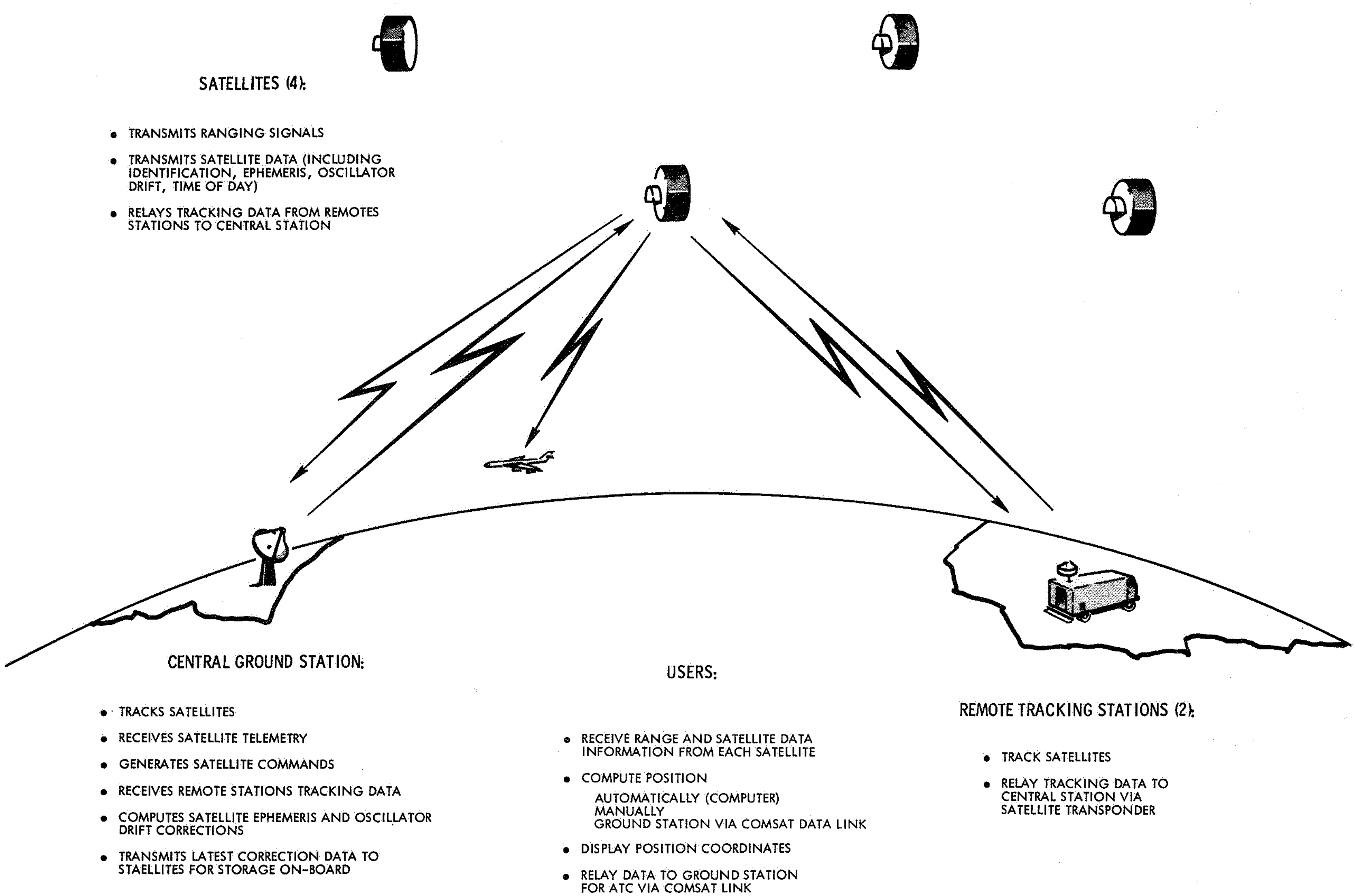

Figure 2. NAVSTAR Information Network

Two remote tracking stations are shown containing equipment similar to that of a normal user, but of high quality. They "track" each satellite by receiving the satellite navigation transmissions. No angle tracking is required or performed. These data, together with ground station ID and time of day, are continually relayed via an L-band transmitter and the satellite transponders to the central ground station. The central station as shown also includes ranging signal-receiving equipment.* Any two of these three "tracking" stations can be unoperational (e.g., for maintenance) and the network will still function, but with some degradation in accuracy.**

The central ground station contains the data processing computer which continually keeps track of the ephemeris and oscillator drift of each satellite. The computer generates updated satellite ephemeris and satellite oscillator drift correction data which are transmitted periodically to each satellite via an S-band command link for storage on board and subsequent broadcast to system users as part of the navigation signal broadcasts. Other functions of the central station are generation of satellite commands and reception of satellite telemetry via an S-band telemetry carrier. In addition, equipment is located at the central station to perform the tracking function.

The satellite navigation signal broadcasts are received by the NAVSTAR users and position fixes are computed from the range and satellite data information. A position fix is computed by one of three modes, depending on the user sophistication. In the automatic mode, the computation is done by a digital computer and the position coordinates are displayed for the user's information. In the manual mode, the received range and satellite data are displayed visually for the user. From the displayed data, the user calculates the position fixes. In the third mode, the range data are automatically relayed to a ground station via a data link. The

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*Alternatively (see sec. 7) a third tracking site remote from the central ground station could be used with no tracking performed at the central station.

**As demonstrated in vol. II, tracking accuracy will be strongly affected, but the effect on user location will not be nearly as serious as the result of error correlations.

ground station computes the position fixes and sends these data back to the user over the data link for display to the user. Finally, position fixes or raw range data can be relayed to an air traffic control center (ATC).

This interim report is concerned with the use of the system for navigation. The study was so oriented because it was first necessary to resolve numerous technical and system design questions associated with the navigation technique. A communications capability for the traffic control data link discussed above must still be added in addition to studying the use of the system for collision avoidance. The addition of traffic control is a straightforward design exercise which will be accomplished and then documented in an ensuing report.

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3. SYSTEM ANALYSIS

The purpose of the system analysis was to accomplish the following:

- Analyze the selected satellite constellation for coverage and navigation accuracy with respect both to an interim regional system and a worldwide system
- Determine the effect on coverage and accuracy of variables, such as orbit determination errors, error correlations, and orbital perturbations
- Develop navigation equations to provide varying degrees of accuracy
- Establish the satellite eclipse seasons and their effect on the launch window.

This section provides a summary of the analysis, which is the subject of vol. II of this report

3.1 SYSTEM DEFINITION

The satellite constellation selected after limited analysis of several configurations consists of two orbit planes with eight satellites equally spaced in each plane. The satellites are at synchronous altitude (24-hr periods). The two planes are inclined 18.5° to the equatorial plane with their ascending nodes spaced 157.5° apart. Satellites are positioned within their planes to provide the configuration shown in Figure 2.

Selection of a truly optimum constellation requires exact definition of the coverage requirements for each region of the earth, followed by detailed accuracy, coverage, and boost vehicle analysis. The present study did not extend to this degree of detail, but provides a conservative indication of performance that may be expected from the proposed NAVSTAR program and identifies the principal factors affecting system performance (Ref. 1).

3.2 ERROR SOURCES

The accuracy of navigation by satellite is affected by uncertainties in satellite position determination and by errors in the measurements made by ground stations and users. Satellite position errors are discussed in subsec. 3.4; the measurement errors considered, and their magnitudes, are listed in Table I. The rss of these sources cannot be used directly because correlation effects cause different interpretations to be appropriate for different cases. Nevertheless, the values in the table give an idea of the orders of magnitude of measurement errors. Further details, including definitions of the high- and low-accuracy users, are given in vol. II.

In the calculations of navigation accuracy, an additional error included was the uncertainty in ground-station location (station survey error). This was taken to be 100 ft in all cases. User altitude uncertainty was generally taken to be 75 ft.

The measurement uncertainty used in the navigation accuracy calculations was 50 ft in all cases. This allows for the effect of correlation in the troprospheric and ionospheric errors, which similarly affect all measurements to the same satellites.

TABLE I.

MEASUREMENT ERROR SOURCES

Error Source	Range Measurement Uncertainty (ft)		
	Ground Station	High-Accuracy User	Low-Accuracy User
Troposphere	2.3	2.3	46
Ionosphere	28	28	56
Receiver noise	7.8	14	32
Quantization	5.1	10.2	29
Multipath	0	45	45
Receiver drift	12	17	17
Oscillator error	-	9.2	9.2
RSS	32	59	98

3.3 ACCURACY AND COVERAGE ANALYSIS

The accuracy and coverage analyses made extensive use of the Navigation Satellite Accuracy Program (NAVSAP), which TRW subsequently delivered for use at ERC. The program is described in detail in app. J of vol. II of this report. Other computer programs used in the analysis are also described in the appendixes to that volume.

Since the user-to-satellite geometry varies with time, the coverage and accuracy provided by the system also vary. For the 2 x 8* worldwide system, the spacing of the satellites is such that a given constellation repeats every 3 hr. T_0 is defined as the time at which the system is in the configuration shown in Figure 2. During the subsequent 3 hr, the geometry changes until at T_0 + 3 hr it returns to the original configuration, shifted 45° in longitude. In this summary, only the results for T_0 are given because it was found that, although the accuracy contours change somewhat in size and shape as a function of time, the results are generally comparable to those at T_0. Vol. II contains results at 45-min intervals throughout the 5-hr period.

Figure 3 presents the results of the analysis for the worldwide system at T_0, with the assumption that the satellite positions are perfectly known (i.e., no satellite errors). When satellite errors (discussed later in this subsection) are included in the analysis, the values shown in Figure 3 increase only slightly. The increase is generally between 10 and 50 ft, but at high latitudes can be as much as 100 ft. Figure 3-a** is an overlay associated with Figure 3.

Subsatellite points are shown for satellites in the northern hemisphere, and the contour lines define the absolute navigation accuracy obtainable within each contour. Navigation accuracy is given in terms of C95, the radius of a circle in ft containing the user location with 0.95-probability. This map and those to follow are intended to provide synoptic views of navigation satellite system performance for the case considered;

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*This notation implies 2 orbit planes x 8 satellites per orbit plane.

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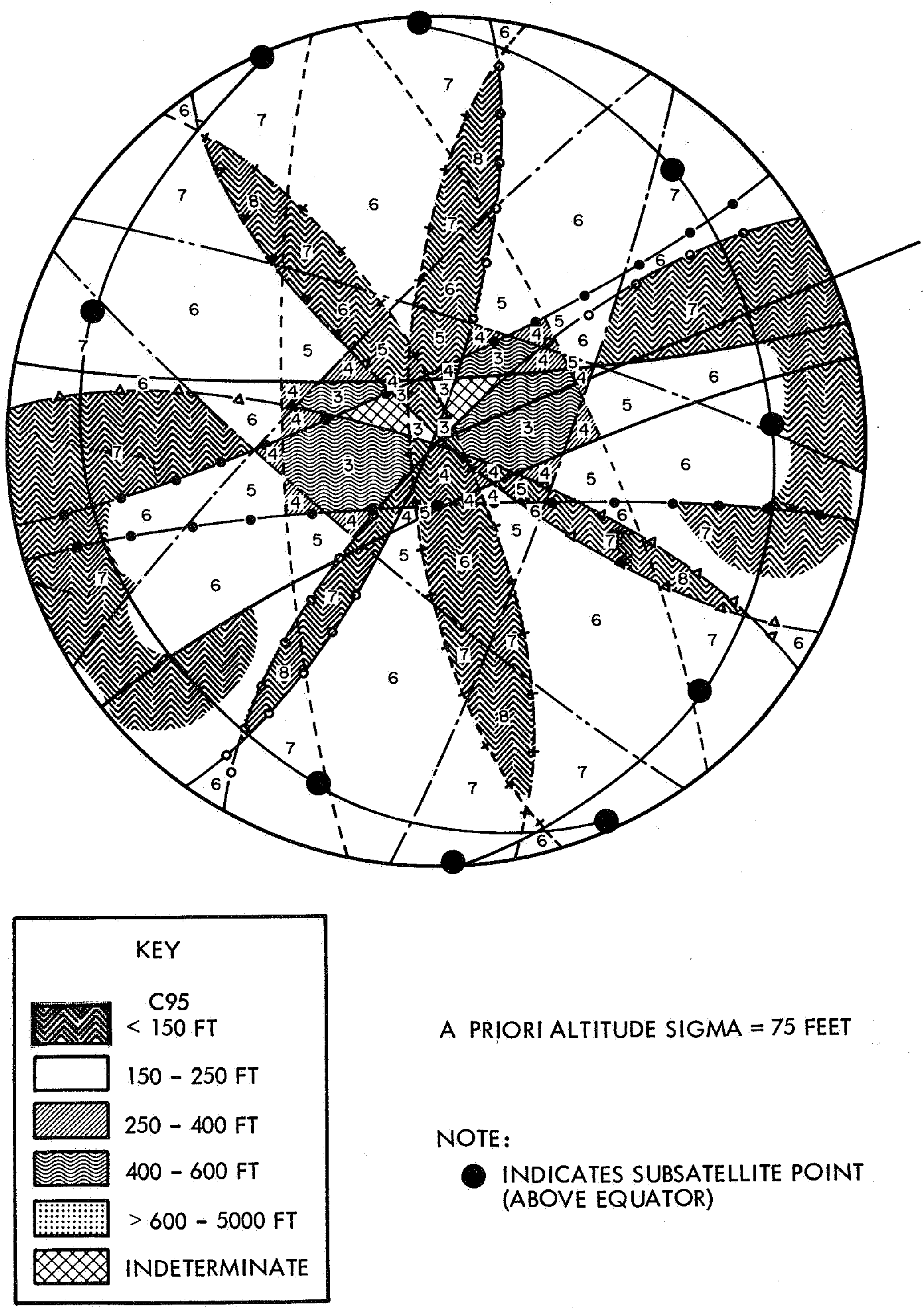


Figure 3. Worldwide Accuracy at T_0

detailed numerical values as a function of latitude and longitude of the user will be found in vol. II of this report

In general terms, it can be seen from the map that for latitudes up to 55° the navigation accuracy is within 250 ft (C95) at all longitudes. The highest accuracies are associated with the larger numbers of visible satellites, but the number required for a given accuracy decreases toward the poles because of more favorable geometry. It can also be seen that near the poles there are two small regions of indeterminacy which rotate as a function of time.*

The above results were calculated on the basis of an a priori uncertainty in user altitude of 75 ft. Since it is possible that aircraft may have larger altitude uncertainties after extended flight times, an analysis was made to determine the effect of this increase. A value of 2500 ft was assumed, with the results shown in Figure 4. There is little significant loss in accuracy over most of the globe, although a significant reduction occurs in regions where only three satellites are visible.

An interim navigation satellite system can be considered to be a subset of the total worldwide system. For the 2 x 8 system considered here, the interim system was taken as a 2 x 2 system, with the four satellites positioned to provide maximum coverage of the North Atlantic corridor. Figure 5 shows the resulting coverage and accuracy at T_0 for the case of no satellite errors. It can be seen that for latitudes below 50° the C95 values are generally less than 400 ft; an aircraft flying from New York to London would have a navigation uncertainty varying from about 400 ft at the beginning of the trip to about 600 ft at the end. This is two orders of magnitude better than the navigation accuracy available today. The addition of a few satellites would increase the accuracy in those regions to that of the worldwide network.

*Subsequent to this study, constellations that have no such regions of indeterminancy have been discovered (Ref. 1).

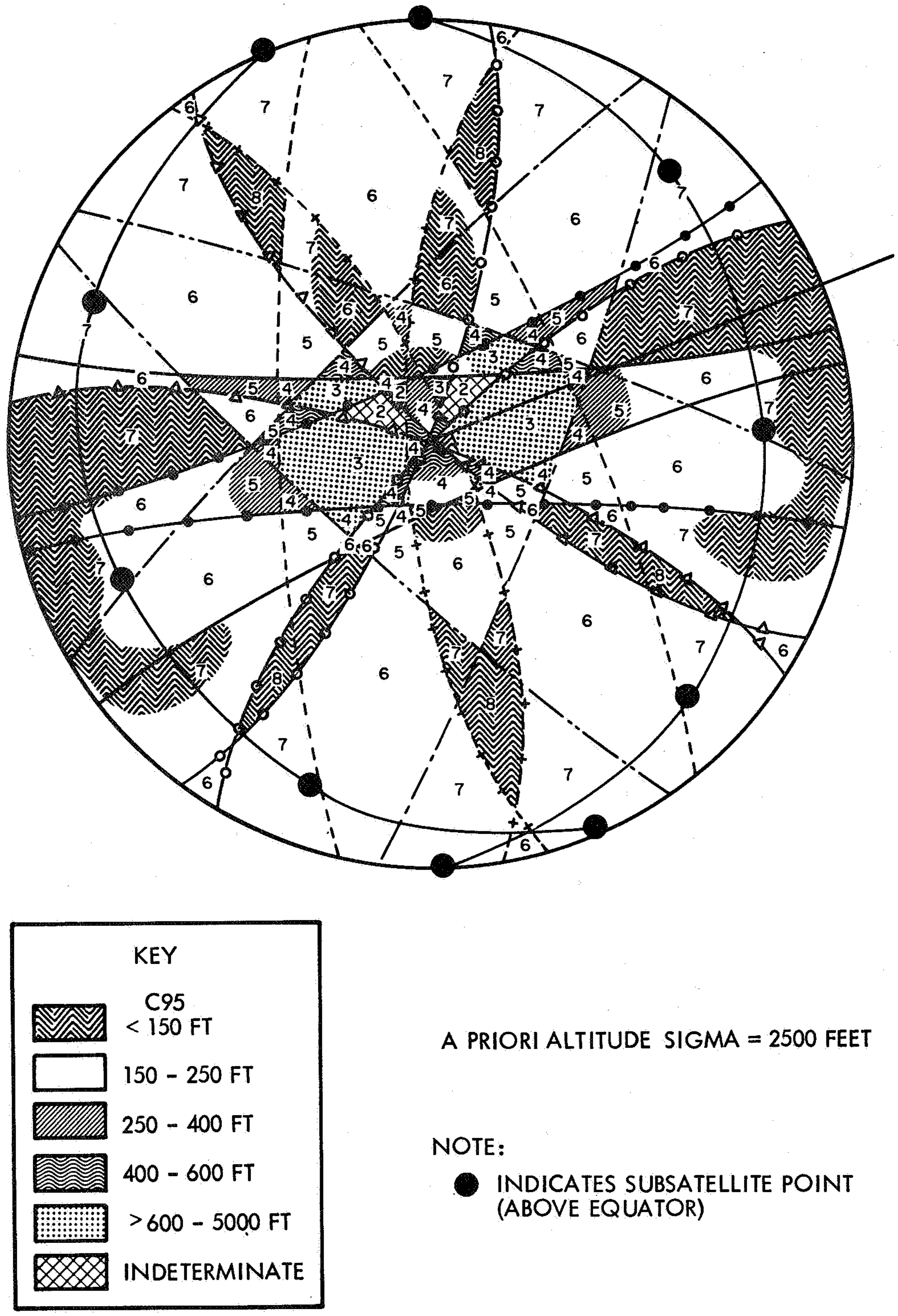
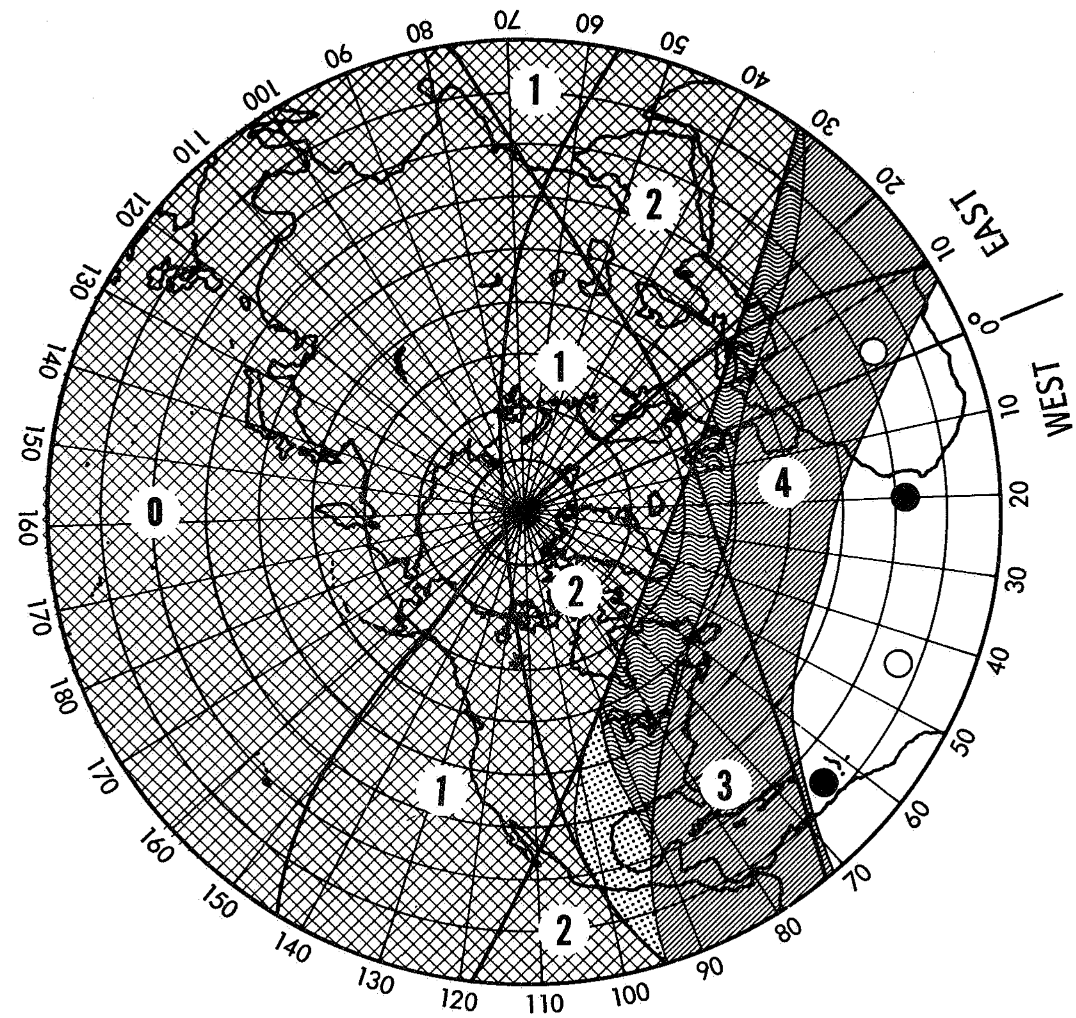


Figure 4. Worldwide Accuracy at T_0 with Poor Altitude Data



KEY

(pattern)	C95 < 150 FT
(blank)	150 - 250 FT
(pattern)	250 - 400 FT
(pattern)	400 - 600 FT
(pattern)	>600 - 5000 FT
(pattern)	INDETERMINATE

NOTE:

1) NUMBERS IN CIRCLES INDICATE NUMBER OF SATELLITES VISIBLE

2) ● INDICATES SUB-SATELLITE POINT VISIBLE ON MAP (ABOVE EQUATOR)

○ SUB-SATELLITE POINTS BELOW EQUATOR

3) A PRIORI ALTITUDE SIGMA = 75 FEET

Figure 5. Interim System Accuracy at T_0

With only two satellites in each plane, the system constellation does not repeat every 3 hr, but only every 24 hr. Coverage and accuracy were calculated for this system at 3-hr intervals in order to determine the variation with time. Results are given in detail in vol. II.

The interim system was also analyzed with satellite position errors included. Again the results showed that the effect of including these errors is minor.

3.4 ORBIT DETERMINATION ERRORS

Since a user computes his position on the basis of a known location of each visible satellite, the uncertainty in the location of the satellites will affect the accuracy of his navigation. These uncertainties have been referred to earlier as "satellite position errors."

The relatively small contribution of satellite errors to overall navigation accuracy was mentioned in subsec. 3.3. Preliminary analysis of orbit determination errors was directed to identification of the components of satellite position errors and to determination of the optimum procedures and techniques for determining satellite ephemerides. The tracking system hypothesized uses only range measurements. The conclusions reached can be summarized as follows:

- The predominant error source is the uncertainty in the earth's gravitational constant μ. This uncertainty leads to period errors, which appear as v (in-track) errors.

- Solving for measurement bias errors, survey errors, and uncertainties in μ and J_2 results in a considerable improvement in accuracy, particularly in the down-range direction.

- Adding angle (AE) and range-rate ($\dot{R}$) measurements to the range (R) measurements does not affect the system accuracy; therefore, the planned use of range measurements alone is satisfactory.

- The J_{22} geopotential harmonic should be solved for. If not, it leads to large increases in total error, especially in the in-track and cross-track directions. It was found unnecessary to solve for J_{33}, however.

- Reducing the tracking period from 72 to 36 hr has little significant effect on the results, indicating that a 36-hr period is sufficient.

With this background, it was possible to analyze a realistic tracking configuration corresponding to the proposed system, which uses essentially the same (but higher quality) equipment as a user, taking measurements from a particular satellite at a rate of one every 16 sec.* Three stations were chosen, collocated with present tracking facilities, and can be considered the interim operational network. The station locations and the satellite ground track used in this analysis are shown in Figure 6. The error sources considered and their values are shown in Table II.

In a realistic tracking situation, the station hardware biases are slowly time-varying. To represent this condition in the program approximately, piecewise constant biases (all uncorrelated) were assumed over 3-hr tracking intervals. The first 15 hr of the tracking period were then run, which produced the results shown in Figure 7. The effects of a constant range bias are also shown for comparison.

Additional study of the tracking of several satellites simultaneously is indicated. Measurements from additional satellites provide more

TABLE II.

ERROR SOURCES FOR ORBIT DETERMINATION ANALYSIS

Measurement errors	
Noise	30 ft
Bias	50 ft
Station location errors	
Latitude	100 ft
Longitude	100 ft
Altitude	100 ft
Gravitational potential uncertainties	
μ	1.06×10^{-11} ft^3/sec^2
J_2	2.0×10^{-7}
J_{22}	2.0×10^{-7}
J_{33}	2.6×10^{-7}

*Subsequent studies indicate that the rate will be one measurement every 12 sec. This will not materially affect these results; hence they were not redone. Twelve sec is the value used elsewhere in this report.

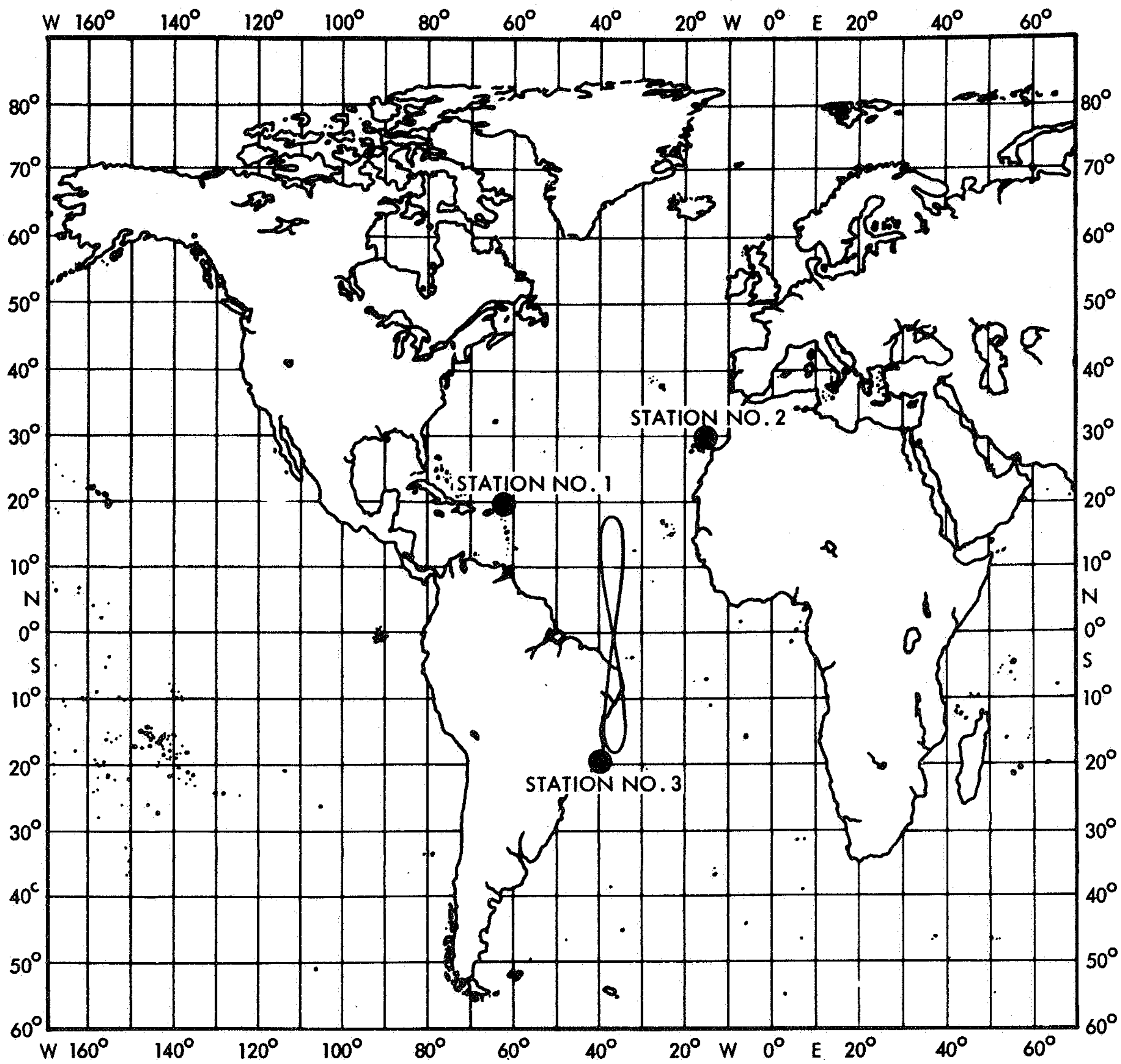


Figure 6. Recommended Tracking Configuration

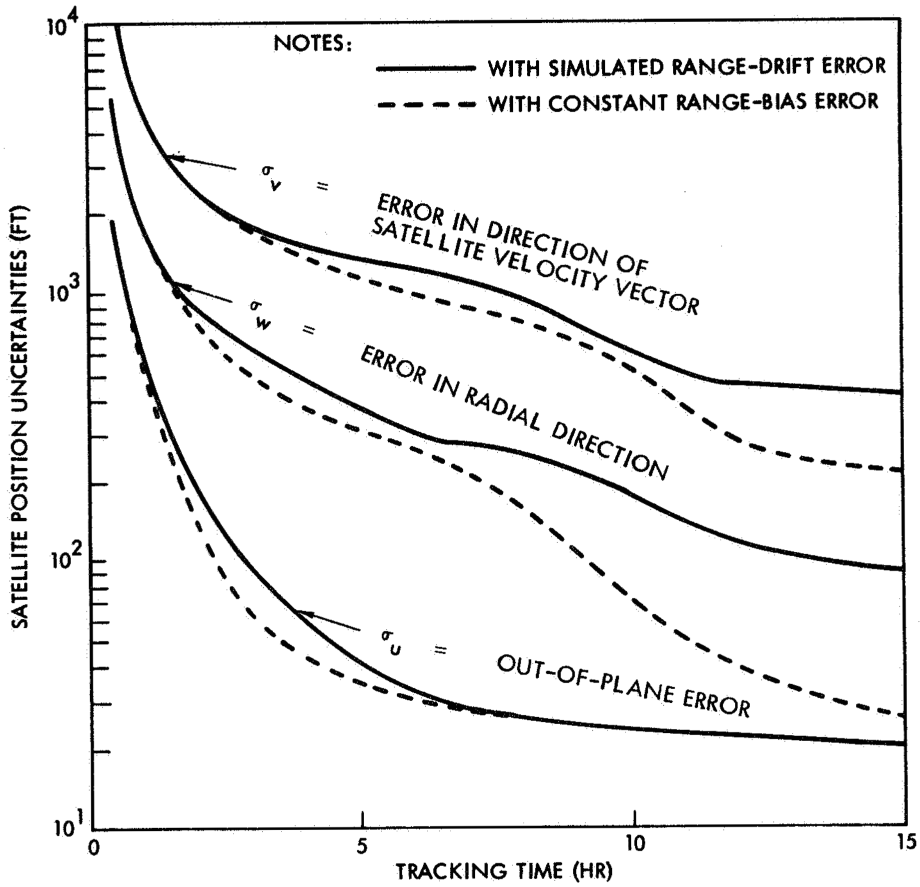


Figure 7. Comparison of Effects of Constant Range-Bias Error With Simulated Range-Drift Error

information for determining geopotential terms and biases, and the satellite position errors become correlated because of common error sources, particularly the uncertainties in the geopotential model. If these correlations are taken into account, then smaller user position errors result, as discussed in detail in vol. II.

3.5 NAVIGATION EQUATIONS

The derivation of the equations to be used in the determination of the user's position on the basis of the range measurements from several satellites was an important part of the study. Separate equations were derived for the following users:

- A relatively sophisticated user such as a supersonic transport, desiring maximum accuracy

- A slowly moving user with more limited computational facilities who nevertheless requires reasonably high accuracy

- A simple class of user who makes use of charts and hand calculations to compute his position to some nominal accuracy

- A user who is provided with additional data to make his computations near-trivial.

All equations are given in vol. II.

The first equations above achieve maximum accuracy by applying the Kalman filter technique in the navigation equations. These equations provide for sequential computation of a minimum-variance estimate of the state of the system and automatically generate the covariance matrix of the estimation error. The second set is a suboptimal version of the same filter to simplify user computations. The approximations made require that the user be moving relatively slowly to achieve maximum accuracy. The third set involves essentially the same calculations as the second, but the satellite ephemeris is assumed to be obtained with the aid of charts. The fourth type of user computes his position by direct interpolation in a transmitted table of measurements obtained at a grid of locations.

The computer requirements for these equations are summarized in Sec. 5.

3.6 RELATED STUDIES

3.6.1 Effects of Gravitational Perturbations on Stationkeeping and Coverage

3.6.1.1 In-Plane Effects

A repeating ground-track satellite is subject to orbital disturbances caused by repeated passage over the same features on the earth. The motion caused by these disturbances is libration, a free oscillation of the ascending node about a stable point on the equator, with an amplitude equal to its initial displacement from the stable point. The effect of libration on eight satellites, spaced at 45° intervals along a 24-hr circular orbit, was determined with results indicated in Figure 8. From Figure 8, one can conclude that the satellites must be station-kept to retain suitable relative geometry.

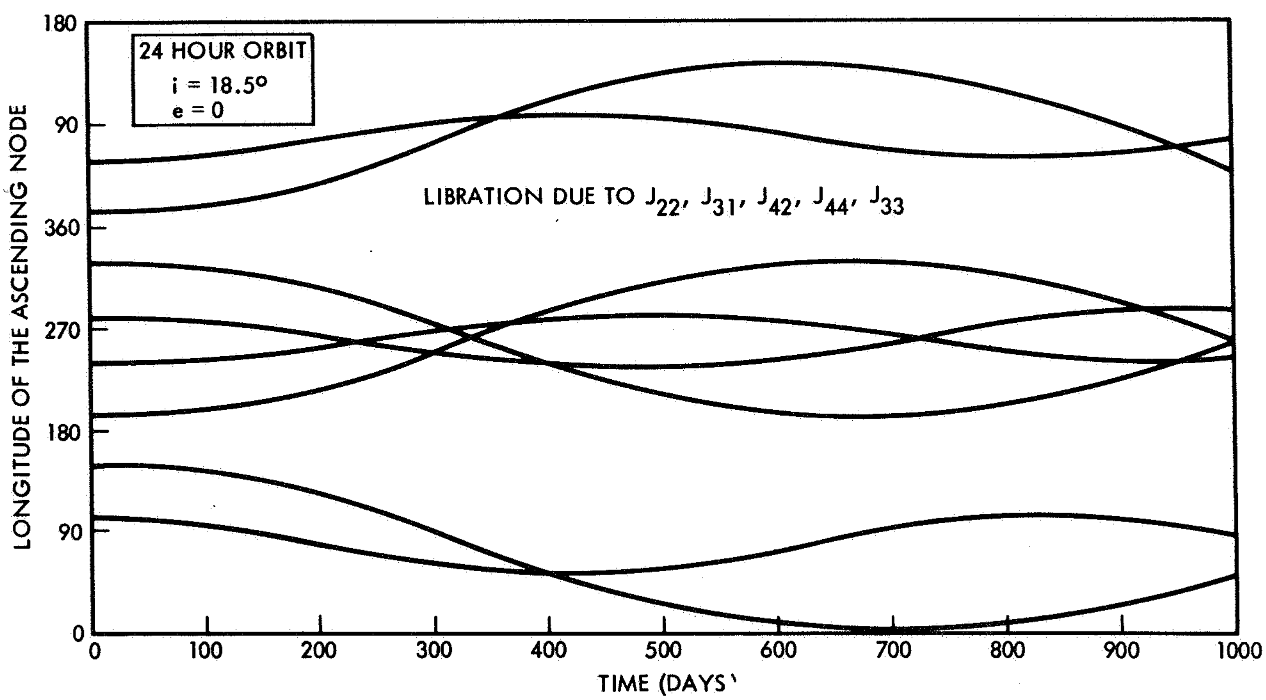


Figure 8. Libration Due to J_{22}, J_{31}, J_{42}, J_{44}, and J_{33}

Figures 9 and 10 present libration histories up to a maximum of 5° displacement for eight satellites, with ascending nodes as indicated on the figure and spaced at 45° intervals. It can be seen that the time to drift 3° is from 60 to 93 days and to drift 5° is from 50 to 118 days. The velocity, ΔV, required to reverse this motion, is shown for both 3° and 5° drifts. The total ΔV requirement over the 5-yr satellite lifetime as a function of longitude of the ascending node is shown in Figure 11. The result is a maximum requirement of 30 ft/sec, with reduced velocities in the vicinities of the stable and unstable nodes.

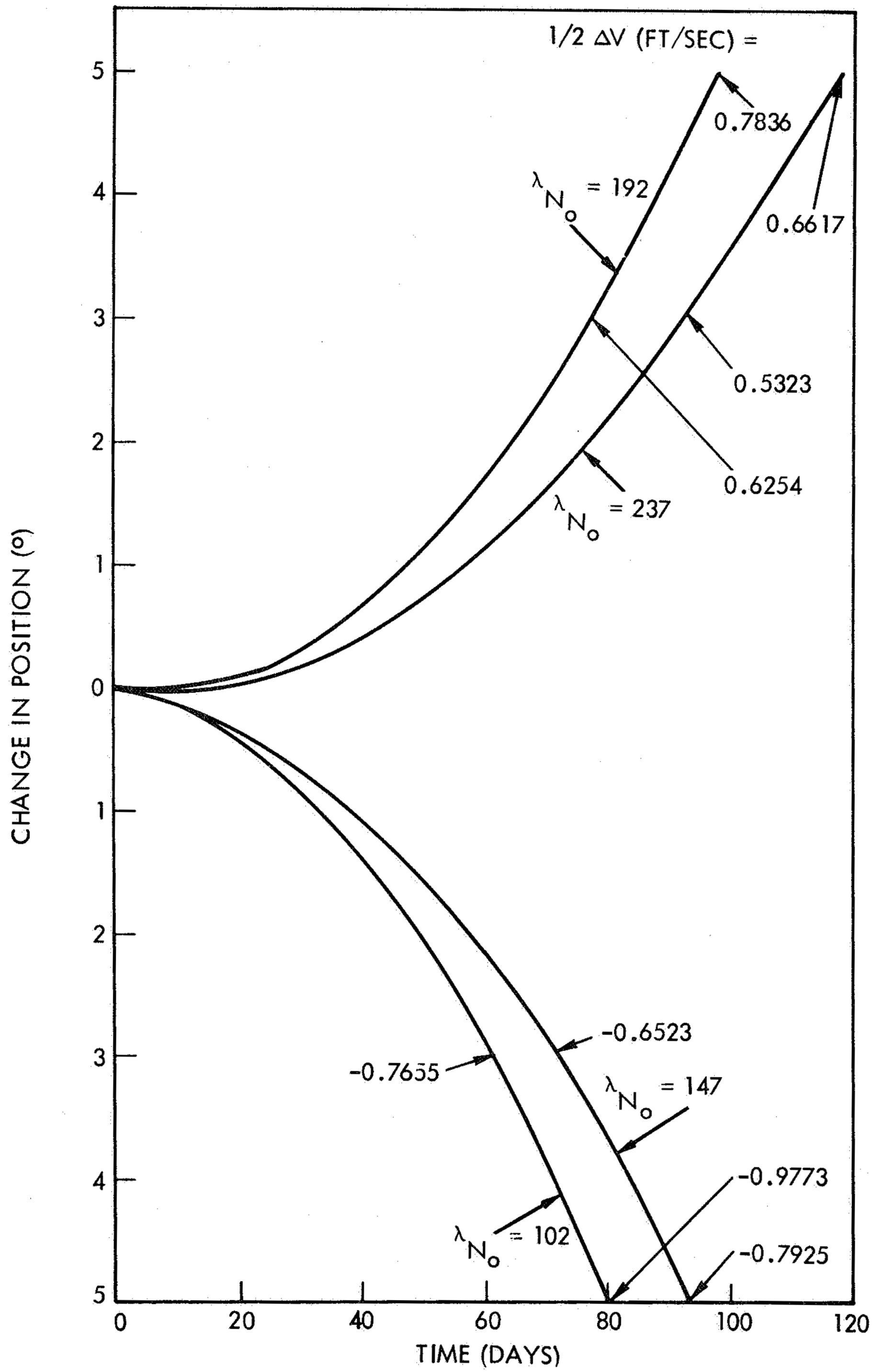


Figure 9. Position-Keeping Requirements of 24-Hr Circular Orbits

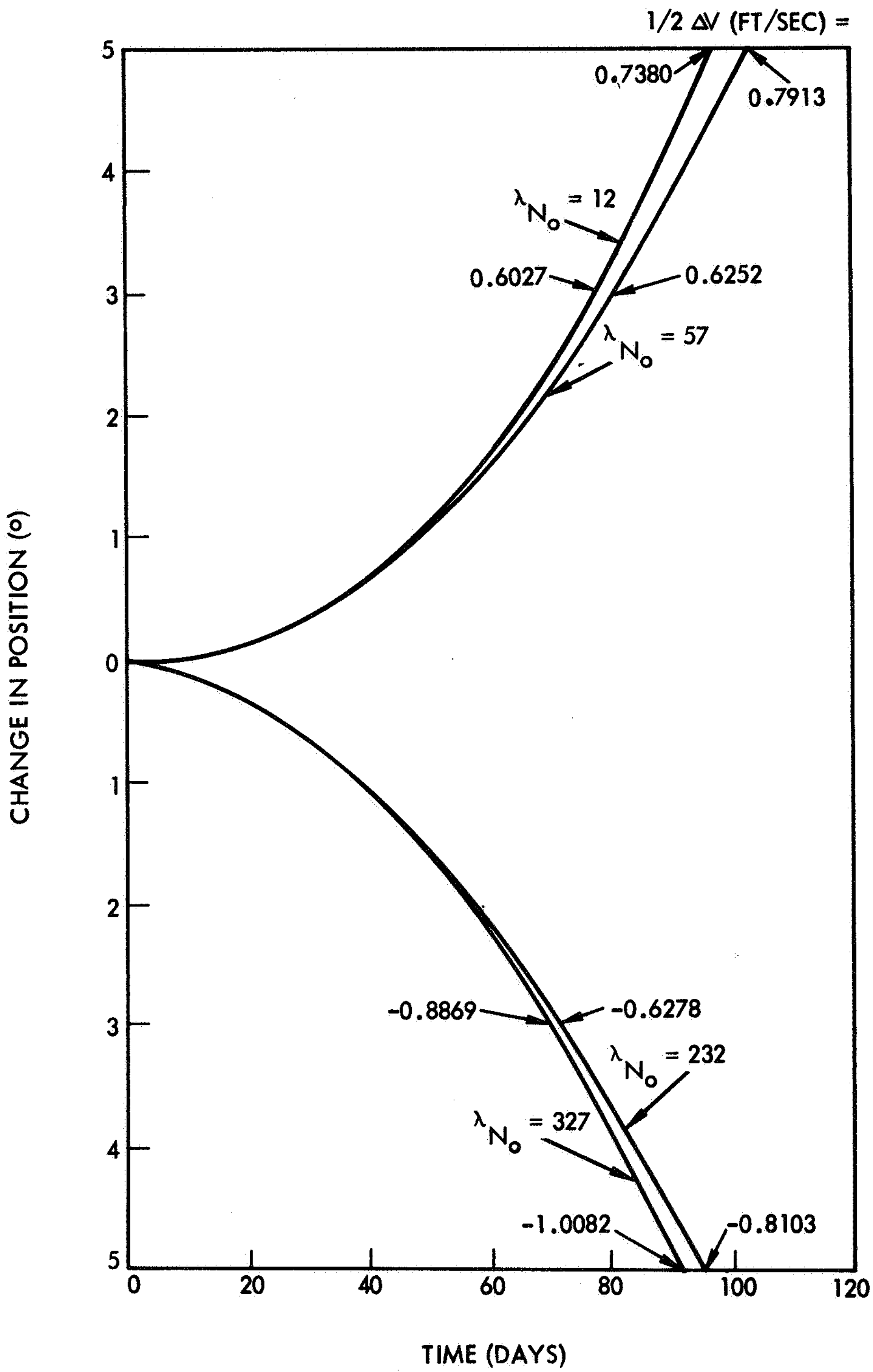


Figure 10. Position-Keeping Requirements of 24-Hr Circular Orbits

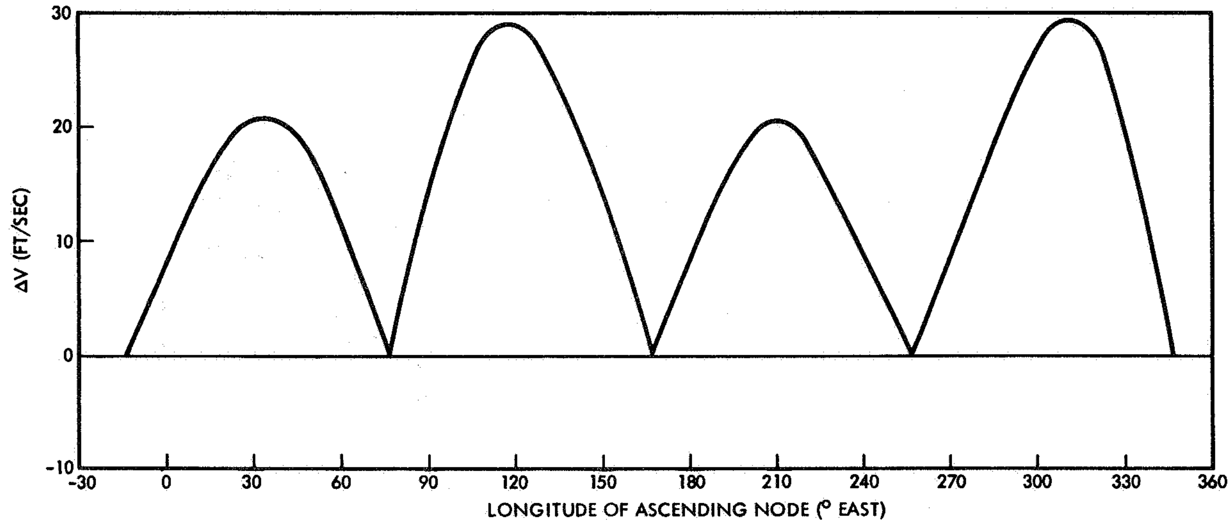


Figure 11. Total Characteristic Velocity Requirement for 5-Yr In-Plane Stationkeeping

3.6.1.2 Out-of-Plane Effects

Earth oblateness, the sun, and the moon exert a torque on the orbital momentum of the satellite. The result is a regression of the line of the nodes and a periodic change of the orbit plane. Figure 12 demonstrates the combined effect of these perturbations on orbits with varying initial inclination. Inclination is plotted along the radius and Ω, the right ascension of the node, in the circumferential direction. All curves start at $\Omega = 180^\circ$, with tick marks at 2-yr intervals. The 10-yr points are connected by dashed lines. Initially, the heliocentric longitude of the ascending node of the moon was $\Omega_M = 0$, which corresponds to Julian date 2440310 (30 March 1969).

Figure 13 was obtained from Figure 12 by starting at an inclination of 18.5° at $\Omega = 0$, 90°, 180°, 270° and following the trend for 5 yr. It can be seen that for $\Omega = 0$ and 270°, the inclination increases 4° and 1°, respectively.

Figure 12 was generated with the moon's initial longitude at zero. Similar curves were generated at TRW with $\Omega_M = 90^\circ$, 180°, and 270°. The greatest difference is for $\Omega_M = 180^\circ$ and, on Figure 13, the dashed lines represent regression based on $\Omega_M = 180^\circ$. The variation is rather small.

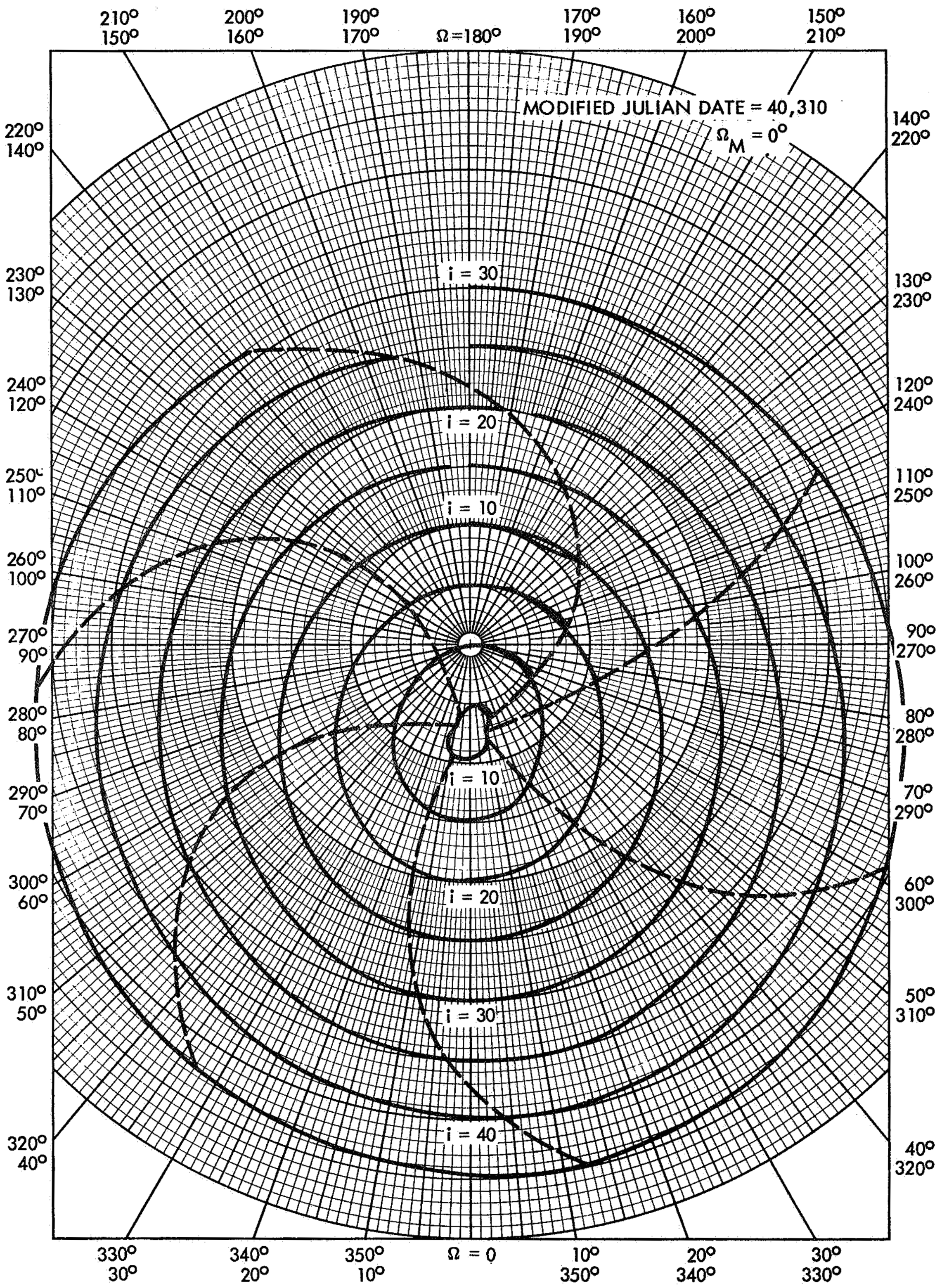


Figure 12. Out-of-Plane Perturbation Effects

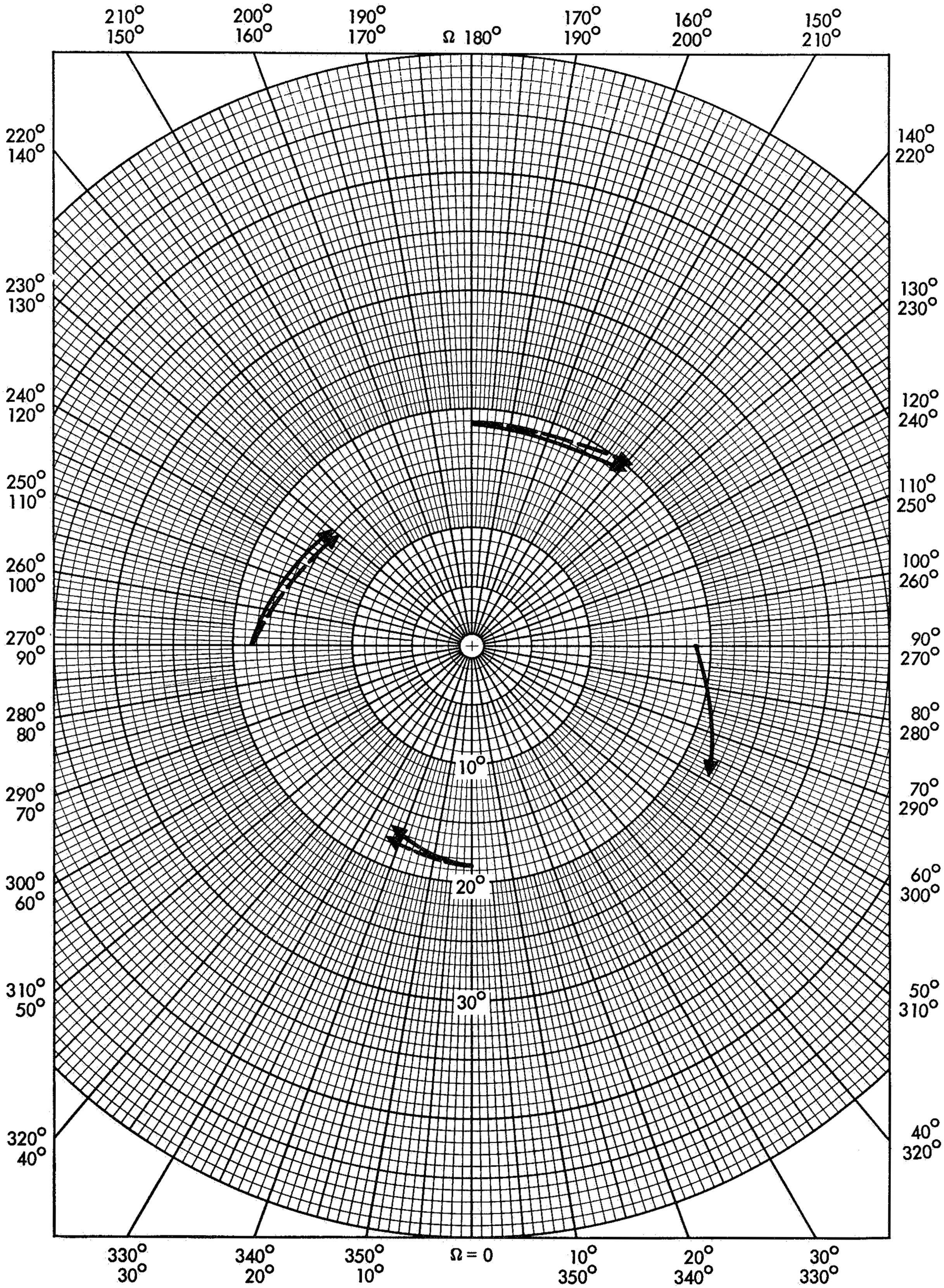


Figure 13. Luni-Solar Effects On Orbital Inclination Over 5-Yr Satellite Lifetime

The effect of inclination change on coverage was determined for a slightly pessimistic value of 4.3°. It was assumed that the orbit planes were positioned initially at 2.15° below the 18.5° nominal value (i.e., at 16.34°) so that, after 5 yr, they had drifted apart to final inclinations of 20.65°. The resulting effect on coverage is negligible and no out-of-plane stationkeeping is required.

3.6.2 Satellite Eclipse Periods

Satellite eclipse duration is important from a satellite design standpoint in that it affects the power supply design and the radiant heat lost through the spacecraft skin. An eclipse of the satellite is defined as the passage of spacecraft through the umbra and/or penumbra created on the dark side of the earth. The eclipse season is defined to be the number of consecutive days that the spacecraft experiences an eclipse during each successive revolution.

An eclipse on every revolution occurs when the inclination of the spacecraft orbit plane to the ecliptic plane is less than the angular radius of the earth shadow at the orbit altitude. For the proposed navigation satellite system, there is a range of injection nodes approximately 41° wide that will produce the continual eclipse cycle. The positions of these bands are dependent upon whether the orbital inclination is positive or negative.

A computer program was used to obtain the eclipse seasons and durations, based on a spherical earth model. The maximum eclipse duration is the same for all the spacecraft in the system, since for this system it is a function of orbit altitude only. Twice each year each spacecraft experiences a maximum of 70.5 min of eclipse duration per revolution. The eclipse seasons are presented in Figures 14 and 15 as a function of injection node for +18.5° and -18.5° inclination.

Batteries must be sized to operate satisfactorily for the maximum eclipse length. Further, the difference between maximum and minimum number of eclipse cycles in this case has no significant effect on battery design. It is desirable to design identical satellite electric-power systems. The satellite inclination relative to the ecliptic should, therefore, be minimized to yield maximum power from the spin-stabilized satellites. The analysis thus indicates that the inclination of both orbit planes to the ecliptic plane should be 26.5°.

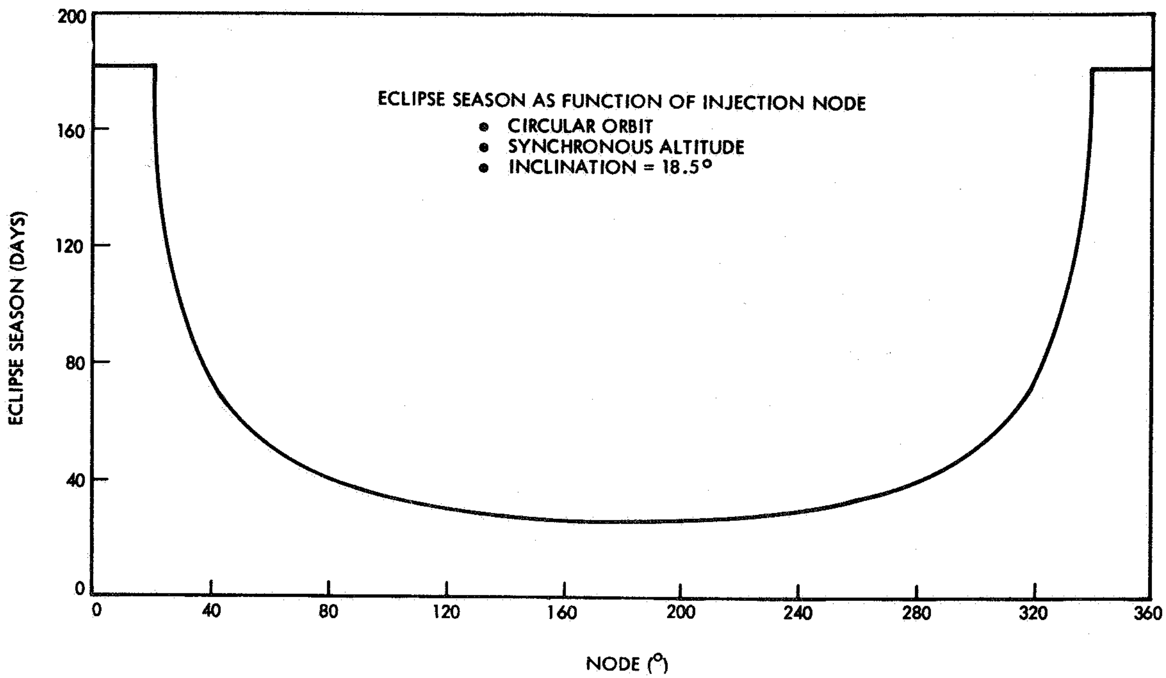


Figure 14. Eclipse Season as a Function of the Injection Node for a +18.5° Inclined 24-Hr Circular Orbit

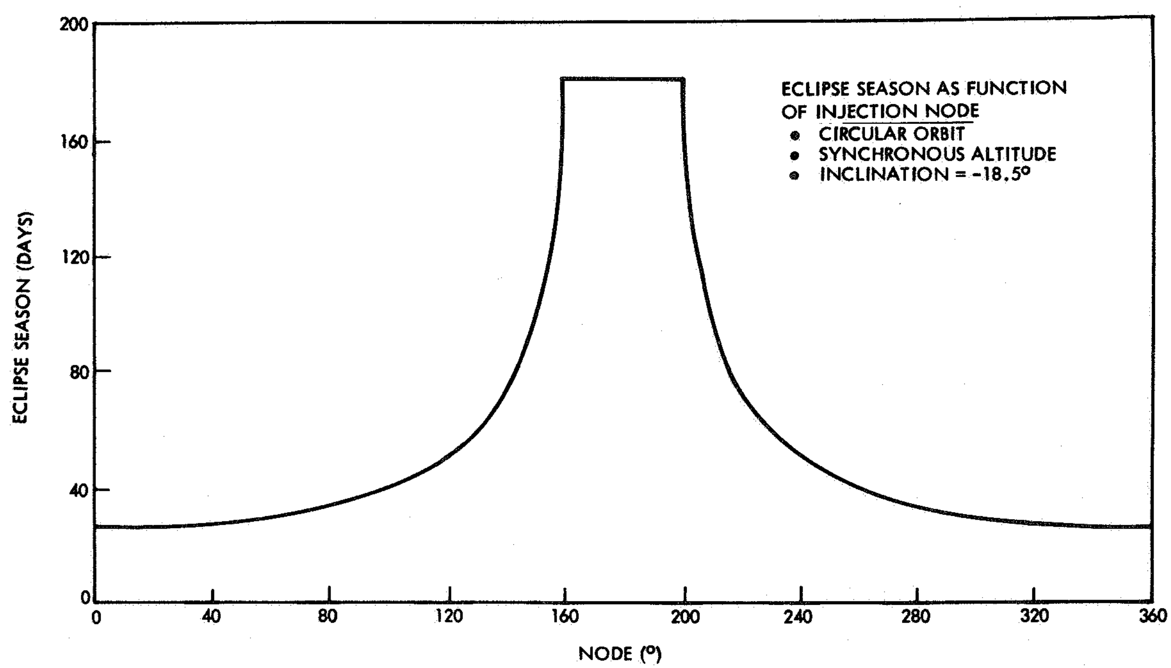


Figure 15. Eclipse Season as a Function of the Injection Node for a -18.5° Inclined 24-Hr Circular Orbit

4. MODULATION TECHNIQUES

4.1 INTRODUCTION

Two items in the NAVSTAR system have a major impact on the user equipment as well as on the entire system characteristics:

1) The multiplexing technique used for the satellite transmissions to the user from the different satellites in the NAVSTAR network.

2) The modulation signal design technique for the transmissions of the range information to a user.

These items were studied with the goal of picking the optimal techniques. For these studies, two ground rules were established: the techniques chosen should result in a high-accuracy system but with minimum equipment cost to the system users; and the satellite transmissions should operate at L-band frequencies (1540 to 1660 MHz).

The important design considerations involved in the choice of the multiplexing and ranging modulation techniques are listed below:

- User receiver complexity and cost
- Ranging power efficiency
- Satellite equipment complexity
- Multipath error sensitivity
- Satellite data transmission
- User position fix rate

Probably the most important consideration was to minimize the user equipment costs. The second important consideration was that the modulation signal design should minimize the signal power required at the receiver to perform the ranging function. High signal-power efficiency is important to keep the satellite transmitter power to a minimum and, even more importantly, to permit signal reception with an omnidirectional antenna at the user. Directional antennas would both increase user costs and result in the operational problems of antenna pointing. Further, while satellite equipment complexity should also be minimized to increase the overall reliability of the NAVSTAR network, simplification of the satellite equipment should not be made at the expense of making the user equipment more complex.

Still another important consideration was the errors in range measurement due to multipath signal reception at the user. The modulation signal design should reduce susceptibility to multipath errors. In addition to the ranging information, the user needs PCM data on the satellite ID, ephemeris, etc., in order to compute position. These data will be transmitted on the same carrier as the range signal, again to minimize user equipment by utilizing the same receiver for both functions. Therefore, the design of the ranging signal modulation should include provisions for satellite PCM data modulation on the same carrier. The final important design consideration is the rate at which a user can fix position with the NAVSTAR network. This fix rate should be as high as possible to accommodate fast-moving aircraft, e.g., the supersonic transport.

The following subsections describe the studies made on satellite multiplexing and modulation signal design. Time-division multiplexing of the satellite transmissions was chosen to reduce user costs. With this choice in mind, several candidate ranging systems were studied and evaluated on the basis of the above considerations. The goal was to pick one or more candidate ranging systems for the NAVSTAR system.

4.2 SATELLITE MULTIPLEXING

Since the NAVSTAR network consists of multiple satellites, some form of multiplexing the satellite signal transmissions must be used to accommodate the user signal receptions. Multiplexing techniques can be separated into two main categories: those in which the satellite transmissions are operating continuously and those in which the satellite transmission are time-sequenced. In the first category are frequency-division multiplexing (FDM) and code-division multiplexing, (CDM)*. In the

*In CDM all of the satellites transmit on the same frequency but the modulations are modulated with orthogonal signals so that a user separates each carrier by correlation with the proper signal.

second category are time-division multiplexing (TDM) and pulse-address, or pulse-position, multiplexing. However, the latter technique is compatible only with pulse-type ranging signals.

With FDM or CDM, while the user position fix rates can be very rapid (limited chiefly by the computation speed), the result is high cost to the user in the form of added equipment. To achieve the high fix rates, determination of range from two or more satellites must be made simultaneously, requiring two or more receivers. If a user has only one receiver and switches between satellites, demultiplexing equipment must still be provided for separating the transmissions, which adds to the cost of the receiver. The fix rate in this case is limited by the time it takes the user receiver to acquire the range information from one satellite. Consequently, by limiting the user to one receiver, TDM was chosen since it results in minimum complexity to the user receiver and, in addition, reduces the satellite primary power requirements since each satellite transmits its signal intermittently rather than continuously.

In the TDM system, each satellite in the view of a user is assigned a fixed time slot in which to broadcast its range signal. Since (with the present orbit configuration) a maximum of eight satellites can be seen by a user anywhere in the world, each satellite will repeat its broadcast every eight time slots. Therefore, the fix rate for a user is limited to the reciprocal of the duration of eight time slots. The duration of each time slot is dependent on the time the receiver needs to acquire the range information (including satellite PCM data) broadcast by each satellite. Therefore, a key parameter that determines the fix rate is the receiver acquisition time which, in turn, will depend both on the ranging modulation scheme and the available signal power at the user receiver. The receiver acquisition times as a function of the available signal power were derived for the modulation schemes studied and are discussed in discussed in subsec. 4.3.

4.3 MODULATION STUDIES

A study of several ranging and PCM data transmission schemes was made for the purpose of picking an optimal scheme for the NAVSTAR system, based on the ground rules and considerations covered earlier. A complete report on the study is given in vol. III. The study and its results are summarized in the following pages.

The ranging schemes listed below were investigated in the study and a design was made for each scheme based on a 2000-nmi range ambiguity and 30-ft rms random-noise error in the range measurement at the receiver. The schemes were broken down into two major modulation categories:

1) CW modulation: fixed tones
   swept tone
   digital code

2) Pulse modulation: pulse
   pulse compression

Several PCM data transmission schemes were also investigated for each of the ranging designs. The primary purpose here was to investigate the best way to incorporate the data transmission with the ranging.

4.3.1 CW Modulation

In the CW schemes, a phase-lock receiver is assumed that provides for coherent demodulation of the ranging and user PCM data signals. Consequently, in addition to acquisition of the ranging and user PCM data, the receiver must first acquire the RF carrier. Because noncoherent receivers (though having the distinct advantage of not requiring acquisition of the carrier) are prohibitive in their received power requirements, they were not considered. Consequently, a parameter common to all of the CW schemes studied was the carrier acquisition time.

Carrier Acquisition and Tracking. To minimize the carrier acquisition time, an unmodulated carrier will precede the modulation during each time slot broadcast by a satellite. This technique places all of the signal power in the carrier, which not only aids the receiver in achieving a rapid acquisition of the carrier but also prevents the possibility of false lock on a modulation sideband component. The portion of the time slot devoted to the unmodulated carrier will be equal to the maximum time the receiver needs to acquire the carrier. A plot of this time as a function of the received signal power is shown in Figure 16. Also shown in the figure is a plot of the corresponding phase-lock loop, two-sided noise bandwidth required.

The derivation of these curves is shown as follows: when the receiver is not locked to an incoming signal, a carrier search is automatically conducted wherein the phase-lock loop VCO (which acts as the receiver front end LO) is swept over a predetermined frequency uncertainty. This uncertainty is equal to the sum of the uncertainty in the frequency of the VCO and the incoming carrier frequency, which are functions of the VCO and transmitter frequency stabilities and the carrier doppler shift. The uncertainty was found to be 52 kHz (±26 kHz)* due principally to the VCO center frequency stability that can be readily achieved. Consequently, Eq. B-4 of app. B, vol. III, becomes

$$\tau = 1.66 . 10^{7}\left(\frac{\Phi}{C}\right)^{2} \qquad (1)$$

where

τ = maximum acquisition time in seconds of the receiver (equal to one full sweep time of the loop VCO)

C = received carrier power at receiver

Φ = receiver noise spectral density

and this result is plotted in Figure 16 for the maximum acquisition time of the receiver. The curve for the loop bandwidth is derived from the

*See subsec. 4.2, vol. III, receiver design, for a derivation of this value. While a smaller uncertainty range might be achieved with special techniques, the reduction in overall satellite broadcast time or frame period would be slight.

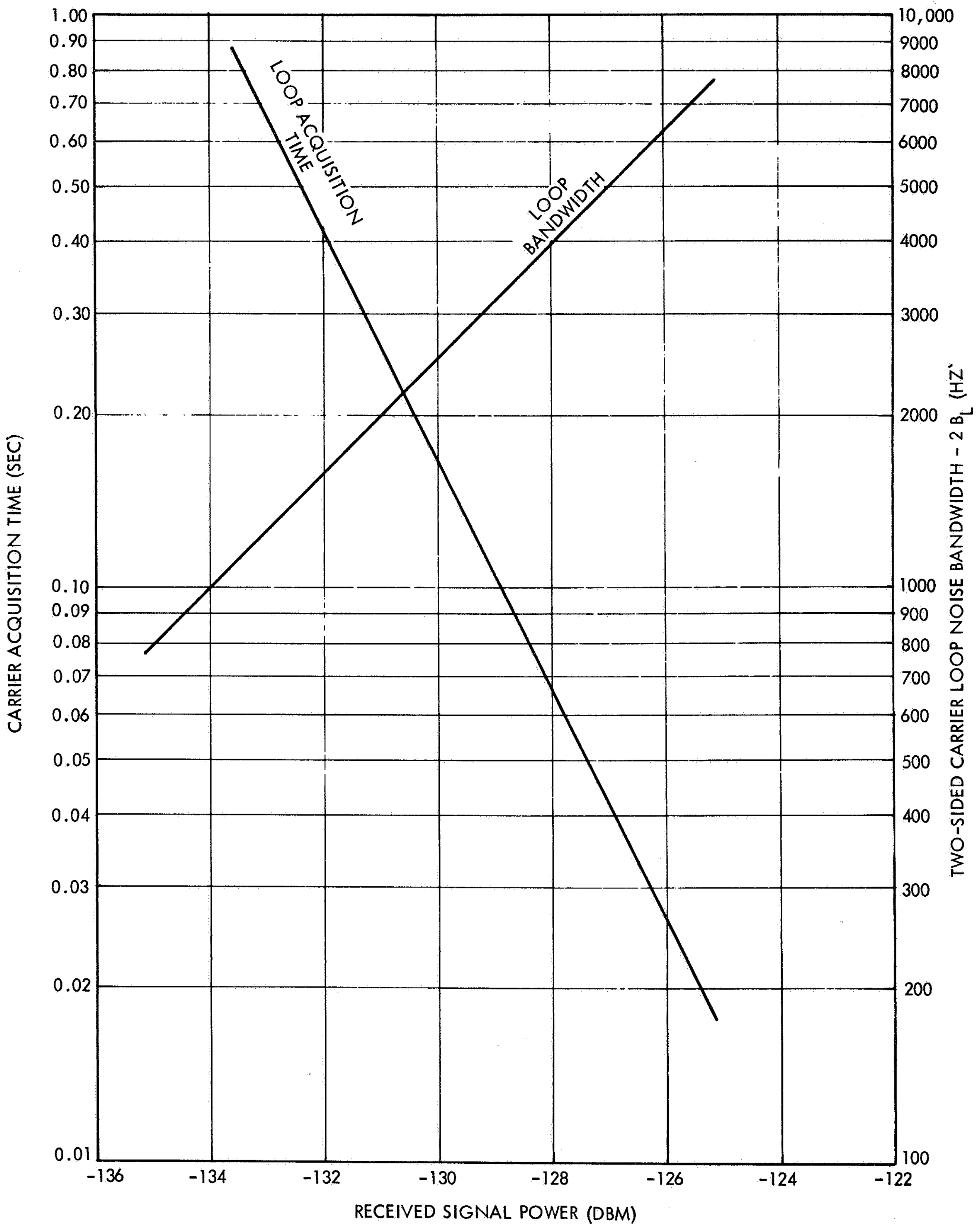


Figure 16. Carrier Loop Acquisition Time and Noise Bandwidth as a Function of the Received Signal Power

requirement for carrier acquisition that the loop signal-to-noise ratio (SNR) equal 6.0 db. A SNR of at least 6.0 db is required to achieve a high probability of carrier acquisition on one sweep of the VCO. While this probability will be in excess of 90 percent, the true value should be established by a testing program on an actual receiver design. A probability of 99 percent would be highly desirable since failure to acquire within one sweep time causes the satellite broadcast to be missed, and the user must then wait for the next broadcast.

After an interval during which the unmodulated carrier is transmitted, equal to one sweep time of the receiver, the ranging signal modulates the carrier. The modulation causes power in the carrier to drop significantly. Therefore, to prevent the carrier phase-lock loop from losing lock, the loop bandwidth is automatically narrowed after carrier acquisition. In addition, the loop bandwidth must be small enough to prevent the loop from tracking out any modulation sidebands close to the carrier. From a power standpoint, the loop should be as small as possible to minimize the carrier power requirements. However, the bandwidth must be large enough so that the loop will maintain carrier lock when the user undergoes high-acceleration maneuvers, e.g., high-performance aircraft. A two-sided loop bandwidth of 50 Hz was selected to meet the above requirements, allowing the user to undergo a better than 6-g maneuver and still maintain carrier lock.

Ranging Techniques. After acquisition of the carrier by the receiver, the user must acquire the range information. This acquisition time is dependent on the range technique and the received signal power at the receiver input. Figure 17 plots the acquisition time as a function of the received signal power for the different CW ranging techniques studied. The plots, made for 99.9-percent probability of correct acquisition, assume a receiver system noise temperature of 725°K. A description of each technique and derivation of the acquisition times is given in vol. III. The fixed-tone technique uses five phase-coherent tones in frequency ratios of 8 to 1, with a top tone of 320 kHz. The swept-tone technique uses one tone, which is swept over a 48-kHz range from 272 to 320 kHz. The PRN and BINOR techniques are binary codes with a bit rate of 640 kbits/sec. The PRN code is a three-component clock code of the type developed by Jet Propulsion Laboratories. The BINOR code (BINary Optimum Ranging) is a minimum acquisition time code derived from a fixed-tones system with frequency ratios of 2 to 1. All the above ranging signals phase-modulate the carrier.

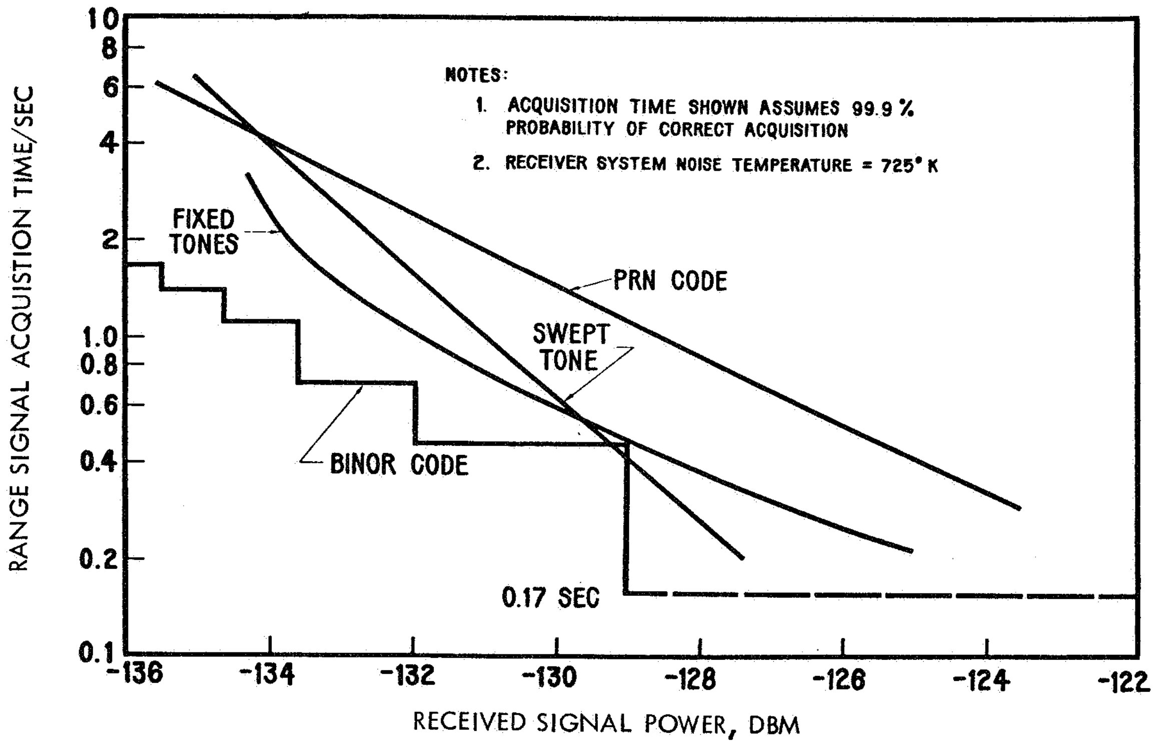


Figure 17. Acquisition Time as a Function of Received Signal Power for CW Ranging Techniques

Figure 17 shows the superiority of the BINOR code ranging technique with respect to minimum acquisition time for a given received signal level. In addition to this advantage, the range acquisition circuitry for the BINOR code should be the simplest to implement of the CW systems. This is based on the assumption that the digital techniques used for the range acquisition of the code are both easier to design and more reliable in resolving range than are the analog filtering techniques of the tone systems. Bias errors in the ambiguity tones of the fixed-tones technique and the swept tone of the swept-tone system must be carefully controlled in the receiver and filters in order to assure reliable resolution of the range ambiguity. In the BINOR code technique, bias errors are essentially eliminated by the digital circuitry used to resolve the range ambiguity. The PRN code also uses digital techniques to resolve ambiguity, but the amount of equipment required is much greater and involves multilevel correlation decisions using an analog-to-digital converter. The BINOR code correlation decisions are all two-level (binary) decisions and, hence, simplify the range acquisition procedure.

For many of the same reasons that the BINOR code should result in the simplest user equipment design, it also should result in the simplest satellite equipment design for generating the navigation signal. For example, with a given range acquisition time, the transmitter output power will be at a minimum with the BINOR code. Also the code is simply generated from a counter and majority logic, while for the fixed-tone technique, sinusoidal tones must be formed from a digital counter and then summed before modulation onto the carrier. Phase shifts between the tones must be carefully controlled to prevent unacceptable bias errors. With the swept-tone tehcnique, each satellite must transmit the same number of cycles during a sweep of the tone, and, consequently, control circuits must be designed to provide this function.

The susceptibility of the ranging modulation to multipath reception errors in the range measurement is important in picking the ranging technique. A discussion of multipath error and a method of reducing it for each ranging technique are contained in vol. III. However, a lack of adequate knowledge of the exact nature of the magnitude and frequency of multipath* and of its quantitative effect on the accuracy of the range

*Largely dependent on user antenna patterns, satellite-user geometry and terrain (especially sea water) reflection characteristics at L-band.

measurement made it difficult to select a ranging technique on the basis of multipath errors. In general, the susceptibility to multipath errors is reduced by increasing the RF bandwidth of the ranging modulation. Therefore, the square waveforms of the binary codes should be less susceptible than sinusoidal tones when using low-deviation phase modulation. By increasing the bit rate for the binary codes or increasing the phase deviations for the tone techniques, the RF bandwidth is increased, reducing multipath error sensitivity. Therefore, if multipath errors are excessive, the bit rate for the BINOR code can be increased beyond 640 kbits/sec. A penalty is paid in a slightly more complicated user receiver and in an increase in the code acquisition time. Similar penalties occur with a high-phase deviation, fixed-tone or swept-tone system. Further studies and actual experiments must be conducted on multipath to arrive at meaningful conclusions on multipath errors. At this time, it is felt that multipath errors would be no more severe with the BINOR code than with the other CW systems.

Satellite Data. In addition to the range-signal, each satellite transmits information on the satellite ID, ephemeris, oscillator phase drift, and time of day. This information, transmitted as PCM data, is needed to help the user compute his position. The PCM data can either be transmitted simultaneously with the range signal (frequency multiplexing of range and data) or they can time-share the satellite transmission with the range signal (time multiplexing). In vol. III, app. B, time multiplexing is shown to be more efficient in utilizing transmitter power. Therefore, immediately following reception of the ranging signal, PCM data are received by the user. The acquisition time for the data is dependent on the number of bits necessary to convey the satellite data information to the user and on the bit rate which is transmitted.

To maximize the bit rate and decrease the data acquisition time, PSK modulation and coherent detection of the PCM data will be used. Figure 18 shows a plot of the data rate that can be used for a given received signal level. Split-phase modulation of the carrier was assumed*. A bit error rate of 10^{-4} for a bit energy-to-noise spectral density ratio (ST/Φ) of 9.5 db was also assumed. This value is 1.3 db worse than

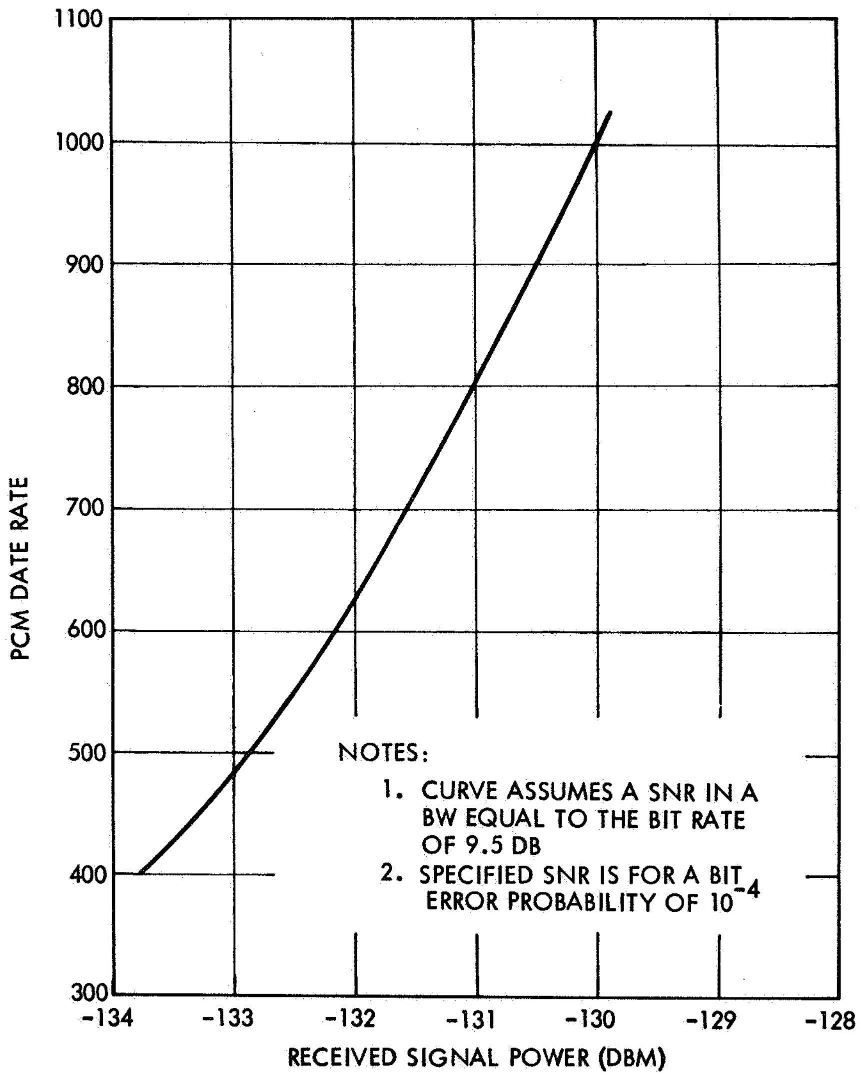


Figure 18. PCM Data Rate as a Function of Received Signal Power for Split-Phase Modulation

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*In vol. III, app. B, the data were assumed to biphase-modulate a subcarrier. If the data rate is much greater than the carrier loop bandwidth (50 Hz), split-phase modulation directly on the carrier results in better efficiency (≈1.0 db) than the use of a subcarrier. Split-phase modulation is obtained by modulo 2 adding the NRZ PCM data to a square wave at the bit rate frequency.

theoretical for coherent PCM detection. Split-phase modulation, rather than direct PCM modulation, is necessary so that the data modulation does not interfere with the carrier loop. It has been estimated that the PCM data rate should be at least 10 times the 50-Hz carrier loop bandwidth to avoid interference with the carrier loop. Therefore, for data rates much below 500 b/sec, a biphase-modulated subcarrier may have to be used which results in slightly less signal power efficiency (1.0 to 1.5 db) than with split-phase modulation.

The total number of bits required to transmit all the satellite data is estimated at 165, including frame synchronization bits and parity bits. Another 35 bits will be required for bit synchronization by the user bit synchronizer so that a total of 200 bits will be transmitted by each satellite following broadcast of the ranging signal. The acquisition time for these data is then 200 divided by the bit rate.

Satellite Broadcast Time. The total user acquisition time will be the sum of the carrier, range, and data acquisition times. This sum will be equal to the satellite broadcast time. However, each satellite broadcast time slot must have a guard band to prevent overlapping of satellite broadcasts. The guard time must be at least as long as the maximum difference in propagation time between any two satellites and a user on the earth. This propagation time is about 40 msec, based on a maximum range difference of ±3150 nmi for the chosen satellite orbits. The guard time will actually be about 100 msec to provide for drift in the satellite oscillator clocks. When a satellite clock drifts far enough so that two satellite broadcasts approach an overlapping condition, the oscillator frequency is reset by a ground-station command.

4.3.2 Pulse Modulation

Pulse ranging has the distinct advantage over CW ranging of not requiring acquisition of a carrier. The pulse receiver is non-coherent and simply detects the presence of a pulse. The time of pulse occurrence is the measure of range. The disadvantage of pulse ranging is the high-peak transmitter-output powers required since the total signal energy occurs in short-duration pulses rather than being distributed over the entire transmission time as in CW systems. Of course, this concentration of energy in a short pulse significantly reduces the range-acquisition time and is the chief advantage of pulse ranging.

Ranging Techniques. Pure rectangular pulses are not practical for ranging, as the peak powers for the transmitter output become excessive at L-band (hundreds of kilowatts). For this reason, a pulse-compression technique is needed to reduce the peak powers to reasonable levels. A chirp-pulse technique was designed to provide 100-to-1 pulse compression in the user receiver. The peak power requirements in the satellite are now reduced to the 10- to 20-kw range.

Two pulses are needed for a range measurement since pulse-coincidence detection will be used in the receiver to decrease the false-alarm probability. The pulse-coincidence detection results in 98.5 percent probability of range acquisition and a mean time to a false alarm of 55 hr, which is unique to the pulse ranging. The PRF will be 78.125 p/sec, which gives a range resolution of about 2000 nmi, the same as with the CW systems. Therefore, receiver range acquisition time is the time between adjacent pulses, or about 13 msec. Increased signal power at the receiver will not change the acquisition time, as in the CW systems, but will increase acquisition probability and decrease false-alarm time. In an actual system design, five pulses will be transmitted for the range measurement both to increase the acquisition probability and to obtain a maximum of four range-measurement samples for increased accuracy. Thus, the range-acquisition time will increase from 13 to a maximum of 52 msec.

Pulse-compression ranging results in the fastest acquisition time for the user, and this is its primary attraction. In addition, the technique appears to have good multipath rejection properties. If the receiver output is squelched between received pulses, multipath interference occurs only when the time difference between direct and reflected pulses is on the order of the compressed pulse length (200 msec). The disadvantage is the practicality and reliability of large peak powers for the satellite transmitter.

Satellite Data. The same satellite data requirements discussed for the CW systems also hold for the pulse-compression system. As in the CW case, the data will follow upon completion of the ranging pulse transmission. The same chirp pulses used for the ranging are used to transmit the PCM data. Two techniques were investigated for utilizing the pulses for data transmission. In the first technique, the sense of the chirp pulse (sweeping up or down in frequency) conveys the PCM information, and, in the second, the pulses are position-modulated.

Pulse-position modulation (PPM) was selected over chirp-sense modulation as the most suitable technique since less equipment is needed in the user data demodulator. Four-position modulation was also selected since each pulse conveys two bits of information, reducing the number of transmitted pulses by a factor of two and since there is enough signal power to detect four-position modulation. Therefore, to transmit the 165 bits of satellite information required, 83 pulses are transmitted at the same PRF (78.125) as the range pulses but they are position-modulated on one of four equal time slots divided into a frame time of 1/PRF. Frame sync is obtained in the receiver from the preceding range pulses, which are periodic at the PRF. Acquisition time for the satellite data, then, is equal to 83/78.125 or 1.06 sec. This time is significantly longer than the range-acquisition time, but the data can be transmitted in several parts to reduce this time. This will require the user to receive several broadcasts from the satellite to obtain all the data. For example, if the data are divided into two broadcasts, about 88 bits would have to be transmitted each time*, reducing data-acquisition time to 0.57 sec.

An alternate way to decrease the data-acquisition time is to increase the PRF after the ranging pulses are received. However, since this requires increases in both the peak and average transmitter powers, it is not being recommended.

Satellite Broadcast Time. The total satellite broadcast time will be equal to the time it takes to transmit five ranging pulses plus 83 data pulses, or a total of 1.13 sec. This time can be reduced significantly

*The reason for 88 bits instead of one-half of 165, or 83 bits, is that frame synchronization and satellite ID must be broadcast each time.

by transmitting only a portion of the satellite data each time. By transmitting the data in two parts, the total satellite broadcast time will be reduced to 0.63 sec. Dividing the data transmission into two or more parts was not considered for the CW systems since, in those systems, satellite data-acquisition time is a small portion of the overall acquisition time and will not reduce satellite broadcast time significantly.

Guard-time considerations for each satellite broadcast are the same as for the CW systems. Therefore, the time-slot duration for each satellite broadcast will be about 1.23 sec (all satellite data transmitted) or 0.73 sec. (one-half satellite data transmitted). In any case, the total transmission times are not significantly reduced.

4.3.3 BINOR Code Description

Here, a more detailed discussion and analysis of the BINOR code system is given. The code is binary and the code sequence is generated from a series of coherent square waves which are related in frequency by multiples of 2. That is, the frequency of each square wave is given by the following relationship:

$$i^{th} \text{ square-wave frequency} = \frac{2^{i-1}}{T} \qquad (2)$$

where

$i = 1, 2, 3, \ldots, n$

T = period of the code sequence

n = number of square waves from which code is derived

The square waves are easily generated from a divide-down chain of flip-flops.

The code is generated from the square waves by the following rule: during each half cycle of the highest-frequency square wave, the number of square waves in binary state "zero" are subtracted from the number of square waves in binary state "one." If the result is zero (possible only when n is even) or positive, the code is put in binary state "one." Therefore, the code bit rate is equal to twice the highest-frequency square wave (also to be called the code clock), and the code period is equal to the period of the lowest-frequency square wave. The length of the code in bits is equal to 2^n. When n is odd, the code is generated by majority logic operating on the square waves. When n is even, the code generated is unsymmetrical (more "ones" than "zeros" in the code sequence) and results in mechanization problems in the receiver due to dc coupling requirements. Therefore, codes from an even number of square waves will not be usable.

The acquisition procedure for the code consists of, first, acquiring the clock (highest-frequency square wave) with a phase-lock loop. The clock acquisition is followed by n-1 correlations of the code with n-1 square waves from a divide-down chain of flip-flops driven by the acquired clock. The correlations are made in sequence starting with the correlation using the one-half clock frequency square wave and going down in frequency to the last correlation using the lowest-frequency square wave. Each correlation will be positive or negative, depending on whether the square wave is in-or out-of-phase with the code. Therefore, a total of n binary decisions (including the clock acquisition as one binary decision) are required to resolve the phase of a 2^n-bit code. From information theory, this equals the minimum number of binary decisions theoretically possible since a 2^n-bit code contains n bits of information. Consequently, the code lends itself to rapid acquisition and, with each acquisition step involving only a binary decision, the mechanization of the code acquisition is considerably simplified.

The correlation values are all equal to each other and have been derived by Stiffler (Ref. 2). The results are given here as follows:

$$\rho = \frac{1}{2^{n-1}}\binom{n-1}{\frac{n-1}{2}} \quad \text{n odd}$$

$$= \frac{1}{2^n}\binom{n}{\frac{n}{2}} \quad \text{n even} \qquad (3)$$

For large n, by Stirling's formula

$$\rho \simeq \sqrt{\frac{2}{\pi n}}$$

With each of the n square waves containing 1/n of the total power, it can be seen that the correlation is reduced by $\sqrt{2/\pi}$ from the case where the received signal is the sum of the square waves. This latter signal is an n-ary wave with n amplitude levels. Hence, the penalty for replacing the n-ary wave with the binary code is 2.0 db when n is large.

For the NAVSTAR application, the BINOR code will be derived from 13 square waves. The clock frequency will be 320 kHz, resulting in a 640, kb/sec data rate, and the lowest-frequency square wave will be 78.125 Hz. The code length will be 2^{13} or 8192 bits long, corresponding to a range ambiguity resolution of about 2100 nmi. After clock acquisition, followed by 12 binary decisions in sequence (correlations), the 78.125-Hz square wave divided down from the clock will be in phase with the received code. The range is obtained by measuring the phase of the 78.125-Hz square wave. The period of this square wave is also equal to the period of the code, so that the range ambiguity resolution is 2100 nmi. The accuracy of the range measurement is determined by the time jitter in the clock loop since this jitter appears on the 78.125-Hz square wave through the divide-down flip-flop chain. The range accuracy is, therefore, determined by the clock loop SNR and is given by the following relation:

$$\sigma_R = \frac{1}{\sqrt{2\,[\mathrm{SNR}]_{\text{clock loop}}}} \cdot \frac{C}{2\pi f_{\text{clock}}} \qquad (4)$$

where σ_R is the rms range error and C approximately 10^9 ft/sec. For 30-ft rms error the clock loop SNR must be 21 db.

The total code acquisition time equals the clock-loop acquisition time* plus 12 correlation times in sequence for the remaining 12 square waves. The clock-loop acquisition time is dependent on the clock-loop bandwidth (see vol. III). For acquisition purposes, the clock-loop SNR can be 10 db. The 21 db necessary for the range accuracy is obtained by transmitting the clock by itself, following acquisition of the code. This increases the clock correlation factor from 22.5, from Eq. (2), to 100 percent or 13 db, and actually increases the loop SNR from 10 to 23 db (ignoring loop bandwidth expansion effects). Therefore, the code transmission will consist of the code sequence for a length of time to allow for code acquisition followed by the clock alone (the 320-kHz square wave) for a short period. This increases the overall code acquisition time slightly. The clock will be transmitted long enough to obtain eight range measurement samples to increase the measurement accuracy by reducing time quantization errors in the range measurement.

The numerical value of the acquisition times is dependent on the available signal power at the receiver as shown in vol. III. For this reason, the values of the acquisition times will be discussed in subsec. 4.4 along with the L-band link power budget. The acquisition time for the satellite data following the code is also discussed.

4.3.4 Preliminary Conclusions

Both the BINOR code and pulse-compression systems appear to be suited to the NAVSTAR system requirements, based on the considerations covered earlier. The required broadcast time-slot durations for the pulse-compression system and, consequently, user position fix times are shorter than for the BINOR code system. However, adding the satellite data requirements to the ranging causes the pulse-compression system to lose some of this advantage. For example, the satellite broadcast time-slot duration for the BINOR code is 1.55 sec. For pulse-compression, the time-slot duration is 1.23 sec when all the satellite data are transmitted as in the BINOR code system, or 0.73 sec when only half the data are transmitted by each broadcast. For ranging,

*Each square-wave correlation time must be an integral multiple of the code period in order to obtain the correct correlation.

the pulse system is superior; for satellite data, a CW system is superior. A hybrid system using both techniques would require two links or two satellite transmitters and two receivers; thus, a hybrid system does not appear very attractive.

In addition to the above considerations, it must be recognized that all BINOR code hardware requirements (satellite and ground) can be met with existing equipment, and no significant design risks. By contrast, the compressed-pulse technique requires high satellite peak-power transmissions, and the hardware for this capability has an unknown lifetime and an unproven reliability for space usage. Further, the chirp filters required have never been built in large quantities, and the effects of aging and drift are unknown. Because of these factors, the BINOR code technique is recommended over the pulse-compression system.

Further design work was undertaken on both the BINOR and pulse-compression systems. A more detailed discussion of the BINOR code is given in vol. III. In vol. III, the navigation L-band link power budgets and ranging and satellite data parameters are discussed for a satellite-to-user transmission link, using both the BINOR code and pulse compression systems. In addition, user hardware (receiver, range acquisition, and data acquisition) designs were made for both systems and are discussed in vol. III. In addition, hardware designs were also made for the fixed-tone system to aid in comparing the complexity and costs of the BINOR code and pulse-compression systems with a fixed-tone system.

4.4 NAVIGATION LINK PERFORMANCE

Link power budgets for the navigation signal transmissions from the satellite-to-the-user are given in this subsection for both the BINOR code and pulse-compression systems, and also for the fixed-tone system. The signal power margins at the receiver and the corresponding receiver acquisition times and satellite broadcast times are also presented. The navigation signal transmissions include both the ranging signal and satellite PCM data on one L-band carrier.

4.4.1 BINOR Code

The power budget for the L-band link is shown in Table III. It assumes a 50-w satellite transmitter power and an earth-coverage satellite antenna. The user will have a near-hemispherical coverage antenna of 0-db gain (in order to avoid antenna-pointing problems) and a receiver with a noise figure of 5.0 db. Antenna gains and the 22,000-nmi range are for a worst-case elevation angle of 10^{o} between the user and a satellite. The user receiver noise temperature is given by the following relationship:

$$T_S = \frac{1}{L}\left[T_A + (L-1)\,T_0\right] + (F-1)\,T_0 \qquad (5)$$

where

T_S = Noise temperature at receiver input

T_A = Antenna look temperature

T_o = Standard temperature of 290^{o}K

L = Line losses between antenna and receiver

F = Receiver noise figure

The antenna look temperature assumed is 60^{o}K, which should be on the conservative side. Average sky noise at L-band is about 10 to 20^{o}K, but earth radiation into the antenna below the horizon will increase this value slightly. The line losses between the antenna and receiver consist of about 100 ft of coaxial line and a bandpass filter at the receiver front end to reject other carriers from the receiver preamplifier. The system temperature will be about 725^{o}K, which results in a receiver noise spectral density of -170 dbm/Hz.

The carrier-loop noise bandwidth for the acquisition mode is 1650 Hz. For a loop-acquisition threshold signal-to-noise ratio of 6.0 db, the threshold carrier power is -131.8 dbm, which results in a 4.1-db signal power margin. This value of threshold power corresponds to a maximum carrier acquisition time of 0.38 sec (see Figure 16).

TABLE III

NAVIGATION LINK POWER BUDGET

BINOR Code Parameter RF Link (f_c=1560 MHz)	
Satellite transmitter power (50 w)	+47.0 dbm
Satellite circuit losses (including diplexer)	1.0 db
Satellite antenna gain (earth coverage)	+16.0 db
Space loss (22,000 nmi)	188.5 db
User antenna gain	0.0 db
Polarization loss	0.3 db
User circuit losses	0.8 db
Net transmission loss	174.6 db
Received power available	-127.6 db
Receiver noise spectral density (NF = 5.0 db, T_S = 725°K)	-170.0 dbm/Hz
Carrier Acquisition	
Loop noise bandwidth ($2B_L$ = 1650 Hz)	32.2 db
Loop noise power	-137.8 dbm
Loop acquisition threshold SNR	+6.0 db
Threshold carrier power	-131.8 dbm
Available carrier power	-127.6 dbm
Margin	+4.1 db
Carrier Tracking (With Modulation)	
Loop noise bandwidth ($2B_L$ = 50 Hz)	17.0 db
Loop noise power	-153.0 dbm
Loop tracking threshold SNR	+10.0 db
Threshold carrier power	-143.0 dbm
Carrier modulation loss (modulation index = 1.2 rad)	8.8 db
Available carrier power	-136.4 dbm
Margin	+6.6 db

TABLE III

NAVIGATION LINK POWER BUDGET (cont'd)

Ranging Modulation	
1. Clock Loop (f_s = 320 kHz)	
Clock loop noise bandwidth ($2B_L$=26 Hz)	14.2 db
Clock loop noise power	-155.8 dbm
Required clock loop SNR (range accuracy = 30 ft)	21.0 db
Required ranging power (100% clock correlation)	-134.8 dbm
Ranging modulation loss (modulation index = 1.2 rad)	0.6 db
Available ranging power	-128.2 dbm
Margin	+6.6 db
2. Code Correlations	
Correlation bandwidth (= 0.026 sec)	15.9 db
Correlation noise power	-154.1 dbm
Required correlation SNR (99.9% probable correct code acquisition)	8.5 db
Correlation loss (22.5%)	13.0 db
Required ranging power	-132.6 dbm
Ranging modulation loss (modulation index = 1.2 rad)	0.6 db
Available ranging power	-128.2 dbm
Margin	+4.4 db
Satellite Data Modulation	
Data bit rate bandwidth (625 b/sec)	28.0 db
Data noise power	-142.0 dbm
Required data SNR 910^{-4} (BER)	9.5 db
Required data power	-132.5 dbm
Data modulation loss (modulation index = 1.2 rad)	0.6 db
Available data power	-128.2 db
Margin	+4.3 db

The ranging signal modulates (PSK) the carrier with an index of 1.2 rad, which results in a drop in carrier power of 8.8 db (carrier modulation loss). After acquisition, the carrier-loop noise bandwidth is switched from a wideband acquisition mode (1650 Hz) to a narrowband tracking mode. A tracking-threshold-loop signal-to-noise ratio of 10 db is specified, which results in a carrier signal threshold of -143.0 dbm and 6.6-db signal power margin. The specified loop signal-to-noise ratio of 10 db is much larger than is necessary for tracking. However, a large value was specified so that the carrier noise jitter will have a negligible effect on both the ranging and user data modulation.

The first step in range acquisition is the acquisition of the code clock (320 kHz) by the clock loop. The clock loop will have a loop bandwidth of 26 Hz, resulting in a maximum acquisition time of about 0.2 sec. Initially the clock loop correlation is 22.5 percent, and hence the loop signal-to-noise ratio is 13 db less than shown for 100-percent correlation in Table III, but is still large enough for acquisition. After code acquisition, the clock is transmitted by itself for the 100-percent loop correlation. A loop signal-to-noise ratio of 21 db is required to reduce the rms noise error in the range measurement to 30 ft. With this requirement, the signal power margin is 6.6 db.

After clock acquisition the square-wave correlations are undertaken. Each correlation will be two code periods long, or about 0.026 sec (2/78.125). The correlation output signal-to-noise ratio required for 99.9 percent probability is 8.5 db. For this signal-to-noise ratio, the signal power margin for the correlations is 4.4 db. Since 12 correlations in sequence are required, the total correlation time equals 0.31 sec (24/78.25). The total code acquisition time is the sum of the clock acquisition and the 12 correlations, or 0.51 sec. The code, including the portion of clock alone, will actually be transmitted for a length of time equal to 58 code periods, or about 0.75 sec. This time includes 14 periods of clock alone to account for the extra time. During the time of clock alone, eight range measurement samples can be made. This reduces by 8 the time quantization error in the range measurement.

After the range code is transmitted for 58 code periods, the satellite data modulation appears on the carrier. The data rate is

625 b/sec and is in the form of split-phase coding for modulating the carrier. In order to transmit a total of 200 bits (165 information bits plus 35 synchronizing bits) the satellite data are transmitted for 25 code periods, or about 0.32 sec. The required data signal-to-noise ratio in a 625-Hz bandwidth is 9.5 db for a 10^{-4} bit error probability, and the corresponding signal power margin is 4.3 db.

Therefore, the navigation link will operate with a 50-w transmitter and a user omnidirectional antenna with signal power margins of 4.1 to 6.6 db. The corresponding satellite broadcast time slot will be structured as shown in Table IV.

TABLE IV

SATELLITE BROADCAST TIME-SLOT STRUCTURE

Event		Time (sec)
Carrier only		0.38
BINOR code		0.75
Satellite data		0.32
Guard time		0.10
	Total time	1.55

With this broadcast time (including guard time), each satellite repeats its broadcast every eight time slots, or 12.4 sec. The user fix rate is, therefore, one position fix every 12.4 sec.

4.4.2 Pulse Compression

The power budget for the L-band link is shown in Table V. The RF power budget is the same as for the BINOR code, except for the 20-kw peak transmitter. The transmitter output consists of 20-μsec peak power pulses with a PRF of 78.125 p/sec. Therefore, the transmitter duty cycle is 0.00156, and the average output power is 31 w as compared to 50 w for the BINOR code.

A total of five ranging pulses periodic at the PRF are transmitted initially. The pulse signal-to-noise ratio required after compression is

TABLE V

NAVIGATION LINK POWER BUDGET – PULSE COMPRESSION

RF Link f_c = 1560 MHz	
Satellite peak transmitter power (20 kw)	+73.0 dbm
Satellite circuit losses	0.5 db
Satellite antenna gain (earth coverage)	16.0 db
Space loss (22,000 nmi)	188.5 db
User antenna gain	0.0 db
Polarization loss	0.3 db
User circuit losses	0.8 db
Net transmission loss	174.6 db
Received power available (peak)	-101.6 dbm
Receiver noise spectral density (NF = 5.0 db)	-170.0 dbm/Hz
Ranging and Data Pulses	
Compressed pulse detection noise bandwidth (6.0 MHz)	67.8 db
Detection noise power	-102.2 dbm
Required compressed pulse SNR	14.7 db
Required compressed pulse power	-87.5 dbm
Pulse compression ratio (100:1)	20.0 db
Required pulse power (before compression)	-107.5 dbm
Available pulse power	101.6 db
Margin	+5.9 db

14.7 db. This value results in a probability of detection, using pulse-coincidence detection, of 0.985 and a false alarm probability of 10^{-12}. The false alarm probability results in a mean time between false alarms of 46 hr. With these values, the received pulse peak power required is -107.5 dbm, resulting in a signal power margin of 5.9 db. The five range pulses allow for four-range measurement samples by a user.

After the 5 range pulses, 86 satellite data pulses are transmitted using 4-position modulation per 1/78.125 sec time frame (PPM). The pulse signal-to-noise ratio of 14.7 db after compression will result in a bit error probability of about 10^{-4}. The signal power margin for this bit error probability will be the same as for the range pulses since the same pulse signal-to-noise ratio is required in both cases.

Thus, the navigation link will operate with a 20-kw peak-power transmitter and a user omnidirectional antenna with a signal power margin of 5.9 db for ranging and for satellite data. The satellite broadcast time slot will be structured as shown in Table VI.

TABLE VI

SATELLITE BROADCAST TIME-SLOT STRUCTURE

Event	Time (sec)
Five range pulses	0.017
Eighty-six satellite data pulses	1.1
Guard time	0.1
	Total time 1.27

With this broadcast time (including guard time), each satellite repeats its broadcast every eight time slots or 10.2 sec. The user fix rate is, therefore, one position fix every 10.4 sec. By transmitting only half the satellite data each broadcast (44 pulses), the fix rate can be increased to one fix every 5.8 sec.

4.4.3 Fixed-Tone System

The power budget for the fixed-tone system is identical to the BINOR code power budget in Table III, except for the portions on carrier tracking and ranging modulation. These portions of the budget are shown in Table VII.

The carrier modulation loss is 4.7 db and results from modulation indices of 0.7 rad for the 320-kHz ranging tone and 0.63 rad each for the other four tones. The signal power margin for the carrier tracking function is 10.7 db.

TABLE VII

NAVIGATION LINK POWER BUDGET – FIXED TONES

Parameter	Value
Carrier Tracking (With Modulation)	
Loop noise bandwidth ($2B_L$ = 50 Hz)	17.0 db
Loop noise power	-153.0 dbm
Loop tracking threshold SNR	10.0 db
Threshold carrier power	-143.0 dbm
Carrier modulation loss	4.7 db
Available carrier power	-132.3 db
Margin	+10.7 db
Ranging Modulation (320 kHz Tone)	
Tone tracking filter noise bandwidth (5 Hz)	7.0 db
Filter output noise power	-163.0 dbm
Required filter output SNR (range accuracy = 30 ft)	21.0 db
Required tone power	-142.0 dbm
Tone modulation loss	10.2 db
Available tone power	-137.8 dbm
Margin	+4.2 db

The ranging modulation portion of the power budget is shown for the 320-kHz high-accuracy tone only. The tone tracking filter noise bandwidth is 5 Hz, which results in a maximum acquisition time of 1.4 sec for the filter. A filter output signal-to-noise ratio of 21 db is required to reduce the rms noise error in the range measurement to 30 ft. The modulation loss results from a 0.7 rad index for the 320-kHz tone and 0.63 rad indices for the other tones. These indices have been chosen to optimize the power distribution between carrier and tones to result in minimum total power required. All five tones will have the same signal-to-noise ratio of 21 db and signal power margin of 4.2 db shown for the 320-kHz tone.

The reason for the lower indices for the four other tones is that the tracking-loop filter bandwidths for these tones can be reduced to 4 Hz or less, and the acquisition times will be no greater than (and perhaps less) for the 320-kHz filter. Since frequency uncertainty at the filter inputs will be less for the lower tones, a narrower tracking filter bandwidth can be used for the same acquisition time. With a 4-Hz bandwidth, the tone powers can be 1 db less than the 320-kHz tone for the required 21 db output signal-to-noise ratio. Therefore, these tones will have a lower modulation index in order that the signal power margins be the same for all five tones.

In the above discussion, phase-lock tracking filters were assumed for the tone-filtering requirements. Passive filters may be possible for some of the lower-frequency tones but because of the narrow bandwidths and phase-stability requirements, the 320-kHz tone will probably require a phase-tracking filter. Hence, the filter acquisition time of 1.4 sec will be the limiting acquisition time for the fixed-tone system.

The satellite broadcast time slot for the fixed-tone system is shown in Table VIII. The times are identical to the BINOR code system times (Table IV), except for the range signal broadcast time. For the BINOR code this time is 0.75 sec, while for the fixed tones it will be 1.5 sec (1.4 sec for filter acquisition plus 0.1 sec for range measurement). Thus the fix rate with fixed tones suffers by comparison with the BINOR code (18.4 sec versus 12.4 sec).

TABLE VIII

SATELLITE BROADCAST TIME-SLOT STRUCTURE

Event		Time (sec)
Carrier only		0.38
Five tones		1.5
Satellite data		0.32
Guard time		0.1
	Total time	2.3

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5. USER HARDWARE

5.1 INTRODUCTION

It was recognized from the beginning of the study that the basic design of the NAVSTAR system must meet the needs of a wide variety of system users. Some users will want the maximum performance capability (self-contained, maximum accuracy, and fixed rates) and will be willing to invest considerable money in user equipment. Others will prefer to invest only a small amount in capital equipment in return for rélaxation of certain capabilities, i.e., ground-aided computations, lower fix rates, and decreased accuracies.

Thus, in the present NAVSTAR user equipment studies TRW Systems has simultaneously reviewed four basic user equipment configurations, designed to appeal to distinct classes of system users. The four user categories are described below. The ensuing sections then summarize the work performed on Antennas, Receivers, Preprocessors, Computers, Displays, and user hardware costs.

- Automatic Self-Contained User Hardware For SST Applications.*

  A block diagram of this configuration is shown in Figure 19. Signal transmissions from up to eight satellites are received by the user's L-band antenna and are demodulated in the BINOR receiver. The preprocessor processes and decodes the two kinds of data appearing during satellite transmission – ranging data and satellite data. The output of the preprocessor is properly formatted for direct entry into the general-purpose computer. Using the range (phase) measurements, ephemeris, and other data received from the satellite, the general-purpose computer calculates the user's absolute position and presents it to the user via his display and control unit.

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*The SST application is generally meant to include the class of high-cost aircraft.

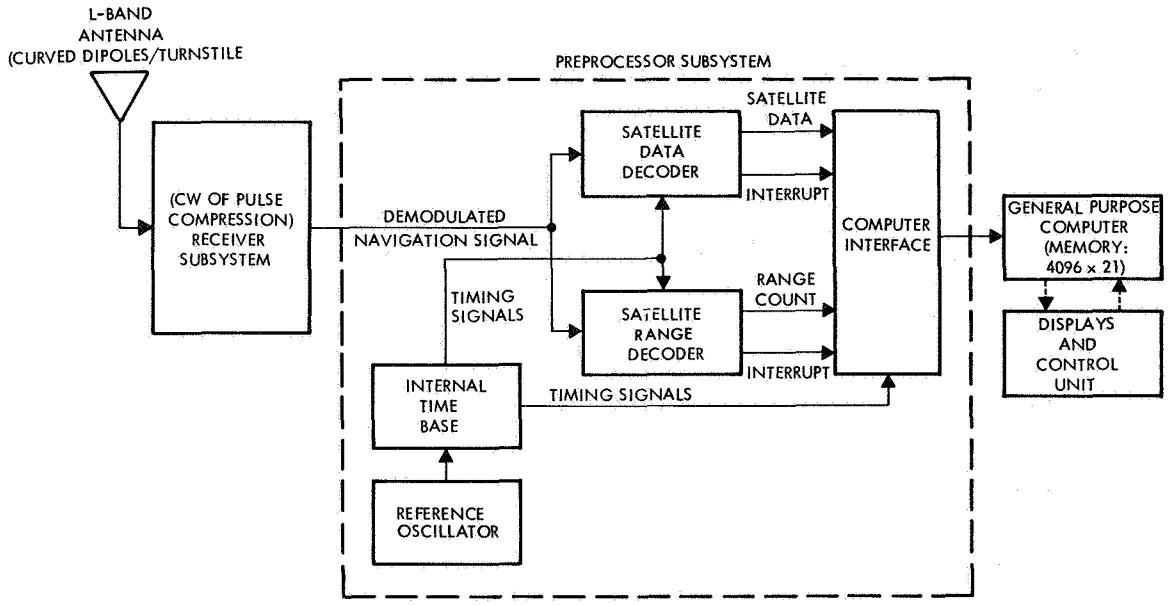


Figure 19. Block Diagram of NAVSTAR User Equipment Configuration A (Automatic, Self-Contained Computation for Supersonic Aircraft)

- Automatic, Self-Contained User Hardware For Moderate Cost Aircraft

  Configuration A_1 is very similar to Configuration A except that a lower performance and capacity computer can be used. Although less complex preprocessor and display units are probably in order, modifications to these units are relatively minor compared to the design changes permissible in the computing element.

- Automatic, Ground-Aided User Hardware

  The third basic user equipment configuration (Configuration B) is the fully automatic/ground station dependent user system shown in Figure 20. It is recognized that certain classes of system users will want a substantial savings in user equipment capital investment. This type of user equipment configuration will accomplish this end through the elimination of the onboard computer.

  To achieve a navigation fix, the user will make the ranging tone phase measurements as before, but will relay this information along with his identification to a ground station where the actual computation will be performed. Once the fix is computed, the

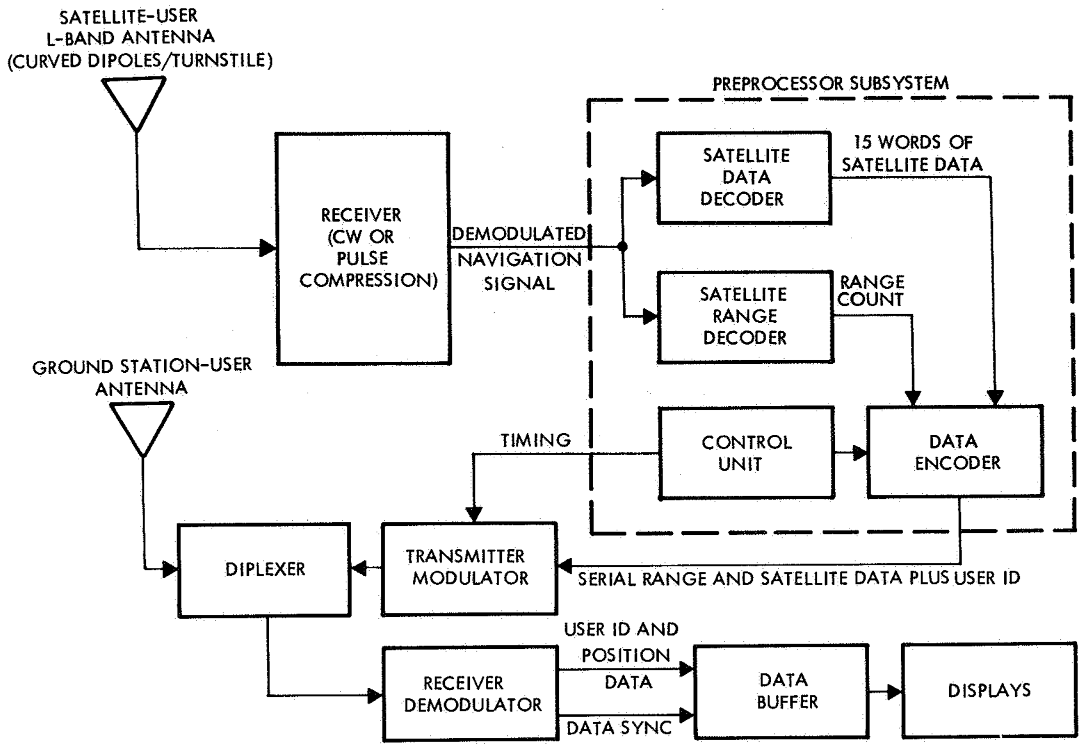


Figure 20. Block Diagram of NAVSTAR User Equipment Configuration B (Automatic, Ground-Aided Computations)

ground station will relay the computed information back to the system user for display. Unlike the fully automatic system, this class of system operation dictates a requirement for a two-way communications link with a ground computing facility.

A user having this basic equipment complex will have sufficient display capability to perform hand calculations on the raw satellite data in event of emergencies when two-way communication with the ground is lost.

It is anticipated that the communication link between the user and ground station will be shared by all users on a time multiplexed basis.

- Manually Operated User Configuration

The fourth class of user equipment configuration (Configuration C) is designed for the user who is satisfied with obtaining fixes having reduced accuracies, and at less frequent intervals in exchange for greatly simplified and relatively inexpensive user hardware.

The basic equipment required is depicted in Figure 21, and utilizes the TRW-designed MINSCO technique for position determination. Again the user equipment contains the basic equipment to determine the ranging tone phase measurements from the navigation satellites within his field-of-view. These phase measurements along with reference data received on a separate channel are displayed on appropriate equipment. The user then solves a set of simple equations to compute his position relative to the nearest reference point based upon this displayed information. This could be done in a few minutes with the aid of a desk calculator. An electronic calculator with temporary storage locations would reduce this time.

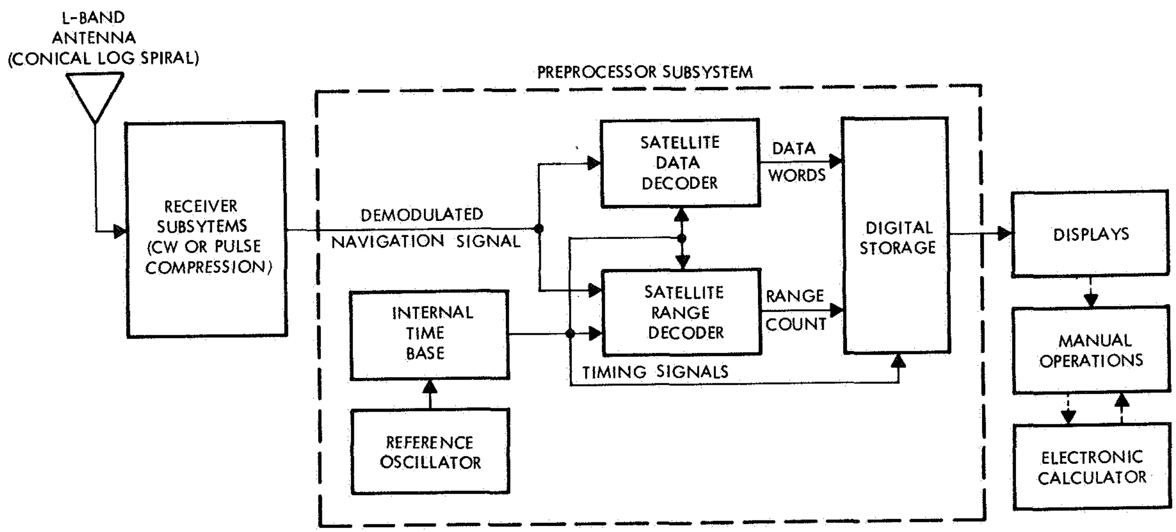


Figure 21. Block Diagram of NAVSTAR User Equipment Configuration C (Manual Computations)

5.2 ANTENNA SUBSYSTEM

The TRW study effort for a NAVSTAR user antenna design was performed primarily in-house using both analytical and empirical measurement techniques.

Based on the technical skills of TRW's senior antenna designers, previous TRW experience, and an extensive literature review, certain antenna configurations were postulated as candidate systems for the typical NAVSTAR user (see Table IX). The most promising designs were breadboarded and subjected to extensive testing at one of TRW's antenna ranges. These test results (given in vol. III) were used iteratively to synthesize several desired antenna configurations.

In addition, a survey was conducted throughout that segment of industry which specializes in the manufacture of airborne antenna systems. The purpose of the survey was two-fold: (1) to determine the availability of off-the-shelf hardware meeting the specified requirements; and (2) to obtain an estimate of recurring costs for large quantity production of current and projected 1970-1975 designs.

5.2.1 Preliminary Specifications

The initial step in this effort was to establish a list of realistic design objectives or preliminary specifications for all subsequent activity. Table X represents the preliminary specifications derived from design studies effected by the key participating designers on the TRW NAVSTAR program. Like all subsystem design goals, the NAVSTAR user antenna specifications are the result of extensive tradeoff analyses between a number of interacting parameters. Some of the more important tradeoffs include: satellite transmitter power output and satellite antenna gain as a function of user antenna gain; satellite ground coverage as a function of user antenna radiation pattern; and acquisition time and system complexity as a function of multimode user antenna configurations.

As with all other user equipment subsystems, the optimizing criterion for selecting one antenna configuration over another is cost. All references to cost in this study refer to the per-unit production cost which the ultimate user will have to pay in order to benefit from the NAVSTAR network.

Table X lists the basic requirements for the user's antenna system(s) including: near-upper hemispherical coverage having high rejection to lower hemisphere signals; operating frequencies within the L-band and a bandwidth of approximately 5 MHz; antenna gain of at least 0 dbi with respect to a circularly polarized standard over a cone area of 160^{o};

TABLE IX

SUMMARY OF ANTENNA CONFIGURATIONS

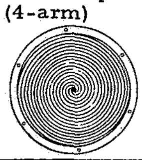
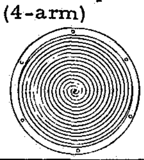
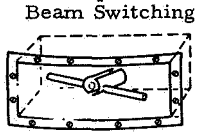
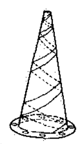
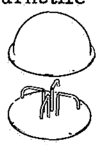
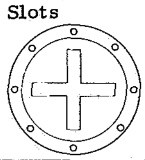
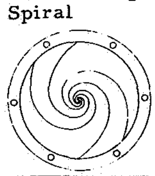
Type	Radiation Pattern	Gain	Axial Ratio (db)	Mounting	Dimension	NAVSTAR User Application	Relative Cost
Planar Spiral (4-arm) 	Directional	6.0 db Peak	< 2	Flush	Circular- 8-in. dia	Inadequate	$500.00
Planar Spiral (4-arm) 	Directional	5.3 db Peak	<2	Flush	Circular- 5-in. dia	Inadequate	500.00
Slot Dipoles Beam Switching 	Hemispherical	3-6 db over 160° cone	<5	Flush	7 x 2.5 x 1.9 in.	Supersonic aircraft	975.00
Conical-Log Spiral 	Hemispherical	0 to 5 db over 160° cone	<5	Medium Profile	Cone shape 7-in. height	Subsonic aircraft and marine vessel	200.00
Curved Dipole Turnstile 	Hemispherical	0-4 db over 160° cone	<5	Low Profile	Hemispherical 2-1/2 in. ht. 3-in. rad	Supersonic aircraft	250.00
Curved Cross-Slots 	Hemispherical	0-4 db over 160° cone	<5	Low Profile	Hemispherical 2-in. rad	Supersonic aircraft	250.00
Dome Surface Log Spiral 	Hemispherical	-2 to 4 db over 160° cone	<5	Low Profile	2 in height 2-1/2-in. rad	Supersonic aircraft	300.00

TABLE X

NAVSTAR USER ANTENNA CHARACTERISTICS

Frequency:	L-band, 1540 to 1600 MHz
Polarization:	Circularly polarized
Axial ratio:	≤5 db
Antenna pattern:	Upper hemispherical, conical beamwidth greater than ±80° about axis
Gain:	≥0 db relative to isotropic
Multipath rejection ratio:	≥10 db
Input VSWR:	<1.5:1 referenced to a 50 ohm impedance
Configuration:	For supersonic aircraft, minimize aerodynamic effects

and an axial ratio within 5 db. Some explanation for the NAVSTAR User Antenna specification is given below.

The upper hemispherical pattern requirement represents optimum coverage for the user antenna since it will enable the user to receive signals from a greater number of satellites (as many as eight can be seen in certain geographical locations). The additional satellites visible to the user (beyond the minimum three) will improve the system accuracy.

The 160°-antenna coverage even at 0 db represents a very difficult design problem, particularly for the supersonic aircraft application. Most known single element antenna designs which are flush-mounted will not meet this requirement because of restrictions in the antenna geometry. To obtain reasonably good upper hemispherical coverage, either some form of surface protrusion should be provided, or multi-element antennas should be used.

5.2.2 Recommended Designs

The antenna design which TRW recommends for the SST is either a low profile design of a modified turnstile antenna or a set of three flush mounted slot dipoles. The first design, which TRW has breadboarded and tested, consists of a pair of curved dipoles mounted approximately 2-1/2 in. above a metal surface. The turnstile antenna configuration utilizes the height and curvature of the arms to produce an antenna pattern of near upper hemispheric coverage. Pattern measurements conducted on a breadboard model have produced encouraging results. However, additional measurements and refinements are required before the present design can be finalized.

The second design provides extremely good performance and can be flush mounted. The ability to switch between antennas can be based upon using measured energy, or, if the user has a combined inertial/NAVSTAR system, the inertial data can be used to provide automatic switching.

For applications where drag is no problem, the antenna design which TRW recommends is the conical log spiral. This antenna configuration provides excellent characteristics at low cost.

5.3 RECEIVER SUBSYSTEM

The NAVSTAR receiver subsystem amplifies and demodulates the L-band carrier transmissions containing the range and satellite data information from the satellites. The demodulated receiver output is sent to the preprocessor which measures the range and decodes the satellite data information.

The NAVSTAR receiver subsystem design study has considered three modulation techniques (BINOR code, fixed tones and pulse compression) which can be implemented through two receiver design configurations (CW and pulse compression). The choice of the BINOR code has been based on cost, satellite peak power, and the use of doppler from a carrier.*

*It is not possible to obtain doppler of useful accuracy from a compressed pulse.

In this instance, both the receiver and preprocessor costs have been considered since each is affected by a change in the modulation configuration.

A simplified block diagram for the CW and pulse-compression receivers are presented in Figures 22 and 23.

5.3.1 Receiver Specifications

CW Receiver. A preliminary specification for the CW receiver is shown in Table XI. The 5-MHz bandwidth is more than adequate to handle either the BINOR code or fixed-tones modulations. The receiver noise figure, loop bandwidth, and carrier-acquisition signal threshold specified were assumed in the power budget for the BINOR code (see sec. 4). The sweep range of ±26 kHz about the L-band carrier is derived as follows:

Maximum carrier doppler:	±4.8 kHz (3000 ft/sec)
TCVCXO stability:	±19.6 kHz (10 PPM long term plus 3 PPM temp. stability through -10°C to +60°C)
TCXO stability:	±1.6 kHz (1 PPM)
TOTAL	±26.1 kHz

Pulse-Compression Receiver. A preliminary specification for the pulse-compression receiver is shown in Table XII. Two pulse-detection thresholds are specified for the receiver: one to be used in connection with the ranging pulses and the other for the PPM data pulses. For the ranging pulses, the probabilities of detection and false alarm specified are given in reference to the detection of one pulse; however, the use of a two-pulse coincidence detector (which is part of the preprocessor) reduces these probabilities to 0.985 and 10^{-12}, respectively. Another detection threshold is established for the PPM data pulses, which result in equal false alarm and miss probabilities. The probability of a miss is equal to one minus the probability of detection.

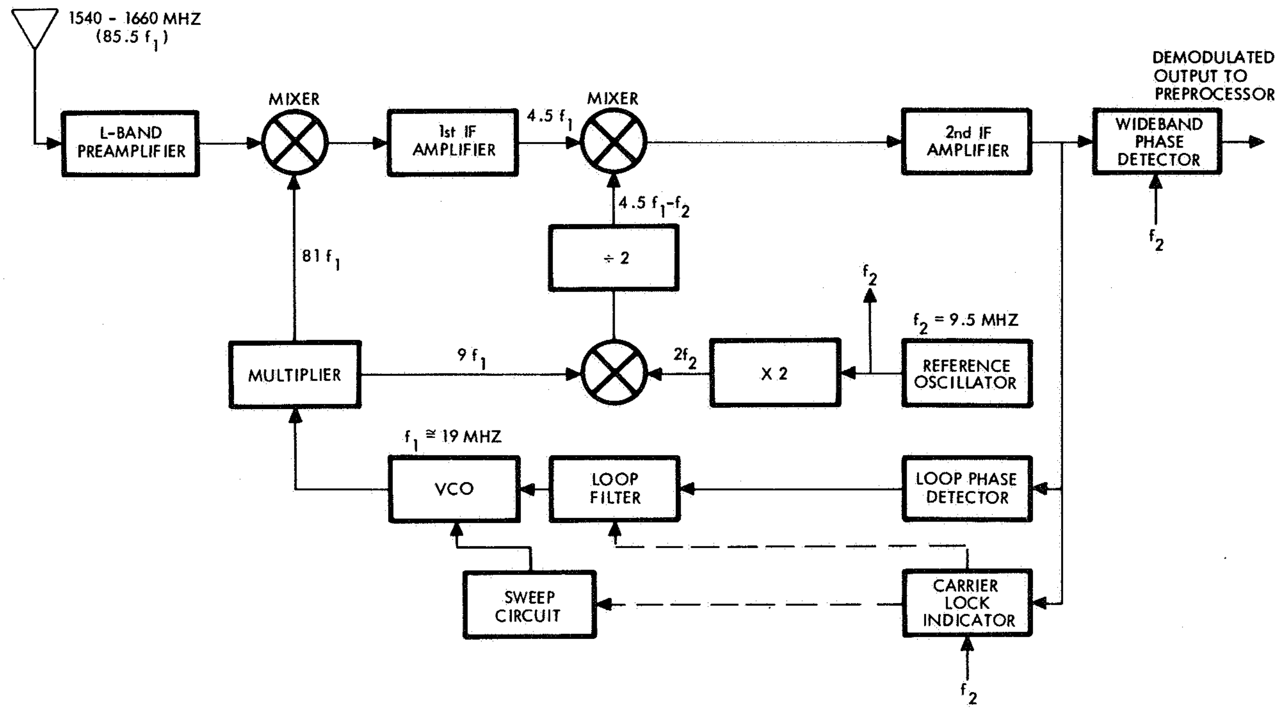


Figure 22. Simplified Block Diagram of NAVSTAR CW Receiver

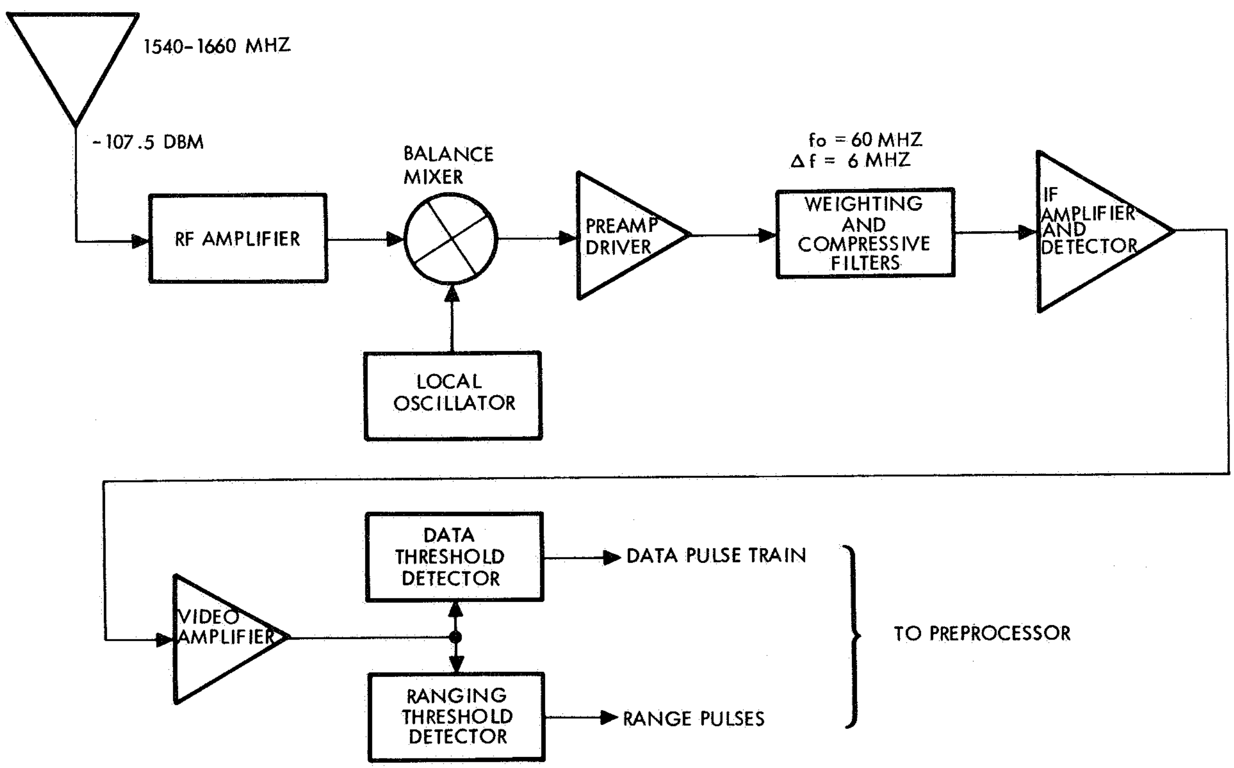


Figure 23. Simplified Block Diagram of the Pulse-Compression Receiver

TABLE XI
CW RECEIVER PRELIMINARY SPECIFICATIONS

Functions:	1) Continuous sweep in frequency over a search range when not locked to an incoming carrier 2) Phase locked to a carrier in the sweep range 3) Coherent demodulation of ranging signal and split-phase data modulating the carrier
Signal input:	Unmodulated carrier for 0.38 sec period followed by phase modulation of carrier by ranging and split-phase data
Carrier frequency:	In band 1540 to 1660 MHz
Dynamic range of signal:	-120 dbm to -135 dbm
Bandwidth:	5 MHz
Sensitivity:	Carrier acquisition threshold power at input of -132 dbm
Sweep range:	±26 kHz about nominal L-band carrier frequency
Sweep period:	0.38 sec
Probability of lock:	0.99 or better on one sweep
Carrier loop bandwidth (two-sided):	1650 Hz during sweep, automatically reduced to 50 Hz upon carrier acquisition
VCO stability:	±0.001% long term
Receiver differential time envelope delay:	±5 nsec variation over dynamic range of signal input at fixed frequency, and over input carrier frequency range of ±26 kHz at fixed input signal level
Receiver output:	Demodulated range signal followed by split-phase satellite data to preprocessor

TABLE XII

PULSE-COMPRESSION RECEIVER PRELIMINARY SPECIFICATIONS

Functions:	1) Detect ranging pulses 2) Detect PPM data pulse train
Signal input:	20 μsec chirped pulses at PRF of 78.125 pulses/sec
Pulse-carrier frequency:	In-band 1540 to 1660 MHz
Chirp range:	5 MHz linear sweep above nominal carrier frequency
Dynamic range of pulses:	-96 dbm to -110 dbm
Bandwidth:	6 MHz
Sensitivity:	Minimum detectable pulse input power of -107.5 dbm
Pulse compression ratio:	100:1
Compressed pulse length:	200 nsec
Compressed pulse SNR:	14.7
Range pulses detection threshold:	Detection probability = 0.993 False alarm probability = 10^{-6}
PPM data pulses detection threshold:	Miss probability and false alarm probability equals 10^{-4}
Output:	Detected range pulses and data pulses to preprocessor

5.3.2 Availability of Off-the-Shelf Equipment

The major manufacturers of UHF receiver equipment were solicited to match their existing product lines against the NAVSTAR receiver requirements. It was later determined that their off-the-shelf equipment did not meet the desired NAVSTAR receiver characteristics, however, the development of appropriate hardware poses no real risk and all hardware is well within current state of the art. Although all companies solicited indicated their strong desire to support the NAVSTAR effort, they needed time for study before submitting their design and production cost data. None of them were prepared to make this effort without further consideration, which was clearly beyond the scope of the present study.

5.4 PREPROCESSOR SUBSYSTEM

The preprocessor serves as the link between the NAVSTAR user receiver and the computing and/or display subsystems. The primary functions of the preprocessor are:

1) To perform the range measurement. (The preprocessor receives a demodulated video range signal from the receiver and uses it to measure the range from satellite to user.)

2) To decode PCM satellite data. (The demodulated satellite data from the receiver is decoded by the preprocessor and then grouped into the appropriate word structure.)

3) To provide computer/display interface. (The preprocessor reformats range and satellite data for the direct entry to the computing or display subsystem.

Five preprocessor configurations were considered in this study; three are a function of the desired range modulation technique and two are a function of the proposed system operation. The first three types (BINOR code, pulse-compression, and fixed-tones preprocessors) assume that each NAVSTAR user possesses all the necessary equipment for complete and independent position determination. The fourth configuration, which is the inexpensive user mode of operation, utilizes the BINOR code for ranging and assumes that all the computation is done by hand. The fifth configuration also utilizes the BINOR code for ranging, but assumes that the computation is performed by a cooperating ground station and then relayed to the user for display.

As previously indicated in sec. 3, three modulation schemes were available for possible use in the NAVSTAR system after completion of the modulation techniques and studies. The final determination as to which scheme was recommended was dependent on the reflected costs to the NAVSTAR user. Only the receiver and preprocessor are affected by the choice of modulation technique. These units, therefore, were carried through to the design stage in order to permit a reasonable cost determination. The fixed tone design was then shown clearly inferior to the BINOR code.

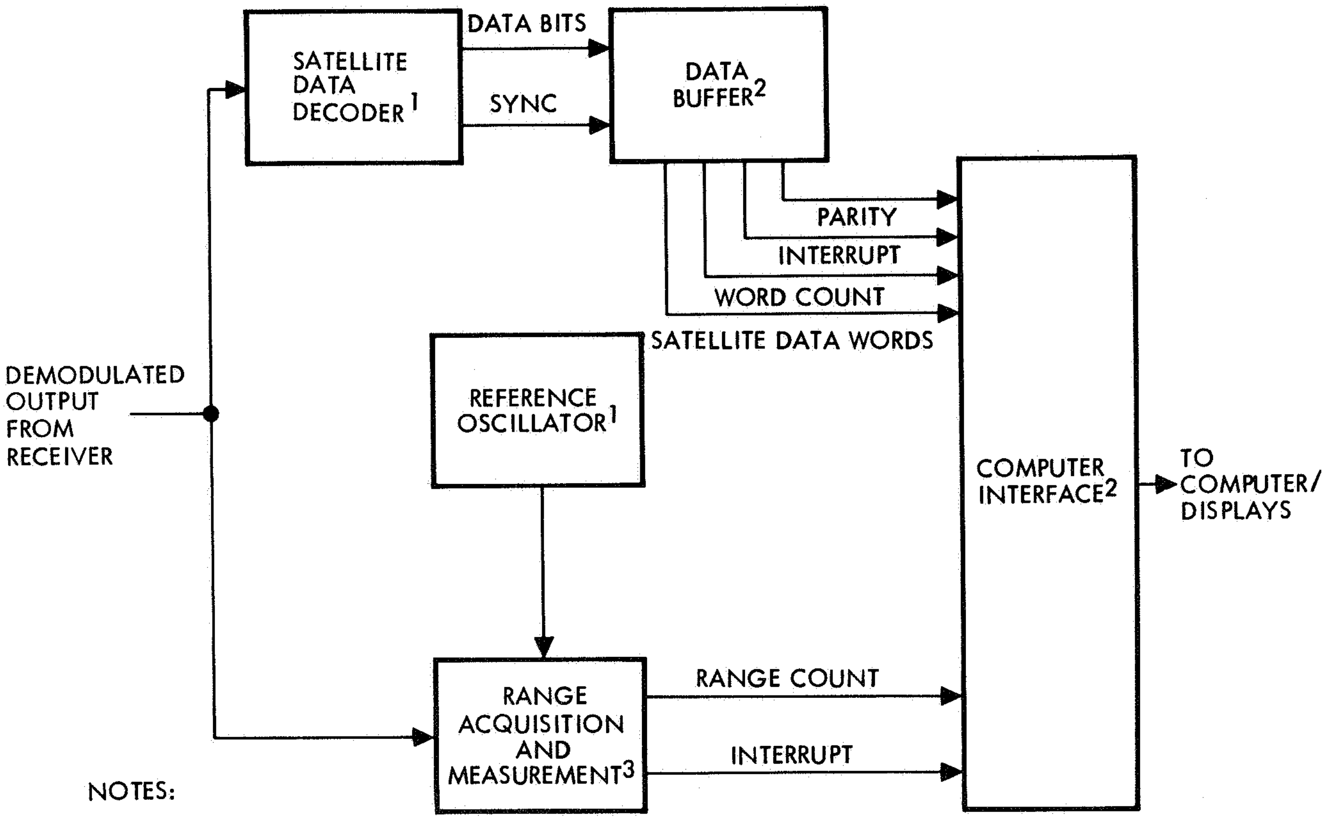
The succeeding subsections describe the design aspects of the preprocessing equipment required to handle each of the above modulation schemes. Also covered are the required preprocessor implementations for the other two NAVSTAR system utilization concepts, namely the manual and ground station aided configurations.

The preprocessor subsystem consists of the following basic elements: a stable reference crystal oscillator, a range measurement section, a satellite data decoder, a data buffer, and a computer interface. The functional interrelationships of these sections are shown in Figure 24.

Three candidate range measurement modulation techniques were reviewed in the course of the present study: the BINOR code, pulse compression, and fixed tones. Preprocessor designs have been prepared to operate with each of these modulation techniques. The corresponding specifications which were used as system design goals are presented in Tables XIII, XIV and XV. A summary of each preprocessor design is given below.

5.4.1 BINOR Code Preprocessor

The BINOR range measurement technique uses a binary code 2^{13} - bits long. The acquisition procedure for the code consists of acquiring a clock component with a phase-lock loop followed by 12 correlations in sequence with 12 square waves, each at half the frequency of the preceding wave. The code is derived from the highest frequency square wave of



NOTES:

1. COMMON TO BINOR AND FIXED TONES.
2. COMMON TO ALL.
3. DIFFERENT FOR EACH.

Figure 24. Generalized Preprocessor Block Diagram

320 kHz (to give 30-ft rms range error) and the lowest-frequency square-wave of 78.125 Hz (to give 2100-nmi range ambiguity). After all of the correlations have been performed, the lowest-frequency square wave will be in-phase with the transmitted code sequence. The desired range can then be secured by measuring the phase delay between the derived in-phase lowest-frequency square wave from the received signal and a reference square wave of the same frequency generated internally. The preprocessor contains a 20-MHz reference oscillator used in measuring the phase delay. The range count is averaged over eight periods during each satellite transmission interval in order to minimize quantization errors.

TABLE XIII

BINOR CODE PREPROCESSOR PRELIMINARY SPECIFICATIONS

Function:	1) Perform range measurement 2) Decode PCM satellite data 3) Provide computer interface
Basic Elements:	1) Code acquisition network 2) Reference oscillator 3) Range measurement unit 4) PCM data signal conditioner and bit synchronizer 5) Data buffer 6) Computer interface
Code acquisition network:	
Input:	BINOR code at 640 kb/sec
Output:	78.125-Hz squarewave in-phase with BINOR Code sequence
Reference oscillator:	
Frequency:	20.48 MHz
Stability:	1 part in 10^9 (per 12 sec)
Range measurement unit:	
Inputs:	1) 78.125 Hz-squarewave from code acquisition network 2) Reference 78.125-Hz squarewave (internally generated from reference oscillator)
Number of measurements:	8 independent range measurements per satellite transmission
Outputs:	1) Timing signals for code acquisition network 2) 20-bits parallel data (representing weight accumulated range counts)
PCM data signal conditioner and bit synchronizer:	
Input:	625 b/sec, split-phase coded
Acquisition time (bit sync):	$\leq$ 35 bits
Bit error rate:	10^{-4} (SNR = 9.5 db in a 625-Hz BW)
Outputs:	1) Decoded satellite data (15 10-bit words) 2) Word count (4 bits) 3) Parity test indicator 4) Interrupt signal
Data buffer:	See Table XVI
Computer interface:	
Inputs:	Binary data from range measurement and data buffer units
Outputs:	Formatted data are 20-bit computer words and data ready signal

TABLE XIV

PULSE COMPRESSION PREPROCESSOR PRELIMINARY SPECIFICATIONS

Functions:	1) Perform range measurement
	2) Decode PPM satellite data
	3) Provide computer interface
Basic Elements:	1) Coincidence detector
	2) Range decoder
	3) Reference oscillator
	4) PPM data demodulator
	5) Data buffer
	6) Computer interface
Range Decoder:	
Input:	200-nsec ranging pulses
Measurement accuracy:	30-nsec rms noise error pulse leading edge
Coincidence detector:	
Probability of detection:	0.984
Probability of false alarm:	10^{-12}
Reference oscillator:	
Frequency:	50 MHz
Stability:	1 part in 10^9 (per 10 sec)
PPM data demodulator:	
Input:	200-nsec PPM pulses at 78.125 p/sec
Bit error rate:	10^{-4} (pulse SNR = 14.7 db)
Outputs:	Sync plus NRZ-L data at 156.25 b/sec
Data buffer:	
Inputs:	NRZ-L data and clock from PPM data signal demodulator
Outputs:	1) Decoded satellite data (15 10-bit words)
	2) Word count (4 bits)
	3) Parity test indicator
	4) Interrupt signal
Computer interface:	
Inputs:	Binary data from range measurement and data buffer units
Outputs:	Formatted data are 20-bit computer words and data ready signal

TABLE XV

FIXED-TONES PREPROCESSOR PRELIMINARY SPECIFICATIONS

Functions:	1) Perform range measurement 2) Decode PCM satellite data 3) Provide computer interface
Basic elements:	1) Range tone filters 2) Reference oscillator 3) Range measurement unit 4) PCM data signal conditioner and bit synchronizer 5) Data buffer 6) Computer interface
Range tone filters:	
Input:	Composite of 5 ranging tones – 320 kHz, 40 kHz, 5 kHz, 625 Hz, 78.125 Hz
Filter bandwidths:	5 Hz (320 kHz tone); 4 Hz (others)
Output:	5 tones, each at SNR of 21 db
Reference oscillator:	
Frequency:	20.48 MHz
Stability:	1 part in 10^9 (per 18 sec)
Range measurement unit:	
Inputs:	1) 5 range tones (from range tone filters) 2) Reference pulse (internally generated from reference oscillator)
Number of measurements:	8 independent range measurements per satellite transmission
Outputs:	20 bits parallel data (representing eight accumulated range counts)
PCM data signal conditioner and bit synchronizer:	See Table XIV
Data buffer:	
Inputs:	NRZ-L data and clock from PCM signal conditioner and bit synchronizer
Outputs:	1) Decoded satellite data (15 10-bit words) 2) Word count (5 bits) 3) Parity test indicator 4) Interrupt signal
Computer interface:	
Inputs:	Binary data from range measurement and data buffer units
Outputs:	Formatted data are 20-bit computer words and data ready signal

The satellite data are extracted by the PCM signal conditioner and bits synchronizer providing NRZ-L data and a sync signal to the data buffer. The data demodulator receives a split-phase code at a frequency equal to the data bit rate of 625 b/sec. The data are received following the end of the BINOR code ranging signal.

5.4.2 Pulse-Compression Preprocessor

Range measurements using the pulse modulation technique are performed by measuring the average time difference between locally generated clock pulses at the PRF rate of 78.125 p/sec and four coincidence ranging pulses. The coincidence pulses are generated by accurately duplicating the time interval $(\frac{1}{78.125})$ between each of the five ranging pulses transmitted by the satellite pulse of each interval, arriving precisely at the completion of this locally generated time interval. The range measurement is performed with a granularity of 20 nsec.

The satelite data are pulse-position-modulated (PPM) with an average PRF of 78.125 p/sec and are transmitted following the five range pulses. The PPM data demodulator operates by detecting the existence of data pulses in the four positions available during each 12.8-msec interval. The data are converted to an NRZ-L format and then fed to the data buffer for processing.

5.4.3 Fixed-Tones Preprocessor

The preprocessor for fixed-tones modulation performs range measurements by determining the precise phase relationships of five ranging tones transmitted from the satellites with respect to the local reference oscillator. The range measurement is accomplished by measuring the time interval between a locally generated markpulse and the point where all ranging tones experience a zero crossing. The reference oscillator must be accurate to 1 part in 10^9 over an interval of 12 sec, since it is used to obtain the precise time mark from which the range tone phase differences are measured. The phase-time interval is measured to an accuracy of 50 nsec.

The satellite data are extracted in an identical manner to the BINOR code system. As in the latter system, the satellite data are received following the end of the range tones signal.

5.4.4 Common Preprocessor Elements

The operation of the data buffer section of the preprocessor is independent of the range measurement technique or data decoder employed. The data buffer receives the NRZ-L data stream and data (bit) sync signals from the data decoder and performs a cross correlation test for data frame sync. The data format transmitted from the satellite contains a frame sync code and fifteen 11-bit words. Each word contains a parity bit that maintains even parity over the word.

When frame sync is detected, the data following are collected, a word at a time, and checked for correct parity. A data interrupt is then generated and the word is outputted in parallel. The word count is provided to aid interpretation or placement of the data by the computer.

The preprocessor is designed to accommodate a wide range of user hardware options. By adding circuit elements to the basic unit the preprocessor is mechanized to meet the user equipment requirements.

The basic preprocessor unit, as shown in Figure 24, supplies outputs compatible with an on-board computer. This comprises the fully automatic user configuration. The outputs of the basic preprocessor unit are: 20 bits of range count data and a range count interrupt; fifteen 10-bit satellite data words issued consecutively comprising the satellite data frame, data word interrupt issued for each word, 4 bits of word count, and a data word parity signal.

5.4.5 Other Preprocessor Configurations

For the automatic ground-dependent user configuration, the basic preprocessor unit requires the addition of a data encoder. The data encoder circuits temporarily store the range count and the satellite data as they are received and serially outputs these data to a transmitter/modulator for transmission to the ground station. Outputs from the preprocessor are also provided for a display unit if manual calculations are required because of interruption of the user/ground station link.

The outputs of the basic preprocessor unit are equally applicable to a display unit incorporating an internal data register. However, a small number of additional circuits in the data buffer of the preprocessor are required for individual satellite data selection. This feature enables continuous display of data from selected satellites, facilitating data presentation for manual position-fix calculations.

5.5 COMPUTING SUBSYSTEM

There are many possible NAVSTAR user configurations capable of being grouped into different categories of cost, accuracy, fix rate, and military/commercial applications. In the computing subsystem study, however, primary attention has been directed towards generating design and cost data for two major configurations:

1) Supersonic aircraft (SST)

2) Small-to-medium size marine vessels.

Other configurations have also been explored but in considerably less detail. These include subsonic aircraft, military aircraft, and ocean liners.

The approach taken in mechanizing solutions to the computing subsystem requirements for the specified NAVSTAR user has been different than the ones taken for the other user hardware subsystems. The reason for this is the high degree of standardization and versatility which is characteristic of the stored-program digital computer. A general-purpose computer which has been designed and constructed for one set of avionic applications will probably be adaptable to an equally complex, albeit different, set of avionic requirements. With the possible exception of the display subsystem, off-the-shelf hardware for the other NAVSTAR subsystems does not exist. With this thought in mind, the study effort performed in the computing subsystem area has consisted logically of two parts:

1) Transformation of NAVSTAR user equations into generalized computer specifications

2) Survey of state-of-the-art candidate computing systems which could be used for the NAVSTAR program.

Analysis of the NAVSTAR user computational requirements resulted in three levels of computing complexity based primarily on the accuracy and rate of update demanded by the user. Established goals were:

1) For supersonic aircraft — better than 0.1 nmi in position error and an update rate of no less than once per minute.

2) For general aviation — less than 1.0 nmi in position error and update rate of once every 15 min.

3) For the small marine craft — 1.0 nmi in position error with present position updated once per hour.

In every case these goals were exceeded.

To determine memory size, execution rate, and data word length for the computational subsystem, the sets of equations derived in sec. 3 of vol. II were analyzed. For the high-performance aircraft a medium-speed computer with 4,096 words of memory was capable of providing the required accuracy and update capability (see Table XVI). For the moderate-performance user a computer with 2,048 words of memory was adequate. For the small marine-craft user, the relatively simple set of calculations could be handled using only a small calculator, paper, and pencil.

TABLE XVI

SUMMARY OF NAVSTAR USER TOTAL COMPUTER MEMORY REQUIREMENTS

Computational Requirements	NAVSTAR User Configuration: SST (No. of Memory Locations)	NAVSTAR User Configuration: General Aviation (No. of Memory Locations)
Positional determination	1750	840
Display processing Input/output processing Computer self-test	1000	500
Data (constants and variables)	500	250
Spare	846	458
TOTAL	4096	2048

Unlike the other NAVSTAR user hardware subsystems, off-the-shelf hardware which is capable of handling the user requirements is available for immediate delivery and in most instances has considerable excess handling capacity.

Analysis of the TRW NAVSTAR user equations resulted in the establishment of the processing requirements for the NAVSTAR computer system as shown in Table XVII. The values given are required for position determination alone.

From data on the memory size, processing time, word length, addressing, interrupts and input/output requirements, a generalized set of preliminary specifications was devised (Table XVIII). It should be emphasized that the specifications exhibit no a priori equipment biases; they reflect only the minimum computational capability required to perform within the constraints of the TRW proposed NAVSTAR system.

Of 15 major manufacturers of airborne computers, 10 elected to match their available equipments against TRW performance specifications. As indicated in Table XIX, a large number of off-the-shelf computers are capable of handling the user requirements and have considerable excess computing and data handling capacity. Current estimates, however, show that over 1/2 the cost of computers is associated with the memory module, and future trends in integrated circuit development forecast that in 1970-75 as much as 90 percent of the computer cost will

TABLE XVII

PROCESSING REQUIREMENTS FOR NAVSTAR COMPUTER SYSTEM

Configuration	Memory Locations (No. of Words)	Arithmetic Operations	
		No. of Long Instructions	No. of Short Instructions
SST user equations	1750	1270	1700
Simplified user equations	840	558	515

TABLE XVIII

NAVSTAR COMPUTER TYPICAL CHARACTERISTICS

Organization:	General purpose
Memory:	Random access core, 4096 words expandable to 8192, nonvolatile DRO operation
Word length:	≥21 bits including sign
Arithmetic:	Binary, 2's complement, fixed point fractional
Add time:	≤50 μ sec
Multiply time:	≤500 μ sec
Indexing:	≥3 index registers
Interrupt capability:	One external interrupt
Input/output:	One serial direct input/output channel at 250 kHz; 6 each input/output discretes
Size, volume, weight and power:	Minimum for stated requirements
Environment:	To be installed in supersonic aircraft

be in the memory subsystem. Thus, reducing the computer capability will not necessarily provide any meaningful overall cost reduction. Furthermore, the existence of extra computing capacity may not be excessively high considering the potential growth requirements such as air traffic control, collision avoidance, etc.

Present computer costs for quantity buys range from $13,000 to $35,000 with an average of about $23,000. Projection into the 1970-75 era indicates that for the supersonic craft, quantity buys will range from $10,000 to $15,000; for general aviation, from $5,000 to $10,000; and for the small marine-craft user, from $500 to $1,000.

Should major breakthroughs occur in the development of low-cost memories for airborne environments, these costs would drop in proportion. Promising developments on batch-processed memories could result

TABLE XIX

SUMMARY OF NAVSTAR SST COMPUTATION CAPABILITY FOR EXISTING HIGH PERFORMANCE AIRBORNE COMPUTERS

Computer	Model No.	Time Required to Make TRW NAVSTAR Computation* Per Satellite	Word Size	Memory** Capacity (No. of Words)	Approximate Unit Cost (In Large Quantities)
General Electric	M-355	17 msec	36 bits	4 K (16 K)***	$40 K
Teledyne	CCC	32 msec	20 bits	4 K (8 K)	$13 K
Univac	1818	35 msec	18 bits	4 K (12 K)	$14 K
Hughes	HCN-305	35 msec	18 bits	4 K (16 K)	$20 K
Nortronics	NDC-1060	43 msec	28 bits	4 K (16 K)	$33 K
Autonetics	D26J	74 msec	16 bits	1 K (16 K)	$35 K
Litton	LC-728	86 msec	28 bits	4 K (32 K)	$31 K
IBM	4π-TC	109 msec	8 bits	8 K (16 K)	$20 K
Control Data	5360	135 msec	24 bits	8 K (32 K)	$18 K
AC Electronics	MAGIC 311	263 msec	12 bits	6 K (8 K)	$27 K

*For position determination, instructions required: 1700 add, 1300 multiply.

**NAVSTAR requirement: 1750 word locations for position determination, and 4 K overall total.

***( ) = Expandable to.

in significant decreases. Successful developments coupled with current trends in large scale integration (LSI) could result in NAVSTAR computers being available for SST applications for less than $10,000; general aviation computers for less than $5,000; and small marine craft computers for several hundred dollars.

Low-cost calculators are available for the manual user as discussed in vol. III.

5.6 DISPLAY SUBSYSTEM

The display subsystem, which provides the man-machine interface between the user and his NAVSTAR equipment, fulfills the system's primary mission of enabling the user to navigate his craft. The display subsystem is designed to display the information required for enhancing the user's decision-making processes, for understanding his craft's status, and for effective control. A number of display subsystems, designed for use with other navigation aids, provide the type of information needed to implement the system objectives. The extent to which these subsystems could be integrated into the NAVSTAR user system has been evaluated (vol. III) and suggestions made for either the new or improved display subsystems required to meet the user's needs.

Consideration of current display practices on high-speed aircraft indicates that the most useful data for navigation purposes, in order of priority, are as follows:

1) User's position
2) Range and bearing of destination (course)
3) Time to go to destination
4) Estimated time of arrival.

Most pilots contacted indicated a need for more accurate traffic control and sea-rescue data. In particular, they cited the need for an alarm method which would warn them of impending collisions or hazardous weather along their flight path.

The design requirements for navigation displays were analyzed. Included in this analysis were controls, display items, data-entry keyboards, and human factors. In general, several constraints on the display design were encountered:

1) Legibility and comprehensibility

2) Limitations on the amount of data to be displayed at any one time

3) The need for small-size, low-weight, and low-power requirements

4) Cost-effectiveness.

The survey of existing displays pointed up the accepted practice of displaying only two quantities at a time, such as latitude/longitude; velocity/heading; or time to go/estimated time of arrival. Other data which may be displayed include altitude, distance from nearest fix points, alarm warnings, traffic control information, position update data, weather alerts, and pertinent data from ground stations.

The SST user will have a navigation computer which may handle navigation with one or more systems (NAVSTAR, inertial, etc.). Generally available with the computer is a control and display unit that can serve quite adequately for any or all systems. Therefore, no special display unit need be purchased if navigation by satellite is added to the older systems as an alternate method.

At the other extreme is the marine craft with severe equipment and cost limitations. A low-cost system will have to be designed for this type of user; table or desk-top calculator for NAVSTAR computations may be all that is available to this user. The display unit will, therefore, be tied into the receiver/preprocessor and will show basic quantities received (constants and variables associated with simplified calculations).

As technology progresses, it is envisioned that cathode-ray tube (CRT) displays or their solid-state equivalent will displace the separate indicators presently in use. Much more versatility will result, allowing a full set of alphanumeric characters and symbols to be displayed quickly and legibly. More quantities can be shown simultaneously upon request. In addition, analog-type displays are possible which will be very helpful in traffic control situations and rescue operations. Bright-tube displays with memory capabilities are now available to eliminate the old CRT problem of low brightness and flicker.

The first step in the design of the NAVSTAR display subsystem was to perform a survey of operator needs and preferences. Several experienced navigators and pilots were interviewed, including representatives from the following organizations: United Airlines, Flying Tiger Lines, TAC, SAC, U.S. Coast Guard, and TRW Systems.

Table XX gives the ranking of information for the various types of craft. While data are provided on the need for traffic control and sea-rescue operation information, the primary emphasis of the study was on navigation information. For navigation, the most important information was present position, followed by range and bearing to destination, time to go, and estimated time of arrival. For traffic control, the need for an alarm condition to warn of impending collision or hazardous weather conditions was most important; and for sea-rescue operations, a distress condition alert was most important.

5.7 SUMMARY OF USER COSTS

The design of the NAVSTAR system to meet acceptable navigation requirements of accuracy, fix rate, world-wide coverage, etc., was never really regarded as an extremely formidable engineering undertaking. A very difficult problem, however, did exist in the engineering selection of techniques and equipments reducing user costs below a reasonable threshold value.

Based on the TRW NAVSTAR design, cost information was obtained from various sources for the four user configurations under study (see Table XXI). The cost data presented throughout this volume are current to 1967. Although the period of greatest interest is 1970-1975 (when the NAVSTAR system is expected to become operational), very

TABLE XX

SUMMARY OF SURVEY ON USER'S DATA DISPLAY REQUIREMENTS

Data to be Displayed	Rank	Commercial Aircraft (SST, 707, 747, etc.)	General Aviation (Private and Business)	Military		Ocean Vessels (Coast Guard Viewpoint)
				TAC Fighter-Bomber	SAC	
1. Navigation Data						
User's position — latitude and longitude	1*	1	1	1	1	1
User's destination — latitude and longitude	7		7		6	
Estimated time of arrival	4	4	3	4	5	
Time of day	6		6			3
Estimated time to reach destination	3	3	4	2	4	
Range and bearing of destination from user	2	2	2	3	3	
Time at which current fix was obtained	5	5	5	5	2	2
2. Traffic Control Data						
ALARM condition (approaching collision, hazardous weather pattern, etc.)	1	1	1	1		1
Steady or flashing warning signal	5	5			1	5
Description of alarm condition	3	3	3	2		2
Recommended corrective action (new course data, heading altitude)	2	4	2	3	2	3
Range, bearing, and altitude of nearest neighbor (s)	4	2		4	3	4
3. Sea-Rescue Operations						
Distress condition alert	1	1	1	1	1	1
Description of distress condition	3	3	2	3	4	3
New navigation data		5				4
Range bearing to rescue area	2	4		2	2	2
Estimated time to make contact and ETA	5	6		5	3	5
Alternate destinations (with modified flight plan data, ETA's, etc.)	4	2		4		

*Ranking in order of importance

little confidence can be attributed to way-out projected figures unless they are firmly based on today's technology and pricing structure. With reasonably good 1967 figures, one can project further on the basis of historical trends, emerging new technologies, etc.

Table XXI presents a summary of average cost for the four NAVSTAR user hardware configurations. Tables XXII through XXV give the supporting cost breakdown in a subsystem basis for each of the four

TABLE XXI

SUMMARY OF AVERAGE COSTS FOR SEVERAL NAVSTAR USER HARDWARE CONFIGURATIONS

	Configuration	Unit Price in Dollars (For Quantities Shown)					
		100		1,000		10,000	
		BINOR Code	Pulse Compression	BINOR Code	Pulse Compression	BINOR Code	Pulse Compression
A	Automatic, self-contained (for supersonic aircraft)	69,785	62,655	45,925	41,805	35,400	32,780
A_1	Automatic, self-contained (for general aviation)	52,710	45,580	39,960	35,840	30,350	27,730
B	Automatic, ground-aided computations	19,445	12,315	12,425	8,305	8,375	5,755
C	Manual computations	20,870	13,740	13,620	9,500	9,580	6,960

TABLE XXII

SUMMARY OF AVERAGE COSTS FOR NAVSTAR USER HARDWARE CONFIGURATION A (AUTOMATIC, SELF-CONTAINED FOR SUPERSONIC AIRCRAFT)

Subsystem	Unit Price in Dollars (For Quantities Shown)					
	100		1,000		10,000	
	BINOR Code	Pulse Compression	BINOR Code	Pulse Compression	BINOR Code	Pulse Compression
Antenna	325		275		250	
Receiver	7,130	6,370	4,410	4,250	2,960	2,840
Preprocessor	11,630	5,260	7,440	3,480	4,890	2,390
Computing	35,700		28,800		23,300	
Display	15,000		5,000		4,000	
Totals	69,785	62,655	45,925	41,805	35,400	32,780

TABLE XXIII

SUMMARY OF AVERAGE COSTS FOR NAVSTAR USER HARDWARE CONFIGURATION A_1 (AUTOMATIC, SELF-CONTAINED FOR GENERAL AVIATION)

Subsystem	Unit Price in Dollars (For Quantities Shown)					
	100		1,000		10,000	
	BINOR Code	Pulse Compression	BINOR Code	Pulse Compression	BINOR Code	Pulse Compression
Antenna	250		210		200	
Receiver	7,130	6,370	4,410	4,250	2,960	2,840
Preprocessor	11,630	5,260	7,440	3,480	4,890	2,390
Computing	27,700		22,900		18,300	
Display	6,000		5,000		4,000	
Totals	52,710	45,580	39,960	35,840	30,350	27,730

TABLE XXIV

SUMMARY OF AVERAGE COSTS FOR NAVSTAR USER HARDWARE CONFIGURATION B (AUTOMATIC, GROUND-AIDED COMPUTATION

Subsystem	Unit Price in Dollars (For Quantities Shown)					
	100		1,000		10,000	
	BINOR Code	Pulse Compression	BINOR Code	Pulse Compression	BINOR Code	Pulse Compression
Antenna	325		275		250	
Receiver	7,130	6,370	4,410	4,250	2,960	2,840
Preprocessor	11,630	5,260	7,440	3,480	4,890	2,390
Display	360		300		275	
Totals	19,445	12,315	12,425	8,305	8,375	5,755

TABLE XXV

SUMMARY OF AVERAGE COSTS FOR NAVSTAR USER HARDWARE CONFIGURATION C (MANUAL COMPUTATIONS)

Subsystem	Unit Price in Dollars (For Quantities Shown)					
	100		1,000		10,000	
	BINOR Code	Pulse Compression	BINOR Code	Pulse Compression	BINOR Code	Pulse Compression
Antenna	250		210		200	
Receiver	7,130	6,370	4,410	4,250	2,960	2,840
Preprocessor	11,630	5,260	7,440	3,480	3,890	2,390
Computing	1,500		1,260		1,255	
Display	360		300		275	
Totals	20,870	13,740	13,620	9,500	9,580	6,960

configurations. Cost summaries present data for BINOR code and pulse compression. Only the receiver and preprocessor subsystems are affected by the modulation technique employed.

The cost data associated with the computing and display units were obtained from major manufacturers in those areas; all other pricing information was generated internally.

A review of the data presented in the summary cost tables reveals the following:

1) Configuration A (Table XXII) – The major cost item ($\geq 65\%$ of total) is the computer, priced over \$20K even in large quantities. Although the total price of \$33K-\$35K is quite reasonable for the SST user, this figure would be reduced by as much as 50 percent in an integrated inertial/NAVSTAR system. The reduction would result from the using a single computer and display and control units for both functions.

2) Configuration A_1 (Table XXIII) — Again the major cost item is the computing element which make up approximately 60 percent of the total cost. A total price tag of \$28K - \$30K is certainly excessive as far as much of the general aviation class of user is concerned. The alternatives available are any of the following: Have the general aviation user utilize configuration B (ground-aided computations) as his primary mode of operation; or make the MINSCO system (configuration C) available to the general aviation user by further refinements to the hardware mechanizations in terms of size and weight.

3) Configuration B (Table XXIV) — The associated costs of \$6K - \$8K for ground-aided computations (in large quantities) should be acceptable for many commercial applications. A 50 percent cost reduction is projected into the 1970-1975 period making a \$3K - \$4K system available for users of this mode of operation.

4) Configuration C (Table XXV) — This configuration shows the greatest amount of promise for the very inexpensive user desiring an independent capability of satellite navigation. The total price tag presented is \$7K - \$10K, with the 50 percent cost reductions, \$4K - \$5K can be projected for the 1970's. This configuration utilizes the TRW-designed MINSCO technique and was created as a clear low-cost alternative to the basic NAVSTAR concept (see sec. 3, vol. II).

   Further cost savings are anticipated as refinements are implemented in the MINSCO design. For large quantities this configuration user hardware should be available in the \$2K - \$3K price range in the 1970's.

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6. SATELLITE DESIGN

The satellite design (presented in detail in vol. IV, sec. 4), is summarized in this section. The satellite transmits a ranging signal and data that define satellite identification, ephemeris, and satellite oscillator correction. In addition, a communication link is provided for transmitting data from remote ground stations to the master computation station. The design presented does not provide for traffic control communication between low-performance terminals such as aircraft. Such capability will be considered in ensuing studies.

The satellite is shown in Figure 25 in a single-launch configuration. The satellite, including all propellants, weighs 516.4 lb and can be boosted into an appropriate transfer orbit by a Thor-Delta vehicle with a weight margin of 208.6 lb.

All satellite subsystems are completely within the state-of-the-art and could be built immediately.

The satellite mission requires that the satellite be positioned to within 5° of the nominal longitude throughout its lifetime. Further, a solid engine is needed on the satellite to provide plane change and orbit circularization at apogee of the injection transfer ellipse. As long as the satellite dc power needed is low (under about 500 w), these requirements can best be met with a spin-stabilized system, which has, therefore, been chosen for this application.

The satellite system block diagram is depicted in Figure 26. All subsystems are discussed in summary fashion in subsecs. 6.1 ff.

6.1 STRUCTURE

The satellite structure is the basic framework of the overall spacecraft. Its primary function is to integrate, with minimum weight, the other spacecraft subsystems. It must also have sufficient strength, rigidity, and other physical characteristics both to withstand all mission environments and to provide the required support and alignment for the spacecraft components and assemblies.

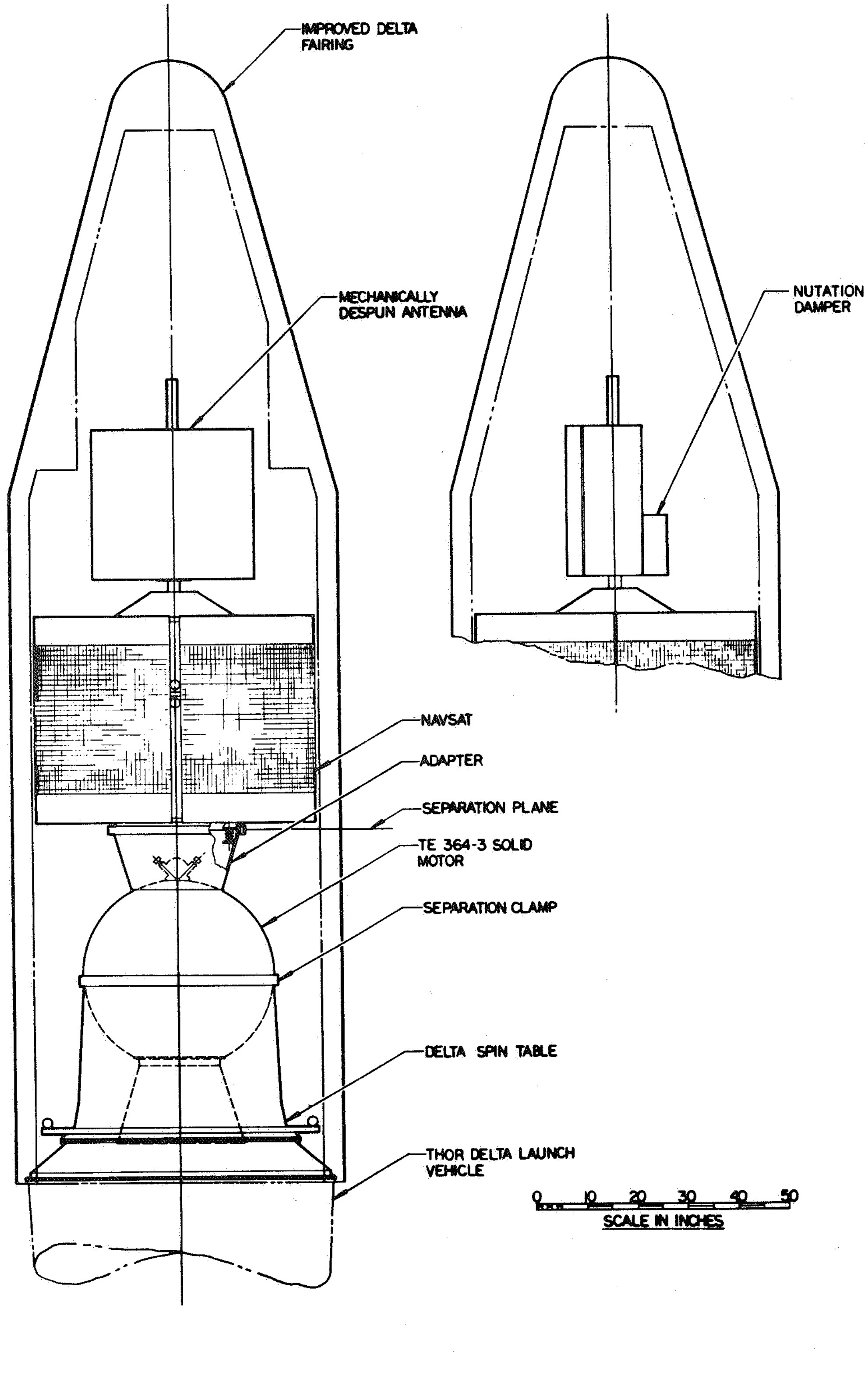
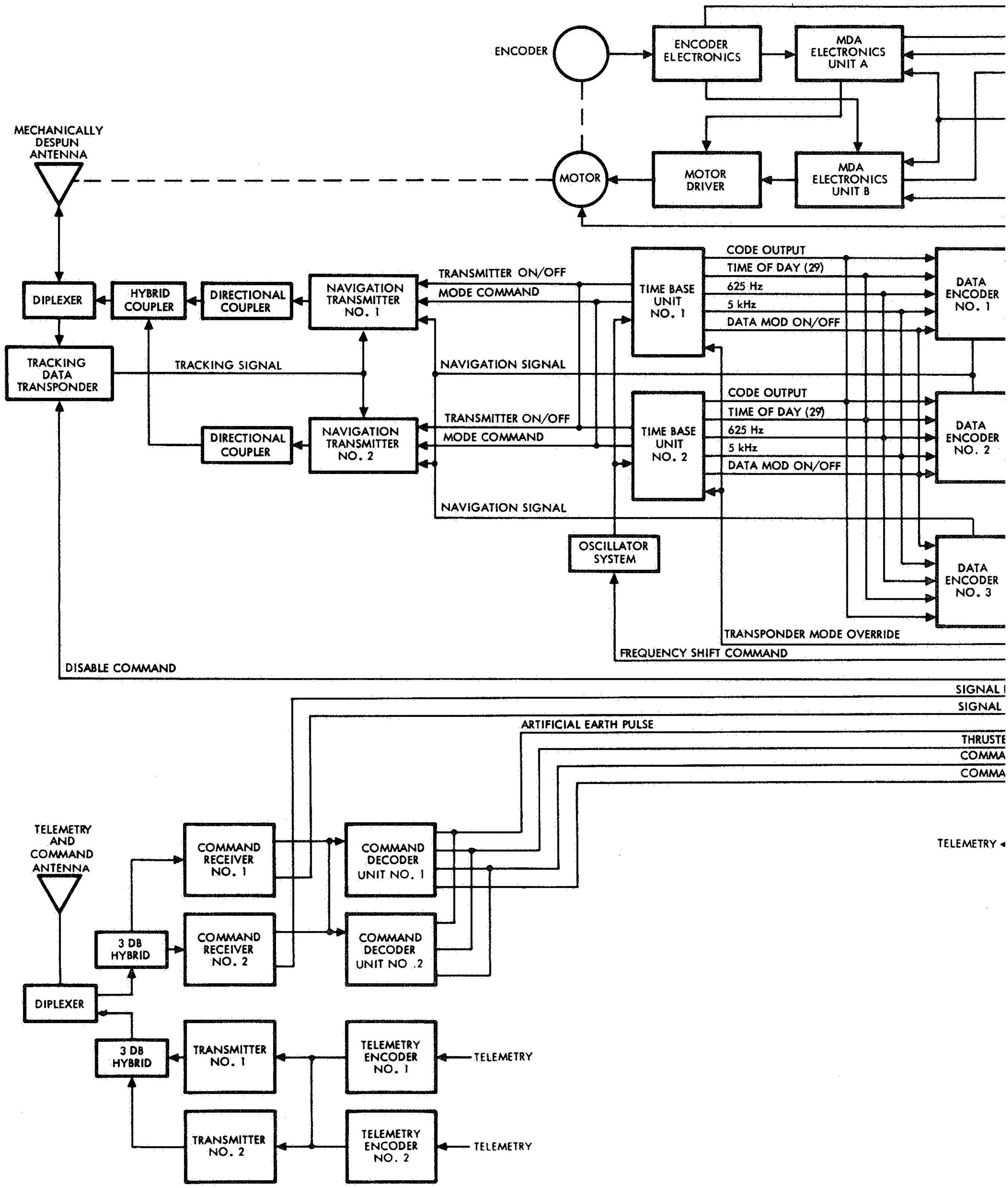


Figure 25. NAVSTAR Single Launch Configuration Booster Installation



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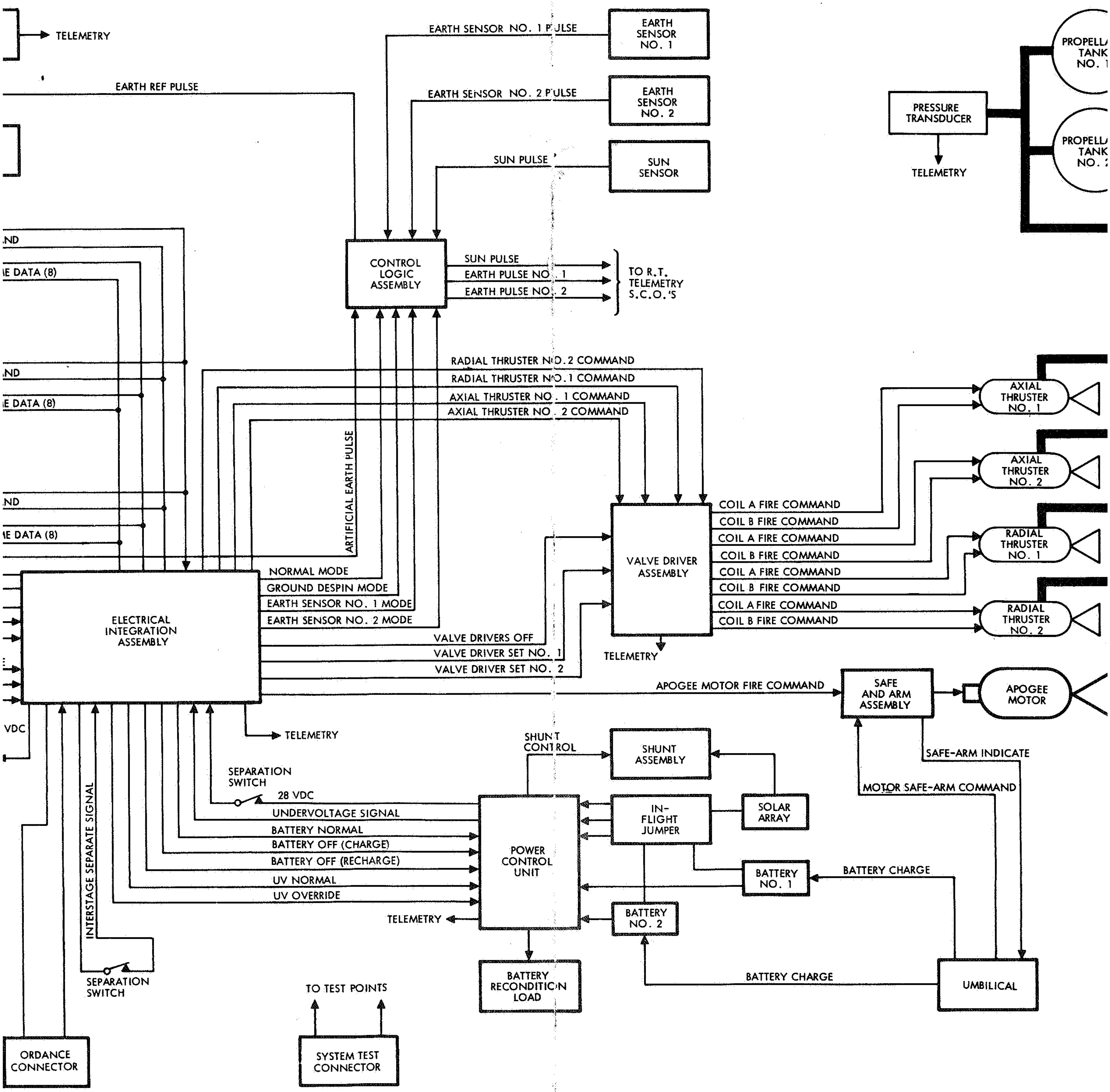

Figure 26. NAVSTAR System, Block Diagram

FOLDOUT FRAME 2

The primary structural member of the spacecraft is the central cylinder as shown in Figure 27. It provides support for the apogee motor, antenna, equipment platform, and solar panels.

6.2 MASS PROPERTIES

The spacecraft mass properties are as shown in Tables XXVI and XXVII. The total spacecraft weight is estimated to be 516.4 lb; the adapter between the spacecraft and the booster is estimated to be 25.0 lb. The Thor-Delta/TE-364-3 boost vehicle has an allowable payload weight of 750 lb, using a 100-nmi parking orbit; therefore, the weight margin is 208.6 lb.

Table XXVII presents spacecraft weights, center of gravity, and moments of inertia at launch, apogee motor burnout, and end of mission.

Since inertia ratio of the satellite, I_x/I_y (as defined in Figure 28), is less than 1, which means that damping in the rotor is destabilizing, the damper must be placed on the despun portion. The damping on the despun antenna must exceed the damping in the rotor and may be accomplished by the spherical pendulum damper indicated in Figure 25.

6.3 ELECTRICAL INTEGRATION ASSEMBLY

The electrical integration assembly (EIA) performs the functions of command processing and distribution, telemetry signal conditioning, power distribution, control of spacecraft ordnance, and redundant command receiver control.

A functional block diagram of the EIA is shown in Figure 29. The EIA accepts a 9-bit binary coded command word from a redundant decoder interface. The command information is contained in 8 bits, while the ninth bit is used as a steering pulse to determine if the information is a discrete command or data to be routed to the navigation system to update ephemeris and time information. The transmission gates interfacing with the navigation system will also accept an enable signal from the navigation system as a prerequisite for transmission of the update data. Discrete command information is accepted in redundant buffer gates and passed on to redundant decode logic, together with an execute pulse from the addressed decoder, generating one of 64 discrete commands.

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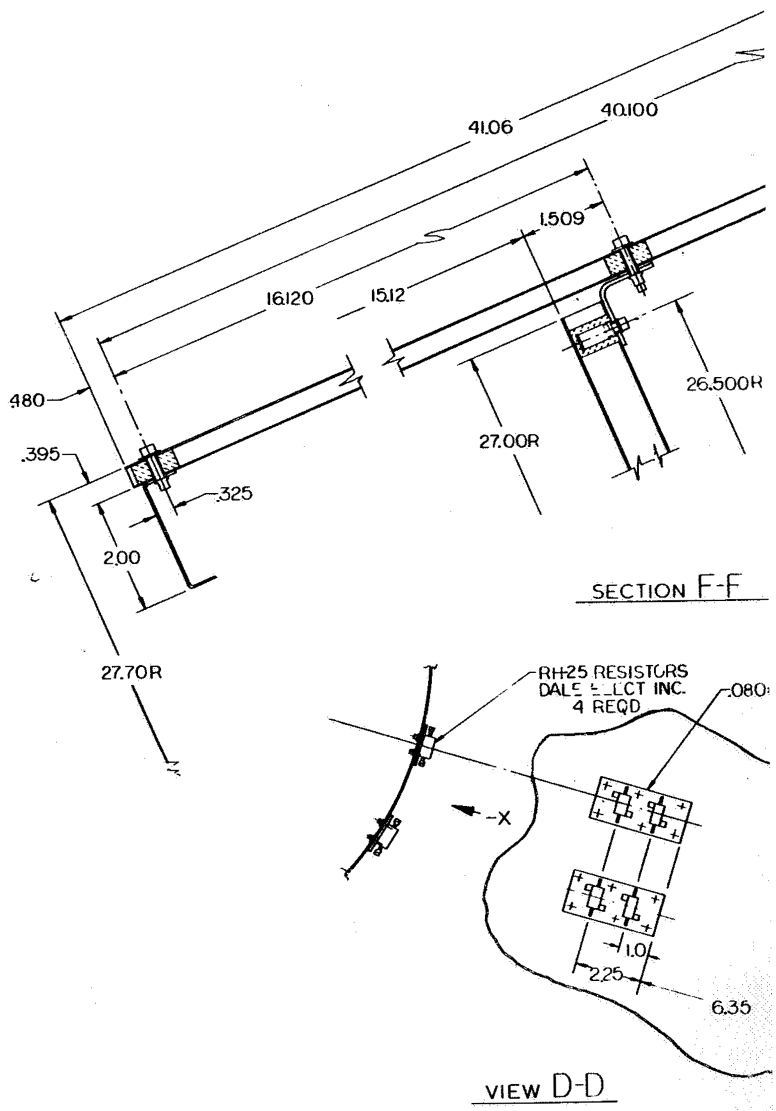
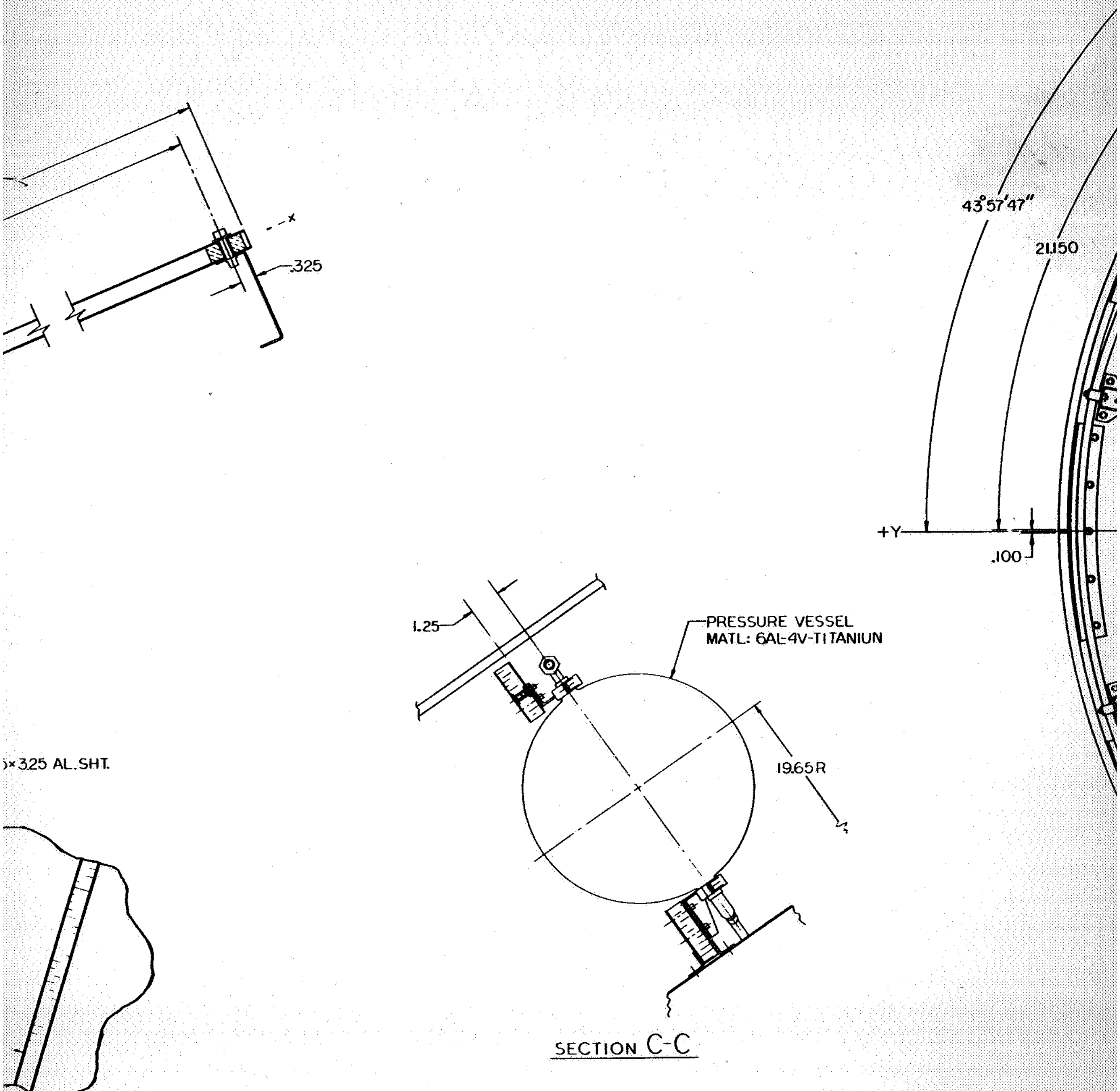
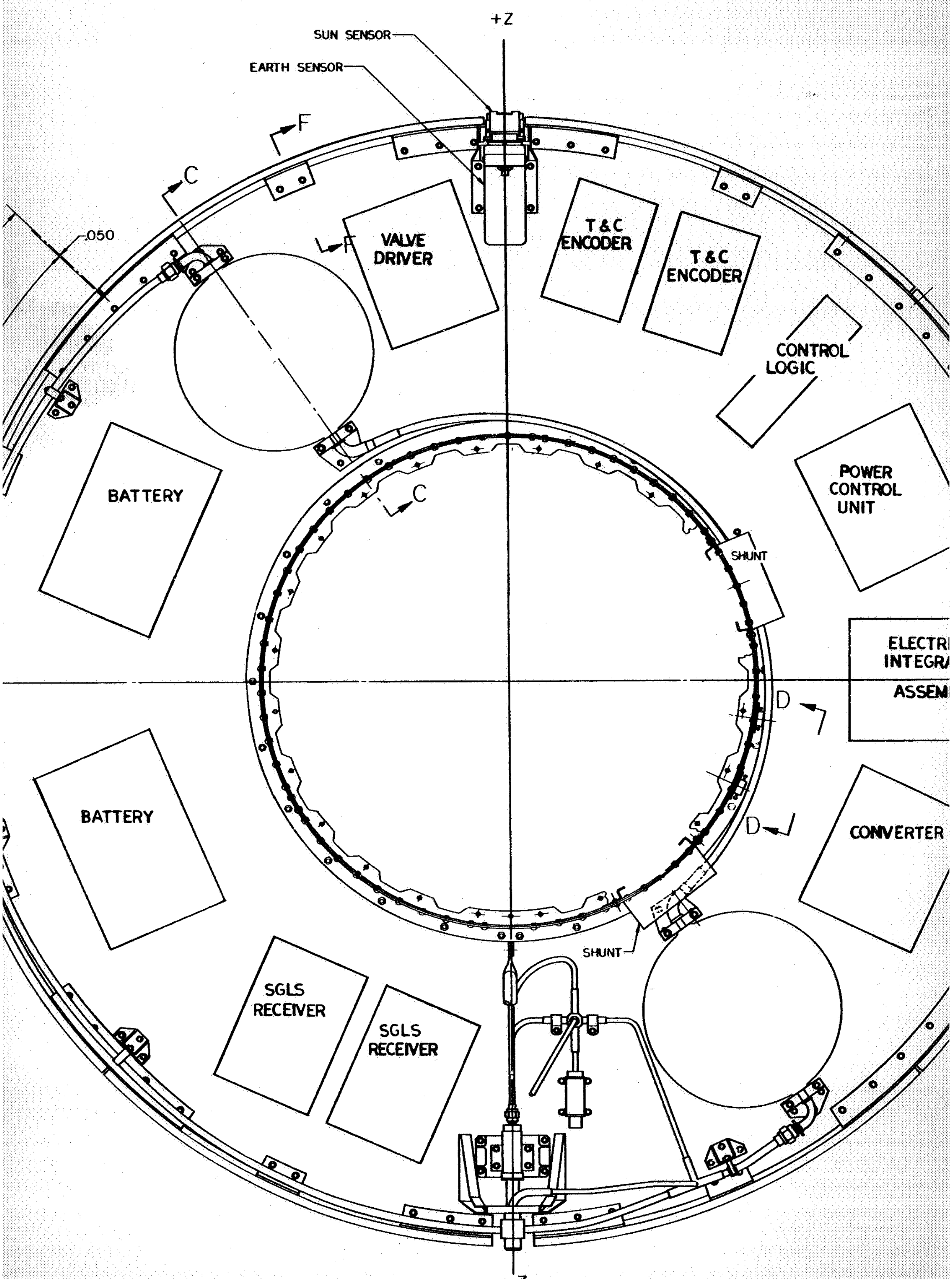


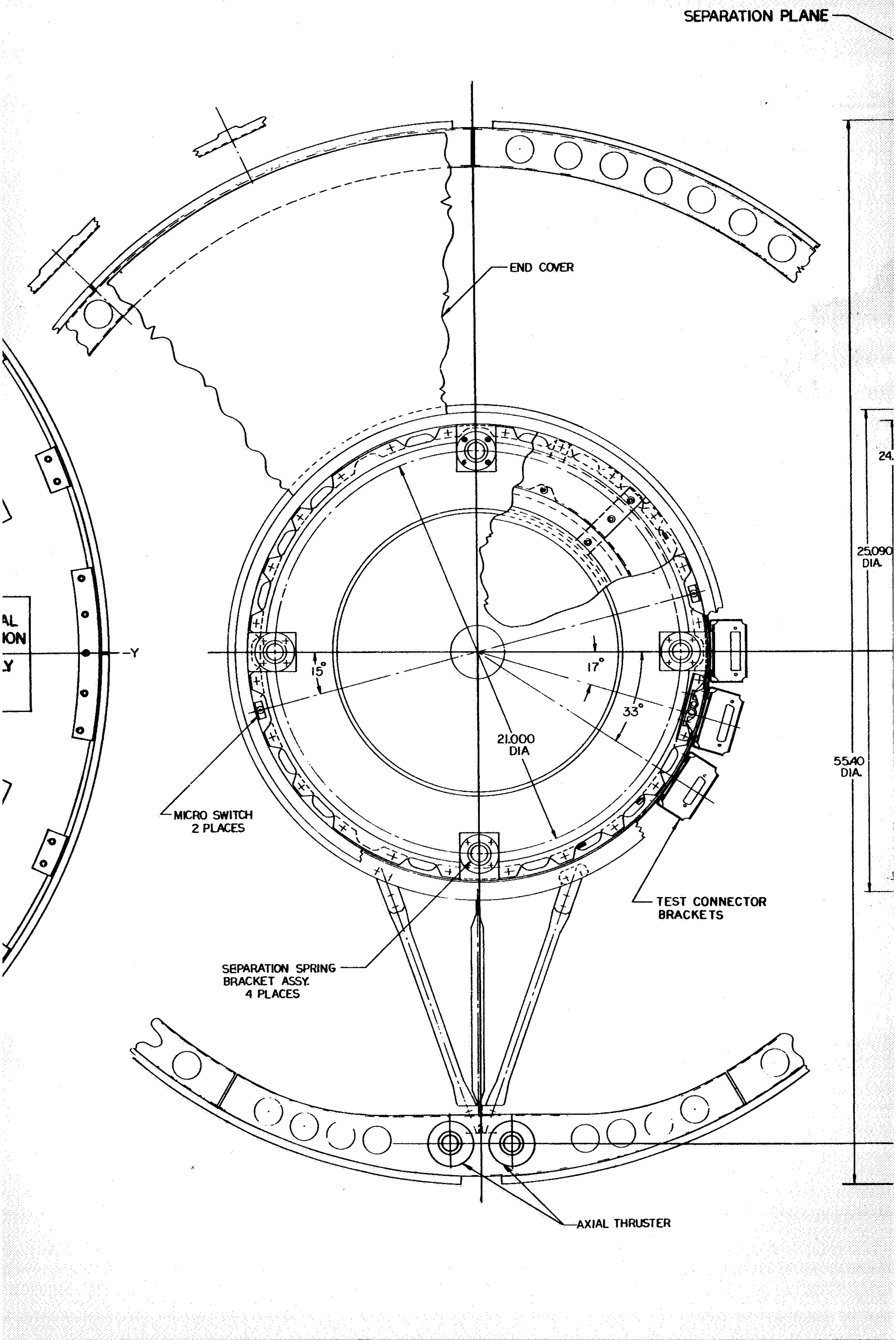
FOLDOUT FRAME 1


43°57'47"
21.150
+Y
.100
.325
1.25
PRESSURE VESSEL
MATL: 6AL-4V-TITANIUN
19.65R
5×3.25 AL. SHT.
SECTION C-C

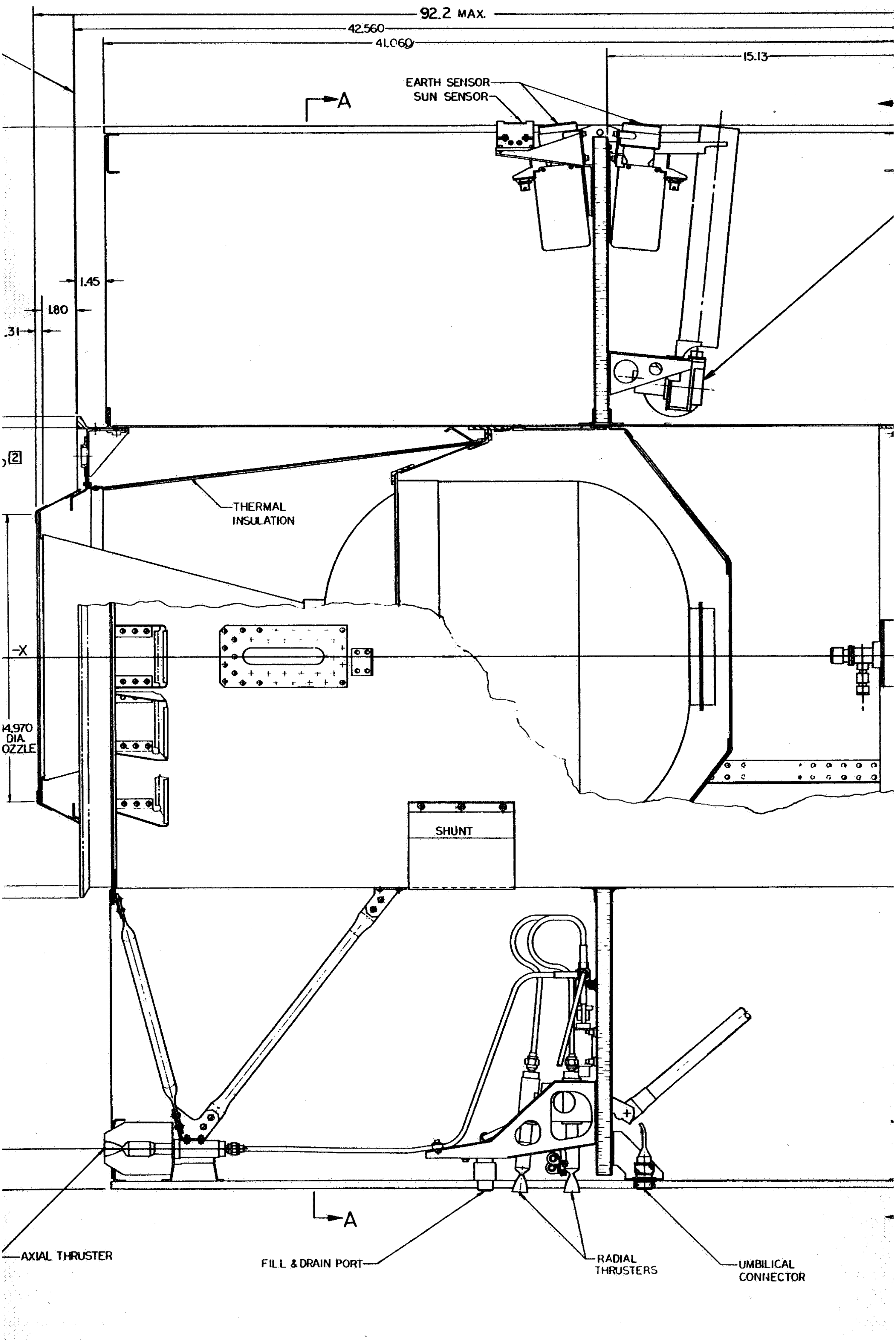


OMITTED APOGEE MOTOR

SECTION A-A



FOLDOUT FRAME 3A



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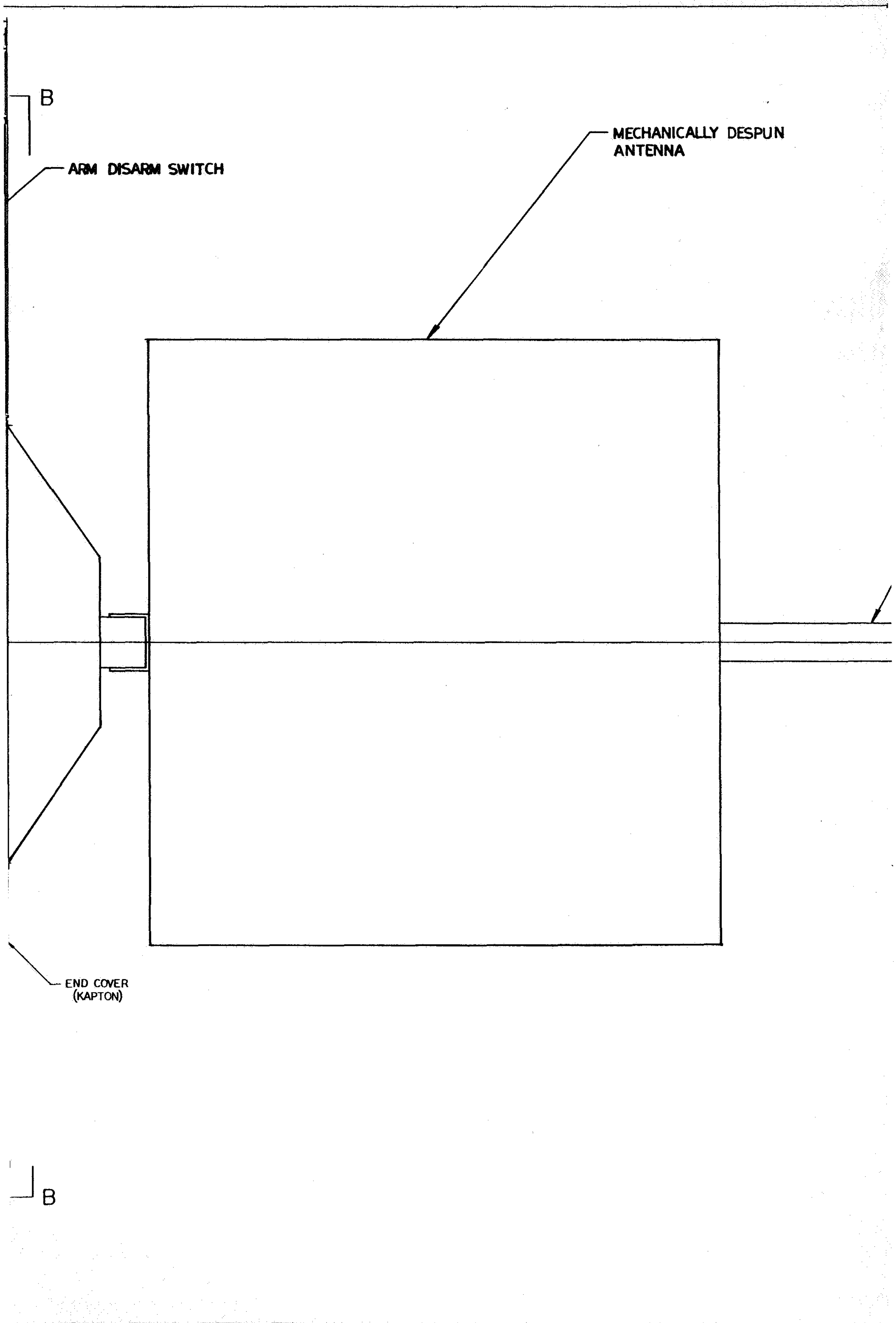
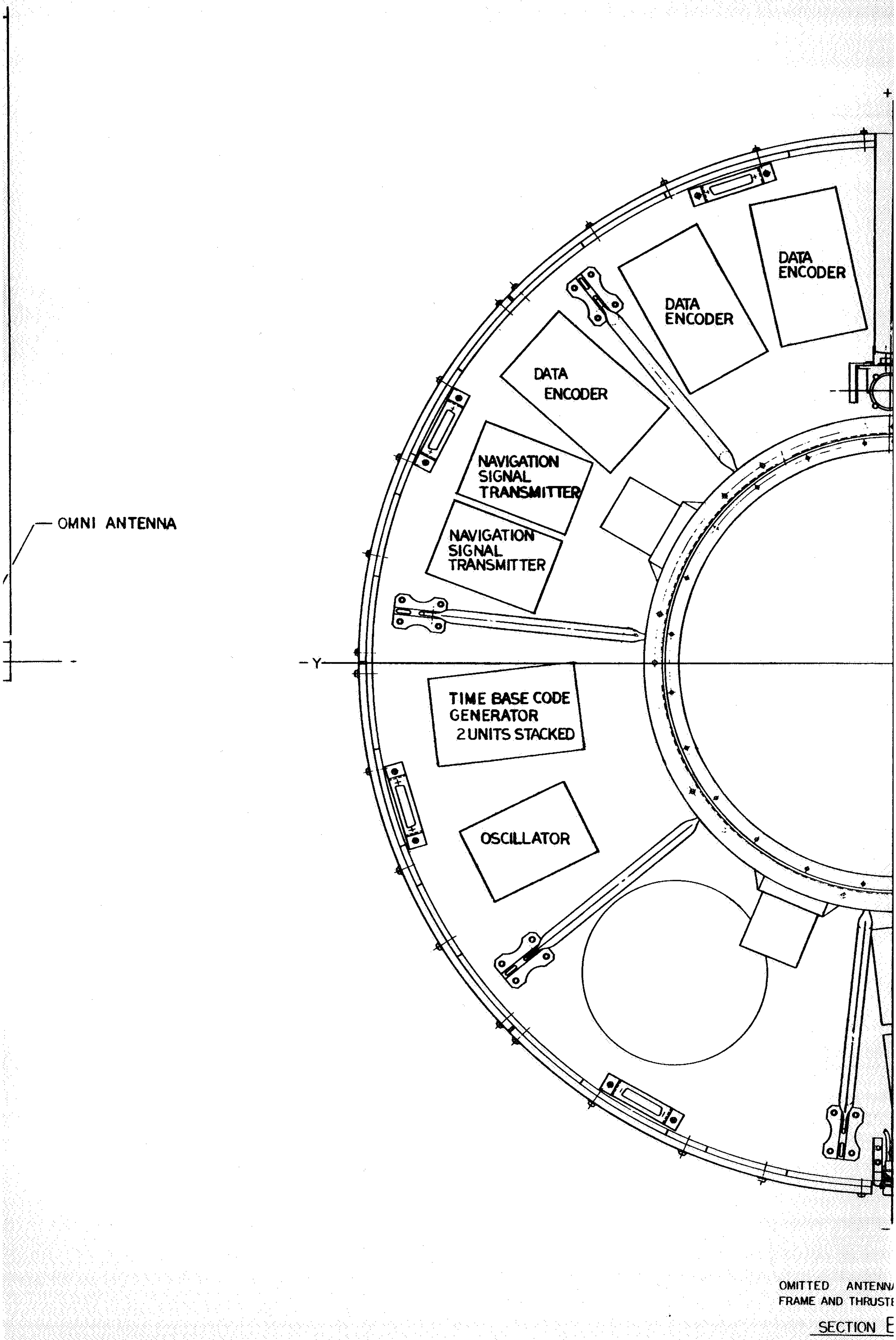

B
ARM DISARM SWITCH
MECHANICALLY DESPUN
ANTENNA
END COVER
(KAPTON)
B



FOLDOUT FRAME 6

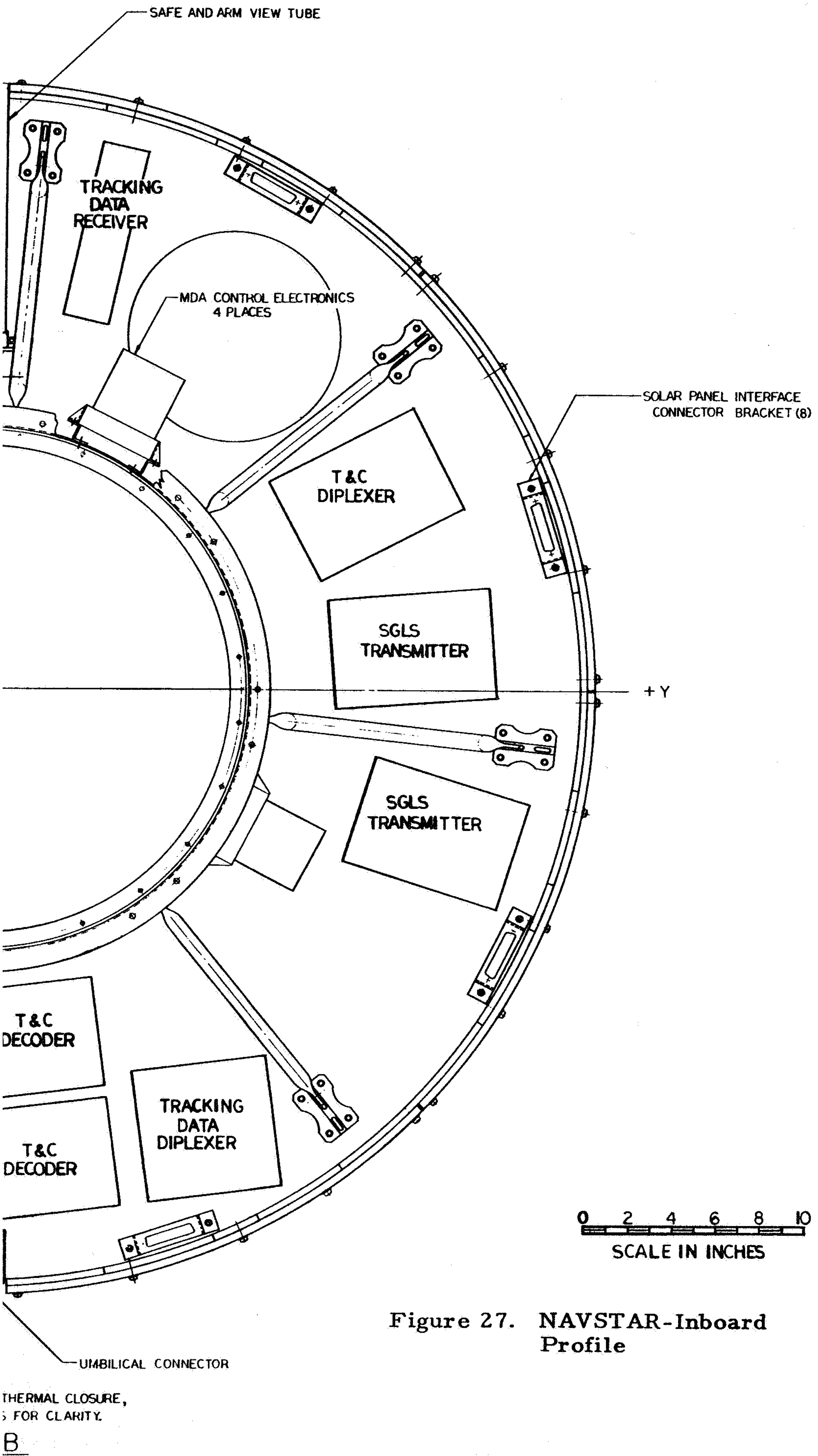


Figure 27. NAVSTAR-Inboard Profile

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TABLE XXVI

SPACECRAFT WEIGHT SUMMARY

Subsystem	Weight, lb
Navigation Signal Subsystem	57.7
Oscillator (redundant)	3.6
Time base code generator (2)	1.6
Encoder (3)	4.5
Transmitter (2)	16.0
Despin assembly	8.8
Despin electronics	8.5
Cabling	1.7
Integrated antenna assembly	13.0
Telemetry and Command Subsystem	18.2
Receiver (2)	6.2
Transmitter (2)	4.8
Encoder (2)	2.2
Decoder (2)	3.6
Diplexer	1.4
Tracking Data Subsystem	4.0
Transponding receiver	3.0
Diplexer	1.0
Electrical Power Subsystem	68.3
Solar array	25.0
Battery (2)	28.6
Power control unit	8.0
Shunt (2)	3.2
Converter	3.5
Electrical Integration Subsystem	19.5
Electrical integration assembly	5.0
Cabling and connectors	14.5
Attitude Stabilization Subsystem	8.7
Control logic	1.5
Valve driver	1.5
Sensor assembly	2.7
Wobble damper	3.0

TABLE XXVI

SPACECRAFT WEIGHT SUMMARY (cont'd)

Subsytem	Weight, lb
Positioning and Orientation Subsystem	7.8
Propellant valve (4)	1.5
Engine assembly (4)	0.6
Tank (2)	2.8
Fill and drain valve	0.3
Pressure transducer	0.2
Filter	0.3
Heat Shield (2)	0.2
Heat Sink (2)	0.3
Lines	0.8
Seals and joints	0.2
Nitrogen pressurant	0.6
Structure Subsystem	50.8
Equipment platform	11.1
Central cylinder	7.5
Motor mount	8.8
Separation ring	3.3
Antenna mount ring	1.4
Struts and fittings	2.6
Platform mount rings	0.9
Solar array ring — upper	1.1
Solar array ring — lower	1.1
Thruster support struts	0.6
Separation fittings	0.7
Hydrazing tank supports	0.5
Sensor mount	0.5
View tube	0.3
Wobble damper mount	0.5
Radial thrust mount	0.3
Aft closure	1.2
Aft end cover	1.3
Forward end cover	0.4
Miscellaneous attaching hardware	6.7
Thermal Control Subsystem	2.1
Thermal blankets	2.0
Propellant line insulation	0.1
Apogee Motor Subsystem	22.8
Apogee motor — burned out	21.5
Arm/disarm switch	1.3
Balance Weights	5.0

TABLE XXVI

SPACECRAFT WEIGHT SUMMARY (cont'd)

Subsystem	Weight, lb
Contingency (5%)	13.2
SPACECRAFT AT END OF MISSION	(278.1)
Attitude Control Propellant	11.8
SPACECRAFT AT APOGEE MOTOR BURNOUT	(289.9)
Apogee Motor Expendables	226.5
SPACECRAFT AT BOOSTER SEPARATION	(516.4)

TABLE XXVII

MISSION MASS-PROPERTY CHARACTERISTICS

Spacecraft Condition	Weight, lb	Center-of-Gravity, in.			Moments of Inertia, slug-ft^2		
		x	y	z	I_x	I_y	I_z
At Booster Separation	516.4	25.59	0	0	23.20	24.97	23.80
At Apogee Motor Burnout	289.9	27.89	0	0	21.33	22.37	21.20
At End of Mission	278.1	27.99	0	0	20.34	21.37	21.20

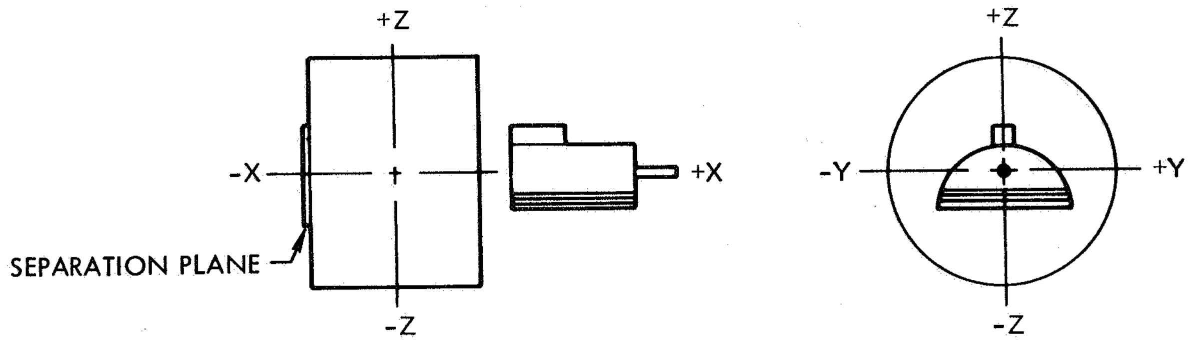


Figure 28. Spacecraft Coordinate Axes System

6.4 NAVIGATION SIGNAL GENERATION SUBSYSTEM

This subsystem generates the BINOR code synchronized by a stable oscillator (see Figure 30 for a block diagram). The rubidium frequency standard originally recommended has been replaced in the current design with a precision crystal oscillator, which, when calibrated for aging over periods as long as one day, will have performance equal to a rubidium standard (Ref. 1a).

The time base and code generator unit employs a straightforward design. The time base unit counts down from the oscillator frequency of 5.12 MHz to 12.39 sec per cycle. A second set of counters generates time-of-day information from the 5-kHz flip-flop in the first set of counters. A group of 13 frequencies in the first set (320 kHz to 78.125 Hz) is used to generate the BINOR code for range measurement. In addition, two control signals are generated for the transmitter: (1) a signal for control of transmission to users (navigation signal control); and (2) a signal for control of transmission to ground stations tracking the satellite (tracking data control).

The data encoder and scanner encodes data for transmission to satellite users (ephemeris and time correction). These data are received by the satellite from command stations at regular intervals and stored in the encoder registers.

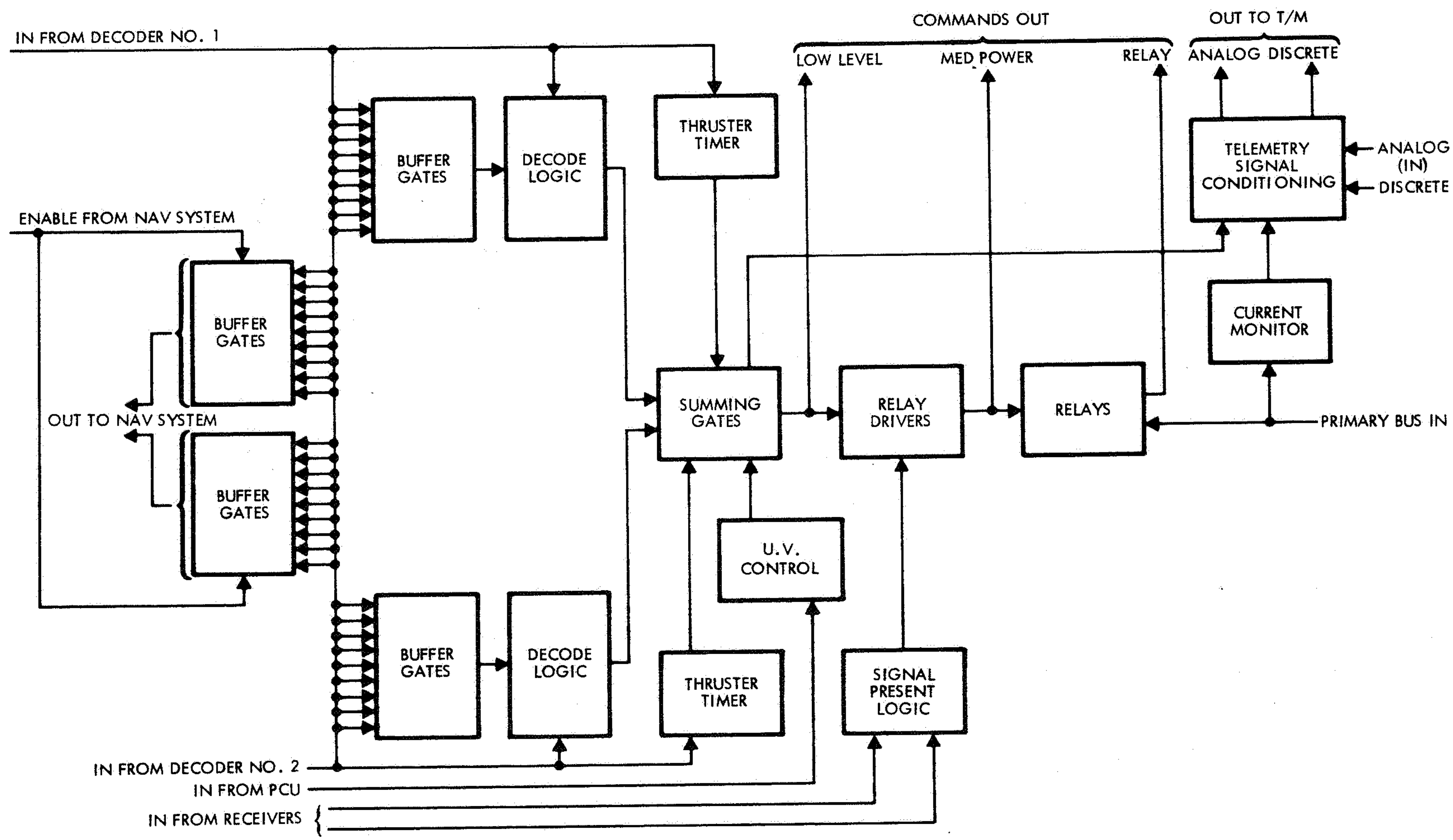


Figure 29. EIA Block Diagram

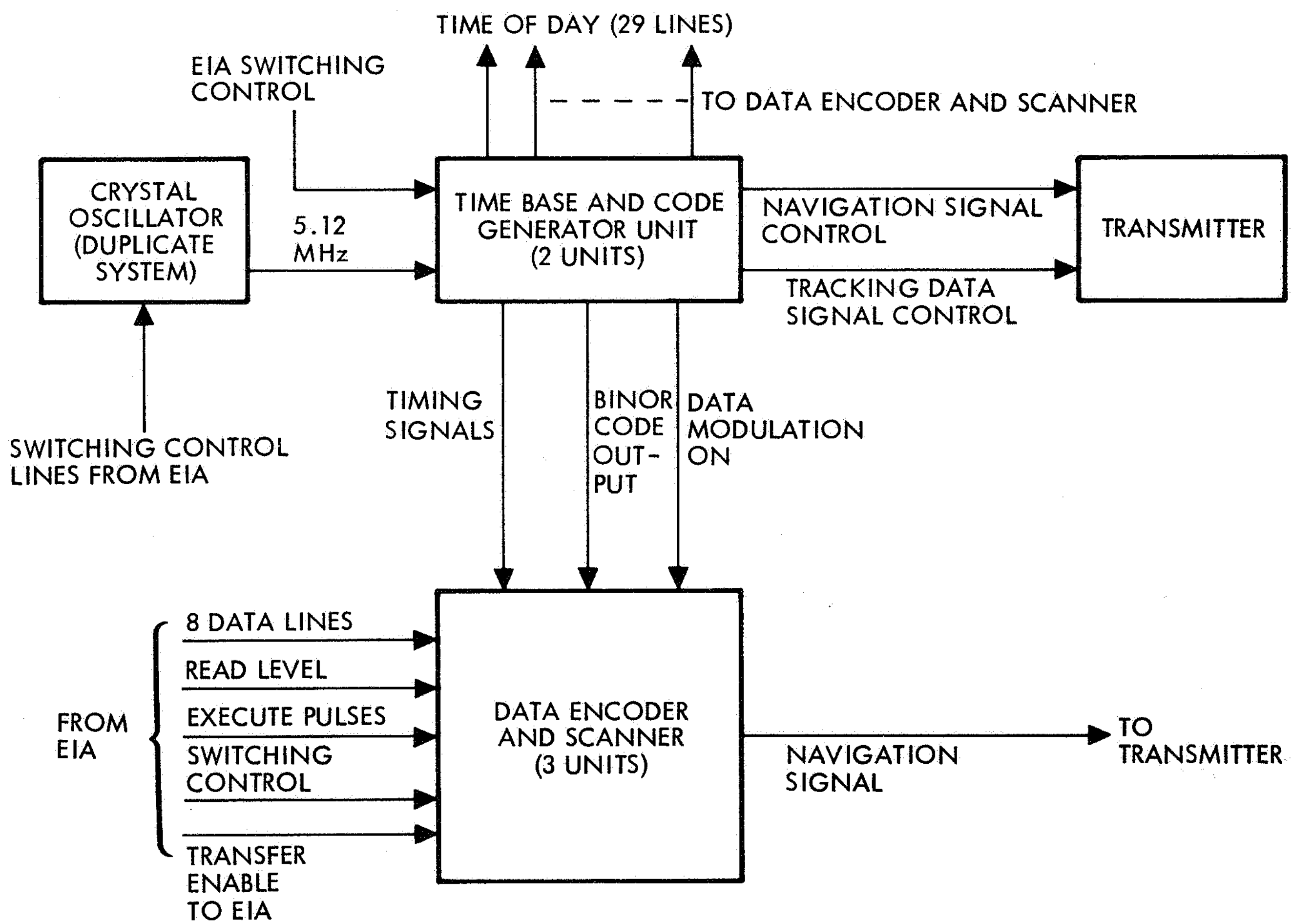


Figure 30. Navigation Signal Generator Overall Block Diagram

6.5 L-BAND TRANSMITTER

A solid-state, 50-w output, L-band transmitter has been considered for transmission of the navigation signal to users. An output of 50-w should be possible within the next year or two as varactor diodes are improved. However, an output of 20-w, solid-state is available today with the use of a power amplifier followed by a varactor multiplier. Alternatively a TWT could be used that might be a superior design.

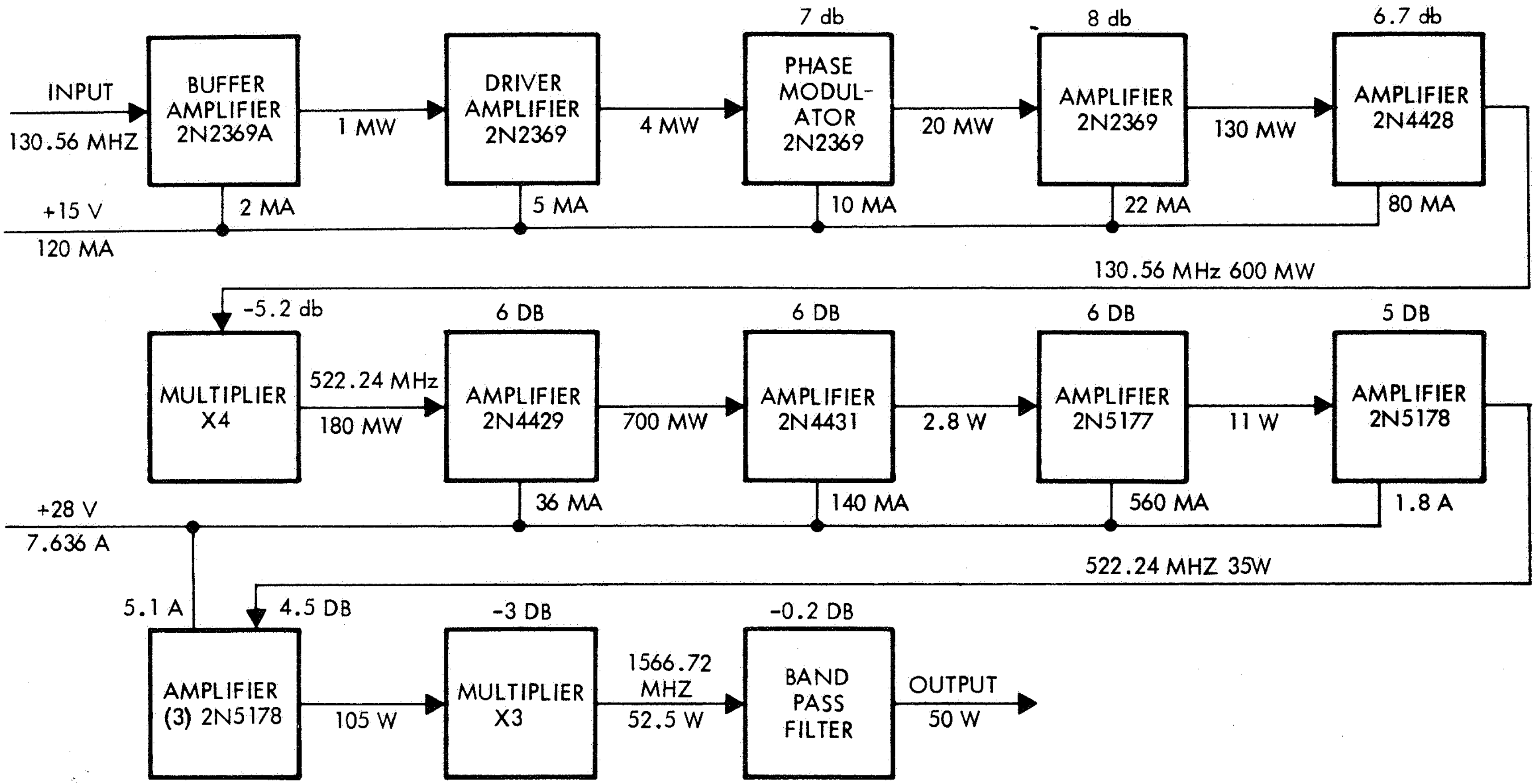
Figure 31 is a block diagram of the transmitter. The 130.36-MHz input signal is amplified and used to drive the phase modulator. After phase modulation, the signal is amplified and multiplied to 522.24 MHz. At 522 MHz, power of 100 w is generated to drive a tripler, which provides 50 w at 1566 MHz. A bandpass filter is indicated to limit any out-of-band energy from the transmitter. Input power, gain or loss, active components, and, in some cases, efficiencies are noted on each block. In the corner of Figure 31 is a breakdown of the input power anticipated and the overall efficiency of 23 percent that can be expected from such a design.

6.6 ANTENNA SUBSYSTEMS

The proposed L-band navigation system antenna consists of a mechanically despun, parabolic, cylindrical reflector illuminated by an array of four collinear dipoles. The resultant linearly polarized wave is converted to a circularly polarized wave by use of a three-sheet printed circuit polarizer in front of the antenna aperture.

The mechanically despun antenna system was selected over an electronically despun antenna system due to its superior electrical performance, lower development costs, and lighter weight. Figure 32 shows the design parameters for this system.

The S-band telemetry and command antenna system operates at frequencies of 1800 and 2200 MHz. A diplexer system is proposed for use with the cavity-backed slot antenna to provide uplink and downlink communications. The antenna, mounted above the collinear dipole array of the navigation system antenna, is fed by the center section of a dual coax system. This slot antenna has a radiation pattern similar to that of



28 V AT 7.6 V = 210 W
15 V AT 0.120A = 1.8 W
DC INPUT = 212 W
RF OUTPUT = 50 W
η OVERALL = 23 PERCENT

Figure 31. 50-Watt Transmitter

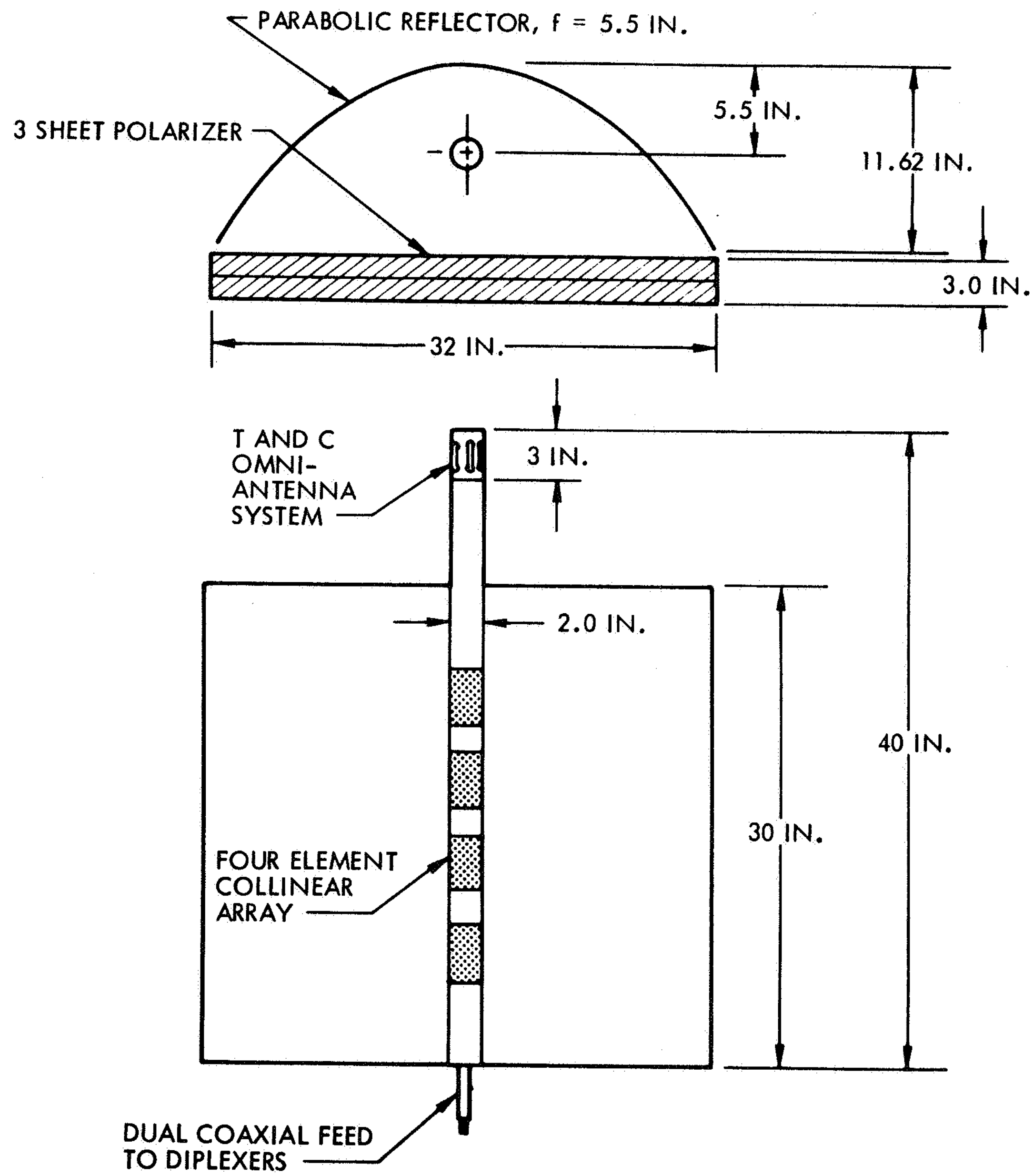


Figure 32. Satellite Antenna

a half-wave dipole antenna. The peak gain of this system is 0 db with respect to a linearly polarized isotropic source.

6.7 ANTENNA DESPUN AND ATTITUDE CONTROL SYSTEM

6.7.1 Antenna Despun System

The mechanically despun antenna control system (MDACS) is designed both to counterrotate an antenna relative to the spin-stabilized satellite so that the antenna is inertially fixed and to point the antenna at the earth. Functionally, the MDACS consists of six subsystems: stepper motor and antenna, encoder, phase-lock loop, digital position circuit, motor damper circuit, and motor starting curcuit.

The stepper motor is a rotary solenoid with 128 equally spaced positions. The motor rotates from one position to the next each time a new pulse is applied to the motor. Thus, the speed of the motor is dictated by the pulse rate applied to the motor. The antenna being part of the motor rotor thus rotates at motor speed.

The encoder provides a measure of the angular position of the antenna relative to a null position or "fiducial mark."

The phase-lock is a digital oscillator that provides the pulse train to drive the motor. The frequency or pulse rate of the oscillator is controlled by an error voltage determined by comparing the phase of the satellite rotation (from an earth-sensor reference pulse) with the phase of the pulse train from the oscillator.

The digital position circuit is used to add or subtract a pulse from the pulse train that is driving the motor.

The motor damper circuit provides rate and position feedback to ensure stable and accurate motor operation. It does this by phase-shifting the pulse train being applied to the motor.

The motor starting circuit provides a train of pulses to the motor. The pulse rate is increased from a low value to the desired rate as the motor is brought up to speed.

6.7.2 Attitude Control Subsystem

The satellite is spun up to about 100 rpm prior to separation. After separation, its orientation can be assessed through the use of onboard sensors (to be described). A reorientation maneuver is then performed so that the satellite attitude is proper for the firing of the apogee motor. The satellite has sufficient angular momentum to maintain the orientation for the worst-case imbalance torques from motor firing. After motor firing, the satellite is placed in the proper attitude both for on-orbit use and initial positioning.

The primary functions of the attitude determination and control subsystem are to provide:

- Sensor information to the ground station so that the satellite's attitude and rotational position can be determined during transfer and final orbits.
- An earth-reference pulse to the antenna for a position reference in pointing the antenna beam toward the center of the earth.
- Electronic power amplification for energizing the propulsion solenoid valves in response to ground commands for positioning and orientation.

A dual, body-mounted, earth sensor and sun sensor system is proposed to fulfill the requirement for ground determination of spin-axis orientation. Two redundant earth horizon sensors and a sun aspect sensor permit satellite attitude and rotational position to be determined on the ground to an accuracy of better than 1° (3σ) with respect to the local vertical and the sun line. This accuracy will be achieved during the transfer orbit and will be exceeded during the final orbit.

The earth sensors are the primary source of spin-axis attitude information. As shown in Figure 33, each earth sensor sweeps across the earth once per satellite revolution and produces a pulse coincident with the instant of crossing the earth's horizon. Under normal conditions, spin axis attitude with respect to the local vertical can be determined accurately and rapidly on the ground by measuring the interval between the leading edge horizon contacts of the two earth-sensor beams. When such times fail to coincide, spin-axis displacement can be computed and then corrected by ground command. In the unlikely case that one of the earth sensors should fail, the same attitude information can be obtained by measuring the interval between leading and trailing horizon pulses from the operating earth sensor.

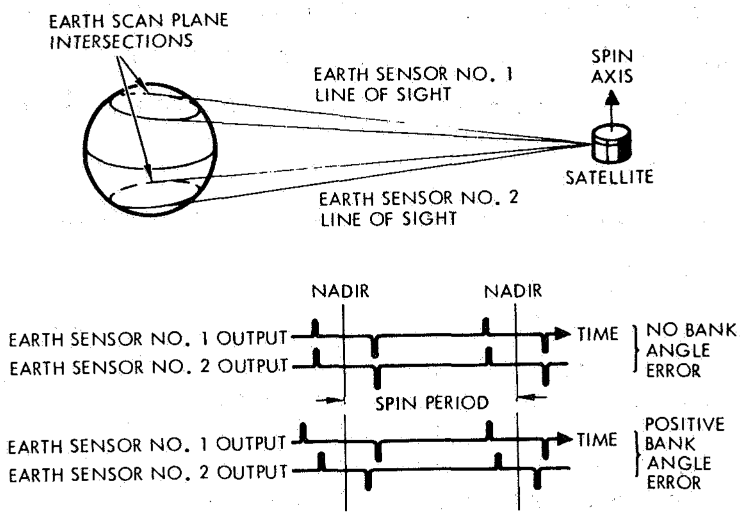


Figure 33. Earth Sensor Operation

Attitude corrections are made by pulsing the axial thruster valve by means of a ground command properly timed to the telemetered earth sensor pulses. Attitude corrections must occur once every 4 months or longer.

6.8 PROPULSION

6.8.1 Apogee Motor

The solid-propellant apogee motor was sized on the basis of the following criteria: a velocity change of 5230 ft/sec at synchronous orbit (apogee), a 10° plane change, and a satellite weight of 516.4 lb.

The motor selected was the BE-3-B1, currently in use for orbit injection of the Vela satellite. This motor has been 100-percent successful in 73 total launches on the Ranger, Sparta, Athena, Amrad, and the advanced Vela spacecraft programs.

6.8.2 Positioning and Orientation Subsystem

The propulsion required for initial spacecraft positioning, stationkeeping, and attitude stabilization is supplied by a hydrozine thruster system.

All maneuvers requiring hydrazine thrusting and the thrust mode are listed in Table XXVIII. The velocities are calculated, using the vehicle weight at the time of firing. The I_{sp} used to calculate required propellant weight was selected for actual conditions of operations, i.e., taking into account I_{sp} as a function of duty cycle requirements which accounts for the efficiency of pulse firing.

6.9 ELECTRICAL POWER

The electric power subsystem converts solar energy into electric power for use by the navigation satellite subsystems. Nickel-cadmium batteries are used to store electrical energy when a surplus is available from the array. During periods when the array is not receiving sunlight, the batteries provide power to the subsystems. The 41.1 ft^2 fixed solar array can deliver 121.6 w when new, and a minimum of 99.8 w after 5 yr. The array has no deploying or moving parts. Nickel-cadmium batteries were chosen both because they have a longer life expectancy than any other type and because they appear to be the only type suitable for the

TABLE XXVIII

VELOCITY REQUIREMENTS

Satellite Maneuver	Velocity ft/sec	Thrust Mode
Spin-axis orientation prior to apogee motor burn (90^{o} +33.16^{o})	12.1	Axial, pulsed
Period correction (3 value)	200	Radial, pulsed
Spin-axis reorientation (64.08^{o} change)	12.4	Axial, pulsed
Longitudinal stationkeeping	30	Radial, pulsed
Attitude corrections	2.0	Axial, pulsed

intended mission. Because of the cycling nature of the navigation transmitter load, the battery must supply power for its operation, both during eclipse and during the sunlit portion of the orbit. Regulation of solar array and battery power within the power system is carried out by a power control unit uniquely suited to the NAVSTAR mission profile. The power subsystem delivers unregulated direct current at between 22 and 29.2 v to the spacecraft subsystems.

The satellite is required to operate continuously for at least 5 yr in a synchronous orbit 26.5° inclined to the plane of the ecliptic. The average power requirements during this period of time are shown in Table XXIX. Near the end of life, the telemetry transmitter is operated infrequently reducing average power to 82 w.

6.10 SATELLITE TELEMETRY AND COMMAND SUBSYSTEM

The main features of the telemetry and command (T and C) subsystem can be characterized as follows:

- Telemetry transmitted to ground stations, which includes housekeeping data, the command status of the satellite, and high-resolution timing information pertaining to satellite attitude.
- Commands at 50 b/sec data rate from a ground station for normal satellite functions, apogee motor and attitude thruster firings, and for resetting of the satellite oscillator frequency.
- Data on satellite ephemeris and oscillator phase corrections sent via the command link for storage on board the satellite.
- Provision for command link security by additional unit and decoder modification.

The T and C subsystem block diagram, shown in Figure 34, consists of a telemetry encoder, telemetry transmitter, diplexer, S-band omnidirectional antenna, command receiver, and command decoder. The omnidirectional antenna provides hemispherical coverage from one end of the satellite.

6.11 SATELLITE TRACKING DATA SUBSYSTEM

An L-band transponder has been added to the satellite to provide for a communication link between ground stations in the NAVSTAR network. This link will be used for relaying satellite tracking information

TABLE XXIX

NAVSTAR AVERAGE POWER REQUIREMENTS

		Watts
Attitude control subsystem		1.70
Control logic assembly	0.29	
Earth Sensor 1	0.70	
Earth Sensor 2	0.70	
Valve driver assembly	0.01	
Navigation subsystem		47.35
Transmitter	28.10	
Data encoder	3.00	
Time base unit	1.00	
Oscillator	1.00	
Tracking data transponder	3.00	
Mechanically despun antenna	11.25	
Telemetry and command subsystem		22.39
2.0-w transmitter	19.3	
Receiver	1.62	
Decoder	0.455	
Encoder	1.015	
Propulsion subsystem		0.25
Electrical integration subsystem		6.20
Electrical integration assembly	5.20	
Cable losses	1.00	
Power subsystem		24.23
Power control unit	1.80	
Shunt elements	0.30	
Converter losses	13.43	
Battery charging	8.70	
Total		102.12

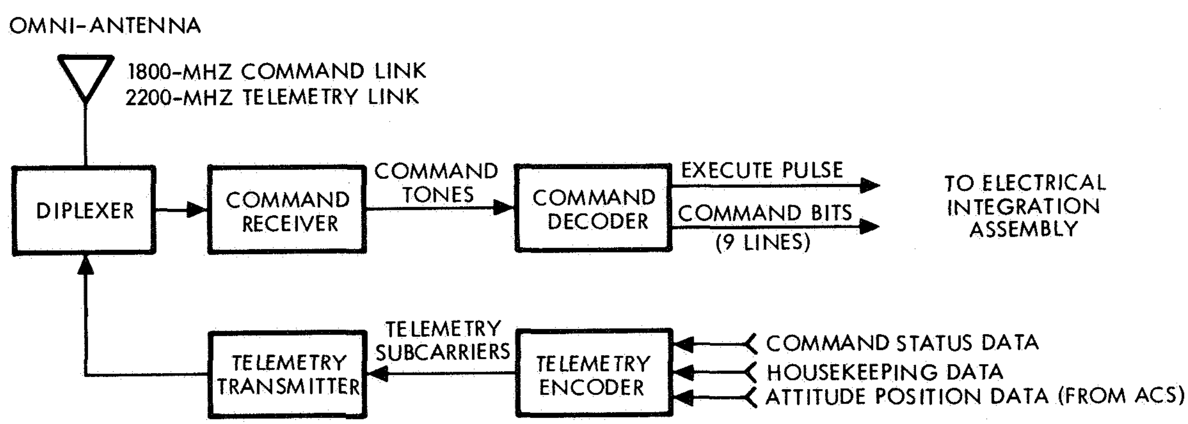


Figure 34. Telemetry and Command Subsystem Block Diagram

from the ground tracking stations to a central station, or stations, where computations of satellite ephemeris and oscillator corrections are made from the received tracking data.*

The data links will be at L-band so that the navigation signal L-band despun antenna can also be used for this service. In addition, the 50-w navigation signal transmitter will also be used. The transmitter will be time-shared with the navigation signal by utilizing it between navigation signal broadcasts. The power subsystem capability of the satellite indicates that the transmitter can be on 2.9 sec between navigation signal broadcasts at the beginning of satellite life. The data rate capability is 400 b/sec/satellite so that 440 b/satellite/broadcast frame is possible at the beginning of life. Since there are eight satellites in a frame, generally in varying stages of life, the data rate is more than adequate.

The list below covers a tentative set of carrier frequency assign- e ments:

1660 MHz: Uplink tracking data carrier

1551 MHz: Downlink tracking data carrier

1567 MHz: Downlink navigation signal carrier

The ground stations can employ the same L-band antennas used for receiving the navigation signal range (difference) data from the satellites. These antennas have been designed to provide 12-db gain (see vol IV, subsec. 4-1). The transmitting stations will require a 1-kw transmitter. The receiving station or stations will require a 5-db noise figure receiver and a noncoherent FSK demodulator.

6.12 THERMAL CONTROL

Thermal control of the satellite and its equipment is accomplished by passive techniques. The system requires that an energy balance be made between the external heat sources, external radiant emission, and

*Ground-station tracking data consist of the range (difference) measurements made from the L-band navigation signal transmitted to the network users.

the internally generated heat at a temperature level within the temperature limits of the components. In sunlit operation, a radiative heat balance is established; in eclipse, the thermal inertia of the individual components serves to maintain the desired temperatures within the satellite.

The thermal control subsystem is required to provide a desired thermal environment for the satellite and its components during five post-launch conditions: ascent, transfer ellipse coast, orbit injection, orbital operation in eclipse, and orbital operation in sunlight.

Table XXX presents the predicted maximum and minimum temperatures for the NAVSTAR components.

6.13 SATELLITE RELIABILITY

The question of orbiting as a function of spacecraft subsystem redundancy has been approached as follows. If a user knows his altitude, he needs to view three noncoplanar satellites in order to determine his posi tion. Thus, the approach to the design of the constellation has been to provide four satellites visible at all times in the region of interest in case any satellite fails and causes a slight degradation in accuracy, but still permits the use of the navigation satellite system. The mean time-to-failure (MTTF) is sufficiently long that it is relatively straightforward to schedule a replacement for the failed satellite.

Given a ground rule of at least one redundant satellite, it remains to then design each satellite such that the overall MTTF is as large as possible consistent with launch physical constraints. This section presents the results of such a study.

The numerical reliability estimate for the NAVSTAR is 0.455 for a 5-yr orbital mission including launch boost and deployment. This corresponds to a MTTF of 61.57. Table XXXI lists the equipment reliabilities per phase for the 3 mission phases for the 10 NAVSTAR subsystems.

TABLE XXX

MAXIMUM AND MINIMUM TEMPERATURES PREDICTED FOR NAVSTAR COMPONENTS

Component	Maximum Temperature (°F)	Minimum Temperature (°F)
Navigation Signal		
Oscillator	93	54
Time base unit	100	36
Data encoder	100	36
Transmitter	152	55
Tracking Data		
Diplexer	70	45
Transponding receiver	70	37
Telemetry and Command		
Telemetry encoder	127	36
Command decoder	127	49
Receiver	70	49
Transmitter	152	60
Diplexer	110	63
Attitude Stabilization		
Control logic	80	17
Valve driver	79	24
Earth-sun sensor package	104	62
Electrical Integration		
Electrical Integration Assembly	113	33
Electrical Power		
Solar array	212	-130
Battery	90	50
Power control unit	94	27
Converter	94	61
Shunt assembly	150	4
Positioning and Orientation		
Thrusters (axial)	120	60
Thrusters (radial)	105	48
Tanks	75	49
Structure		
Central cylinder	300	-31
Equipment platform	122	-10
End cover — top	300	-175
End cover — bottom	950	-175
Thermal Control		
Insulation	68	14
Apogee Motor		
Case	363	35
Nozzle	600	29
Propellant	60	42
Save and arm device	62	33

The reliability values listed in Table XXXI were developed by employing the following conditional probability functions:

$$R_{(deployment)} = \frac{R_{(deployment\ plus\ launch/boost)}}{R_{(launch/boost)}}$$

$$R_{(orbit)} = \frac{R_{(deployment\ plus\ launch/boost\ plus\ orbit)}}{R_{(deployment\ plus\ launch/boost)}}$$

TABLE XXXI

SUBSYSTEM RELIABILITY PER MISSION PHASE

Subsystem	Mission Phases		
	Launch/ Boost	Deploy-ment	5-Yr Orbit
1) Structures	0.9^3488	0.9^3878	0.9^536
2) Thermal control	0.9^8550	0.9^8400	0.9^7105
3) Apogee motor and safe/arm	0.9984	0.9938	0.9922
4) Position and orientation	0.9^5545	0.9^3846	0.9860
5) Attitude determination and control	0.9^3886	0.9^3849	0.9737
6) Antenna despin assembly	0.9^475	0.9^462	0.9437
7) Electrical power	0.9^4860	0.9^482	0.9940
8) Navigation signal	0.9^580	0.9^510	0.8573
9) Telemetry and command	0.9^50	0.9^454	0.7049
10) Electrical distribution	0.9^3677	0.9^3565	0.8436
Total	0.99740	0.9928	0.4592

7. GROUND STATION NETWORK

This section covers the preliminary study of the requirements for a ground system to support a navigation satellite system. Included for consideration are:

- Tracking station — receives the satellite transmitted ranging signal and determines range to visible satellites.
- Telemetry receiving and command site — monitors satellite telemetry and transmits commands and updates to the satellites.
- Master computation center — receives data from the tracking sites, and computes orbital data for transmission to the satellites by the command stations.

Locations for the various stations are suggested and functional descriptions are provided here. Further details are given in vol. IV.

A proposed network of supporting ground stations is shown in Figure 35. The interim Atlantic tracking network is indicated by the lozenge symbols. The distribution of tracking sites permits advantageous tracking geometry. As discussed in vol. II, it is likely that the total number of stations can be reduced.

Figure 36 shows the ground-station system layout in its most general form and represents the functions of a composite station. However, all of the station systems would not be necessarily at every ground station. For example, telemetry and command facilities will be restricted to one station for the Atlantic network. The other stations would provide tracking support for the NAVSTAR system, with communication equipment as required to transmit received tracking data to a computing site. The computing site can be situated at any convenient location. Widespread geometry of ground-station coverage is required only for the purpose of accurate tracking support.

Additional ground-station functions such as aircraft advisory, air traffic control, etc., which may influence the location of and equipment in a ground station are not considered here.

Figure 35. Worldwide Ground Station Network

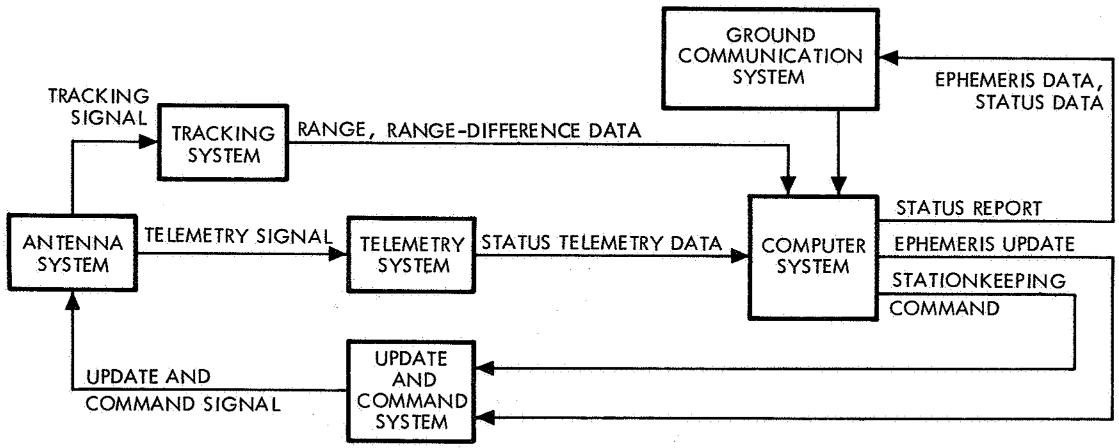


Figure 36. NAVSTAR Ground Station Functional Block Diagram

7.1 TRACKING STATIONS

In the overall ground-station design a number of relatively simple tracking stations are provided which use the L-band satellite signal, transmitting their received data to a regional central computer site. A small number of telemetry receiving sites will maintain data on the satellite status.

The L-band tracking station is basically a somewhat sophisticated and redundant set of user equipment (navigation) which operates in the periodically maintained, but unattended, mode. A different antenna (see Figure 37) is used to take advantage of better gain characteristics.

Tracking stations will be distributed so as to receive tracking data (using the L-band ranging system from the satellites) at enough stations to provide adequate ephemeris determination. Local station clocks will provide time references (these clocks can be equivalent to those of the satellite, but better clocks at added expense would allow the system to consider clock errors as occurring principally in the satellites). Satellite data transmission occurs at a rate of one per 1.5 sec with each satellite transmitting a signal in succession until all satellites in an area (perhaps worldwide) have transmitted; transmission overlap is not allowed. The worldwide example selected is a system of eight satellites at synchronous altitudes in each of two orbits at 18-1/2° inclination. In

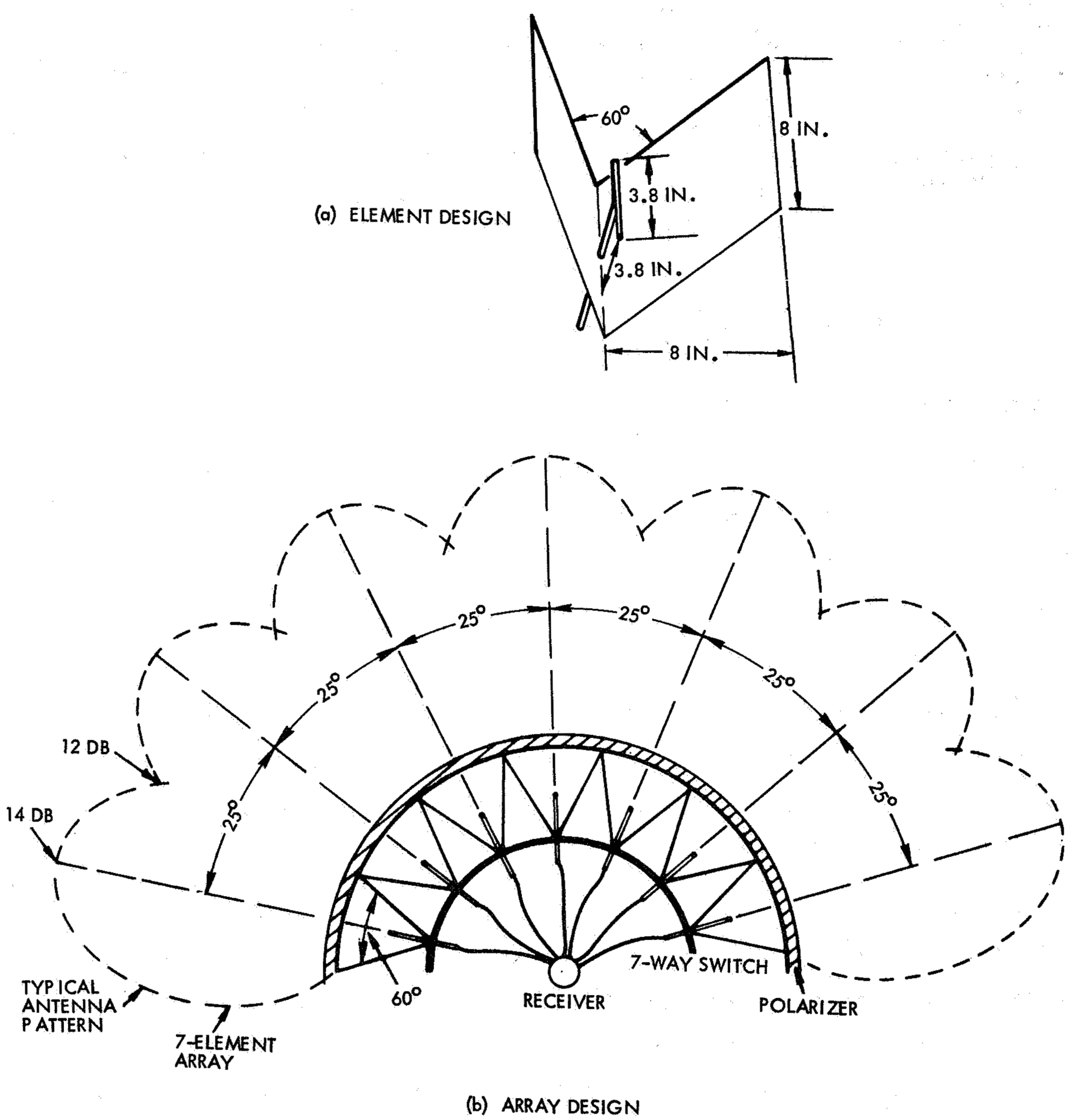


Figure 37. Ground Station Antenna

this configuration, a regional group of satellites would be eight in number. Therefore, 12 sec would be required to complete a regional cycle. Values of range or range difference at each ground station would be transmitted to a central computer site for processing.

7.2 TELEMETRY AND COMMAND STATIONS

The telemetry and command stations are more complex and it is suggested that existing station facilities such as STADAN be used.

Figure 38 shows the command and telemetry equipment in simple block diagram form. The data received in the telemetry would include satellite power levels and environmental data needed to detect failures. It is likely that a worldwide NAVSTAR system, with 16 or more satellites in orbit at one time, would be designed to minimize telemetry requirements following a test phase sufficient to determine system MTBF. Since the primary purpose of the system is navigation-data transmission, the minimum acceptable telemetry requirements should be examined in detail to make cost-effectiveness conclusions on the telemetry system. In addition to the normal telemetry represented by PAM data, satellite attitude position data are received by the telemetry channel. These data are fed to the computer for determinations of satellite attitude.

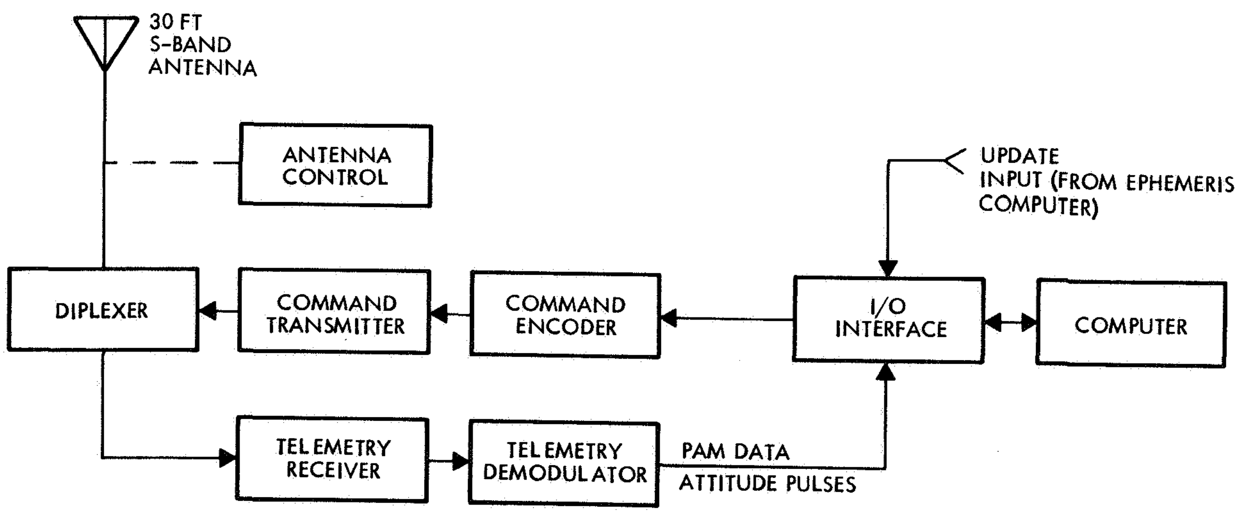


Figure 38. NAVSTAR Command and Telemetry Ground Station Block Diagram

The command system is used to update the values of ephemeris and oscillator bias stored on-board each satellite for retransmission to the NAVSTAR users and to transmit thruster firing pulses for repositioning the satellite attitude as determined by the attitude telemetry data. In addition, various system commands will be transmitted to control the state of satellite equipment, including oscillator frequency reset.

The computer is used to generate the necessary commands, including time and duration of attitude thruster firings and to monitor and display telemetry status. This computer may or may not be part of the ephemeris udpate computer depending on the location of the two functions. If two separate computers are used, ephemeris update information must be provided to the telemetry and command computer to generate the update commands.

7.3 COMPUTATION CENTER

Three general functions are required of ground-station computers:

1) Satellite ephemeris (and clock bias) calculation

2) Maintenance of station operation in the areas of encoding, antenna switching, telemetry supervision, etc.

3) Determination of satellite attitudes.

The first function will be associated with a large master computer serving a large area presumably occupied by multiple ground stations, which will transmit data on satellite measurements to the central station. The computer at the central station would be required to compute the ephemerides of a number of satellites on a continual basis.

The second function is more properly associated with the operation of the individual stations, such as controlling the operation of antenna, transmitting, and operating command and receiving equipment. This function may be that of a smaller computer at each station, with the larger master system devoted primarily to ephemeris determination to computing tasks concerned with system-wide operations. The sizing of computers is consistent with this possible division of tasks, with the ephemeris calculations for multiple satellites and the subsidiary tasks separately sized.

The third function may be performed by either the master computer or by computers located at the telemetry and command stations. In either case, the computer must determine satellite attitude from received telemetry and generate, if necessary, commands for satellite reorientation.

The ephemeris calculation task for as many as 16 synchronous satellites with updates of clock error values at frequent intervals will be a major computation task.

Computer requirements may be estimated by comparison with existing orbit determination programs, such as ESPOD, a large TRW orbit determination program. Processing of the data could be handled with one program sequentially by satellites if the computation cycle time were fast enough to meet data input flow for n satellites. Given a 10- to 15-min update requirement (for clock bias), it is probable that a single program similar in size to ESPOD could sequentially process data satellite by satellite — equivalent to a 2-min computation cycle time per satellite for a regional system of eight satellites. This program uses about 200,000 bytes (8-bit units) in core, which, in a 32-bit word machine, occupies a 50,000-word core storage block. A system such as the IBM 360-50 computer accommodates this program. However, the program does not totally fit the core since links are used, which move into core sequentially for different processes in the computation. Extensive multiprogramming of such a system would be difficult in a 50-K core because of the complicated transfers into and out of core of the program links. Multiprogramming to handle multiple satellites simultaneously would, for reasonable efficiency, require the entire orbit determination program to exist in core at one time. Required capacity for an ESPOD class program is about 100,000 words. To this would be added blocks to accommodate data storage for each satellite.

Current 64-K (core) machines, such as the IBM 360-50, could handle an orbit determination program if satellites were processed sequentially. Simultaneous processing will require upwards of 100-K core storage plus data storage for each satellite. Large, third-generation machines such as the GE system (128 K) might accommodate a multi-programmed system for simultaneous data reduction, although further study will be required. Such a technique would be required for a recursive computation in an efficient fashion.

A lower-level computer will be required at the master site to sort data, edit, and preprocess for the large machine. The IBM 1800 is a representative system. This machine is also a candidate for a telemetry/ command site computer, as it is designed for data acquisition and control systems. It is available with 4 K, 8 K, 16 K or 32 K storage.

Figure 39 shows general data processing flow at the master computing site.

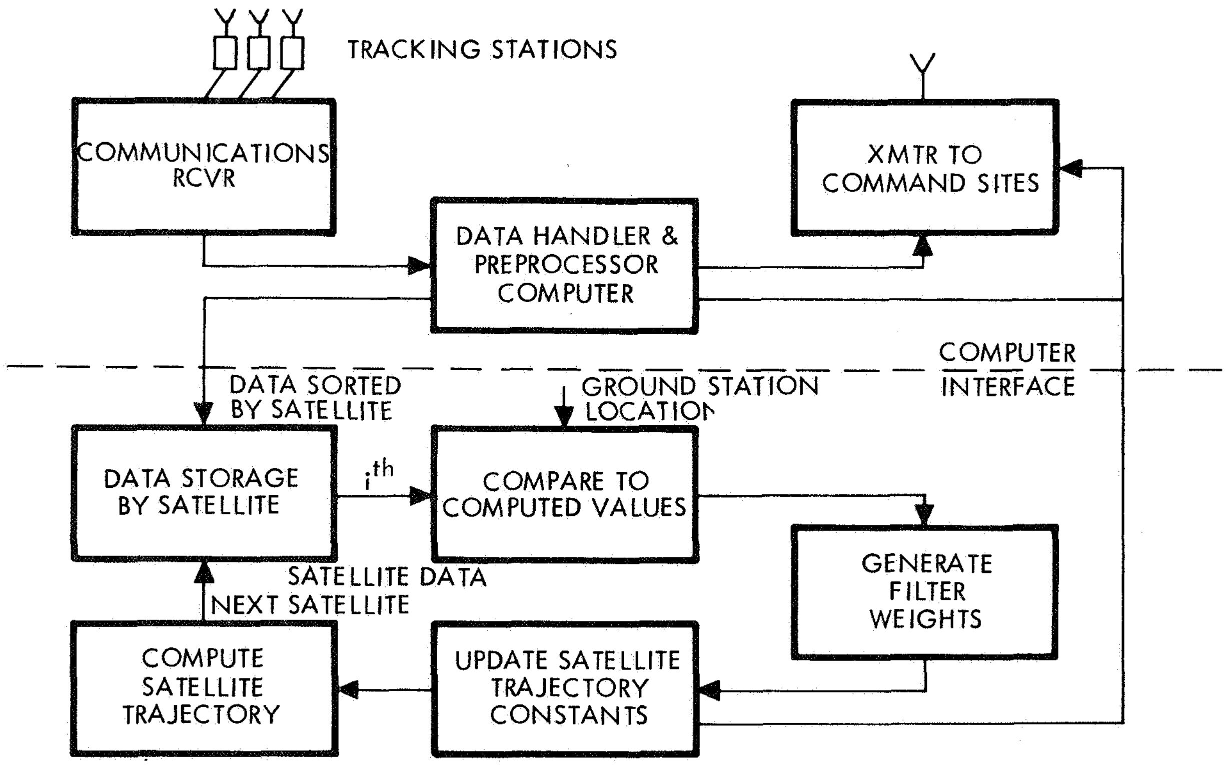


Figure 39. Computer Center Data Flow

8. TRAFFIC CONTROL

8.1 INTRODUCTION

This section examines briefly and describes the data rates and capability of the NAVSTAR system for traffic control purposes. In this discussion, the use of automatic position reporting for traffic control purposes is postulated, and the potential applications of a relative navigation capability to air terminal operations, air/sea rescue, and enroute terminal proximity detection in qualitative terms are shown.

8.2 TRAFFIC CONTROL

The role of any air traffic control (ATC) system is to provide safe and efficient use of the air space. Constraints placed on the movement of aircraft tend to lower efficiency and discourage use of the air space. Thus, as the volume of traffic and the range of aircraft speeds increase, the efficiency of the air traffic control system itself must be improved. One improvement must be to decrease the required time and distance separation of air traffic. The excellent accuracy characteristics of the TRW NAVSTAR technique contribute greatly toward a goal of reduced separation criteria. Another improvement is to increase the capacity and efficiency of communications. The NAVSTAR approach also appears to lend itself to high-speed digital data transfer and automatic data processing since the data, raw or computed position, will for the most part already be in digital form.

8.2.1 Position Determination

Several approaches to position determination using ATC were considered. These are:

- Method 1 - Verbal position reports
- Method 2 - Automatic position reports
- Method 3 - Automatic data reports
- Method 4 - Ground sensors (radar, radio DF).

The ATC method used to determine the position of aircraft should be essentially independent of the pilot or navigator for several reasons. First, the ground operator simply has a higher confidence in his own data as opposed to what he is told by someone in an aircraft. Occasionally, flight crews make mistakes which give the ground controller an erroneous picture of the present situation. But, more important, such a report introduces an error into the system that propagates and increases in magnitude with time, since the ground controller makes his projection by simple extrapolation. Second, the controller does not have to ask for the information because it is at his fingertips. Third, communications problems often introduce significant lags into the position reporting function. It should be noted that a completely redundant system not only provides a higher confidence in position determination results, but it also increases overall reliability in that a navigation capability is still available in case of the loss of any single element in the system.

Method 2 does not strictly meet the often-stated criterion of an "independent of airborne navigation" process as does Method 4, but it does offer two significant advantages over Method 1. First, if the navigation computations that go into automatic position reports are also automatic, then the human error element of the air crew is minimized. Second, automatic data link reporting will eliminate the sizable and frequent delay on position reporting that introduces a great deal of uncertainty into the system today. Method 3 is functionally the same as Method 2, differing from it only in that the computations are performed by an ATC ground-based computer rather than on board the aircraft. In the remainder of subsec. 8.2, the implications of using a combination of Methods 2 and 3 as part of the ATC process are examined. This combination of automatic position reporting and automatic data reporting will be referred to as AUTOREP.

8.2.2 Automatic Reporting (AUTOREP) for ATC Surveillance

8.2.2.1 Scenario

The examination of a traffic control problem involving a heavy load of aircraft which all carry NAVSTAR equipment can lead to an estimate of the communication requirements. A typical peak traffic load in the New York area* today involves approximately 175 aircraft on instrument

*The New York area is considered as an extreme example. Later analyses will be oriented towards the North Atlantic problem.

flight rules (IFR) and approximately 200 to 300 aircraft on visual flight rules (VFR), all operating within 50 nmi of the John F. Kennedy Airport. For the purpose of this problem, a much larger population will be assumed: 400 IFR and 600 VFR aircraft.* In order to examine a case which bounds the communication requirements, all aircraft in the area are assumed to be NAVSTAR AUTOREP equipped. Each aircraft transmits either a position report or raw NAVSTAR data from which position can be determined automatically and frequently. It is also assumed that 150 of the 1,000 aircraft are airliners, business, or military aircraft, each carrying an airborne computer, and that the rest are general aviation aircraft with no airborne computer. In this example, the computer-equipped aircraft will transmit position reports and the others will transmit raw data. The aircraft could report in some predetermined sequence, as is contemplated for some of the time-frequency collision-avoidance system schemes. However, it seems more efficient in this case to use an interrogating/transponding technique and direct communication between aircraft and ground facilities (either line-of-sight or through a satellite) whenever possible. This will provide greater system efficiency in terms of more frequent position reporting since empty time slots would not be wasted.

8.2.2.2 Abbreviated Position Reports

A typical complete aviation position report actually contains much more information than only position as shown in the following listing:

a) Identification

b) Position

c) Time

d) Flight level

e) Flight condition

*Aircraft on the ground, in an airfield VFR traffic pattern, or in ground controlled approach (GCA) traffic are not included. This does not mean such aircraft do not require protection. It simply means that the communication aspect of that portion of the total aircraft population is not included in the model.

f) Next position

g) Estimated time of arrival

h) Endurance

i) Temperature

j) Present weather

k) Wind and position

l) D-value (relates pressure to absolute altitude)

m) Cloud cover

n) Icing

o) Turbulence

p) Remarks

For an automatic position reporting task, however, most of the information is superfluous. The elements of an abbreviated position report are shown in Table XXXII. Those fully equipped aircraft (e. g., military and commercial carriers and business aircraft, all of which are assumed to have full navigation systems, including a computer) would make such a report. With an interrogating/transponding system, the identification is actually transmitted by the ground station to the aircraft so that the process will be made by a roll call, which is the aircraft identification of approximately 20 bits (ground-to-air), and a report of position and altitude to a resolution of 10 ft, which requires approximately 80 bits (air-to-ground). This resolution is probably better than will be required, but is used to bound the communications problem.

The general aviation aircraft would make an automatic data report as indicated in Table XXXIII*. The position determination data which must be telemetered to the ground include satellite identification, time to the

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*While it should be noted that the funding to furnish general aviation with such equipment would not be easy to obtain, cost effectiveness was not the issue here. The objective is to show that even if all military, commercial, and general aviation aircraft use NAVSTAR in a navigation/traffic control role in a highly densely populated area, the associated communication requirements are still not unreasonable.

TABLE XXXII

AUTOMATIC POSITION REPORT

	Decimal Digits	Binary Bits
Identification	6 to 7	20
Position		
Latitude	8	27
Longitude	8	27
Altitude	4	14
		88 ≅ 100 bits
Note: The figures represent an upper bound.		

TABLE XXXIII

AUTOMATIC DATA REPORT

	Decimal Digits	Binary Bits
Identification	6	20
Position		
Satellite ID	1	4
Time	7	22
Data	6 per satellite	20/sat x 8 = 160
Altitude	4	14
		220 bits
Note: The figures represent an upper bound for a seven-satellite fix.		

nearest msec, and the ranging signal, which is a digitally encoded phase difference between the received signal and an oscillator on board the aircraft. This technique is discussed in subsec. 4.3, of vol. III, User Equipment Studies.

With an interrogating/transponding system, the identification is actually transmitted by the ground as the interrogation address. After obtaining the appropriate position determination data, the traffic control facility would then perform the necessary computations to determine the position of each aircraft and would, for traffic control purposes, project their future positions. The accuracy of the projection is essentially limited by the degree to which each aircraft remains on a given flight path. The factors which degrade this accuracy today, i.e., errors* in navigation by the crew, similar errors in calculations by traffic control operators on the ground, delays in reporting, etc., will be substantially reduced by automatic reporting and data processing.

8.2.2.3 Bandwidth Requirements

In the example for the case where there are 150 large and 850 small aircraft, the large aircraft transmit automatic position reports every 5 sec and the small aircraft transmit automatic data reports approximately every 1 min. This will occupy the equivalent of two voice channels as indicated:

$$\frac{100 \text{ bits} \times 150 \text{ aircraft}}{5 \text{ sec}} \cong 3000 \text{ bits/sec} \cong 1 \text{ voice channel}$$

$$\frac{220 \text{ bits} \times 850 \text{ aircraft}}{60 \text{ sec}} \cong 3100 \text{ bits/sec} \cong 1 \text{ voice channel}$$

It would obviously take an additional voice channel for the ground station to give immediate data or periodic voice feedback of position data to each of the general aviation aircraft. Obviously, if, for operational reasons, the position determination on each general aviation aircraft is made at more closely spaced intervals, more bandwidth is required. Furthermore, the computation rates of even a state-of-the-art computer can eventually constrain the number of position determination and associated traffic control computations, and could, therefore, limit the size of the aircraft population. This is discussed in par. 8.2.2.4.

*Errors are not intended to mean mistakes. The latter usually result in obviously incorrect results. "Errors" pertain to roundoff and truncation errors which are unavoidable when position and velocity are determined using relatively crude hand calculators and when position reporting time is rounded off and so reported by the pilot.

8.2.2.4 Computation Requirements

Approximately 20 msec is required for a state-of-the-art ground computer to perform the position determination job for each small aircraft using the software approach discussed in vol. II, "System Analysis." This time could be reduced to 10 to 12 msec for a projected state-of-the-art computer.

Since there are nominally 8 satellites visible, each transmitting for 2 sec, a 16-sec cycle time results for the bounding case of 8 satellites. Thus, to complete each position determination calculation prior to beginning the next cycle of data, 100 aircraft can be accommodated on the position determination computer. Projecting computer state-of-the-art, 200 aircraft could be served. One way to increase user capacity still further would be to sample each aircraft less frequently. For example, if every fourth cycle is sampled, 400 to 800 aircraft could be accommodated by a single position determination computer. Finally, more than one position determination computer can be used in parallel so that conceptually, at least, computation need not be a system constraint. In the example considered here, it appears that a second projected state-of-the-art position determination computer would be required in order to avoid saturation.

The hardware mechanization for data transmission from general aviation aircraft involves trading airborne hardware complexity vs frequency spectrum bandwidth. Specifically, the aircraft can either store the raw ranging data from each satellite and telemeter it on command, or it can immediately relay this information to the ground. The former method requires relatively expensive hardware; the latter method poses severe multiple-access and/or bandwidth problems on the system, since several hundred aircraft could be relaying such information from a given satellite to the ATC ground station at virtually the same instant.

8.2.3 Integration of NAVSTAR AUTOREP into the Air Traffic Environment

The Ad Hoc Joint Navigation Satellite Committee in their final report (Ref. 3) indicated an urgent requirement for better long-distance ground-air-ground communications. There is a need for a surveillance capability to provide air traffic controllers with relative positions of all aircraft under control, independently of aircraft-derived positions, and for improved track-keeping capability for the aircraft. These items are discussed below.

8.2.3.1 Track Keeping

Improved track-keeping capability through high-accuracy navigation is an obvious advantage inherent in the NAVSTAR technique. But taking advantage of this accuracy is not as simple as it might first appear. Navigation accuracy will vary as a function of time (or more explicitly as a function of computation iteration) as indicated in Figure 40. For the airline case, the navigation computer will iterate rapidly, bringing the probable error down to the steady-state value in a fraction of a second; but for the general aviation case, the iterations could be as much as a minute apart. If the aircraft is altering its course, the accuracy of the position determination computation may never get down to a steady-state value. The impact of this factor on the required separation distance would clearly depend on the relative magnitudes of C_1 and C_f of Figure 40.

Predicted position errors must be more definitely related to a traffic control criterion, although the errors in positions experienced by aircraft are not gaussian. Blunders have been extremely difficult to account for analytically. Thus, if one navigation technique will yield a CEP of, say, half that of an existing technique, it is not clear as to what amount that the separation criteria could be lowered without further study and information.

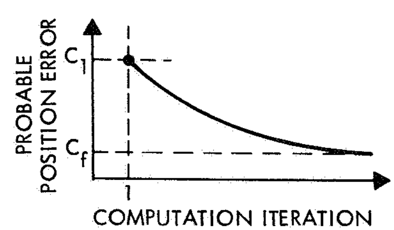

Figure 40. Iteration as a Function of Probable Error

Finally, a mixture of VFR and IFR traffic causes an operational problem. The collision threshold vs VFR-allowed passing clearances must be considered. For example, it may be perfectly safe for aircraft under visual conditions to pass within 600 ft of one another, and yet the navigation traffic control satellite system may require several thousand feet to account for system errors and reaction time.

Further analyses are needed before the high accuracies available can be fully reflected in the traffic control system in terms of reduced separation criteria.

8.2.3.2 Surveillance

The automatic position reporting system which was discussed previously is clearly aimed at surveillance problems. The surveillance tool provided to ATC could bring about automatic data processing throughout the system, which is anticipated in the near future. The formidable problem of displaying great quantities of three-dimensional, time-varying data is beyond the scope of this study, but obviously must be considered in a complete system integration.

8.2.3.3 Communications

It is also clear that for the postulated problem with some 1,000 aircraft under ATC surveillance in an area such as New York, there could be a severe short-distance communication problem, i.e., that of saturating the available communication channels. AUTOREP will significantly reduce the load on voice channels. However, in addition to the automatic position reports, there will be a large number of other inflight transmissions. Various types of such transmissions are shown in Table XXXIV.

The Radio Technical Commission for Aeronautics (Ref. 4) indicates that a number of these messages are suitable for conversion to digital form. Ref. 4 also indicates that each aircraft transmits or receives on a voice channel approximately 1.5 percent of the time. As a result, the controller and the voice channels are busy approximately 40 percent of the time, peaking out at 90 percent. Heavy loads such as

TABLE XXXIV

TYPICAL INFLIGHT COMMUNICATION TRANSMISSIONS

a)	Initiation of contact
b)	Identification (including IFF transponder changes)
c)	Position reports
d)	Clearances
e)	Emergencies
f)	Requests for information
g)	Advisories (air-to-ground or ground-to-air)
h)	Acknowledgments
i)	Miscellaneous

these lead to the delays in position reporting referred to earlier. Such overloads also inhibit useful exchanges of information, e.g., advisories on weather, clear air turbulence, other airborne traffic, etc. Thus, the motivation for replacing much of the voice communication with data is a very strong one. When automatic position reporting is added to the traffic listed in Table XXXIV (reducing but not eliminating the requirement for long or full position reports), the motivation becomes stronger still.

The airborne and ground hardware which will be introduced with the conversion to data transmission will require a large investment and will very likely evolve at first through augmentation rather than by replacement of existing hardware. Clearly, the data transmission system must be reliably demonstrated before airline, military, and general aviation users will be willing to see the available voice channels reduced.

Finally, the requirement for voice communications between aircraft air crews and controllers on the ground will doubtless continue for a long time. Emergency and other unforeseen high-priority transmissions are generally unusual in nature, requiring two-way communications which do not lend themselves to formatting or "canning."

8.3 AIR TERMINAL OPERATIONS

The high-accuracy NAVSTAR technique appears promising both as a navigation aid and as a traffic control device in air terminal operations. As a navigation aid, it would be appropriate for use in the letdown or penetration phase (say down to 1000 to 2000 ft above the terrain) and would probably be adequate as a low-approach device, but it would not be adequate for all-weather instrument landings. An accuracy of about 200 ft (2σ) wouldkeep an aircraft well within air field boundaries, thereby qualifying as a good letdown aide. The same accuracy would probably be adequate for the final approach phase although existing GCA and instrument letdown systems are already more accurate than this. Since runways at major airports are seldom more than 300 ft wide, this accuracy would bring the aircraft across the runway threshold less than 90 percent of the time. It would clearly not provide an all-weather final approach and landing capability when used strictly as an aircraft navigation aid. NAVSTAR might do very well when used in conjunction with GCA where operators could calibrate the system on successive aircraft runs. Analyses to date are not conclusive, but it appears likely that such a system could be made competitive for air terminal operations if it were already in existence for the aforementioned navigation and traffic control missions.

8.4 AIR/SEA RESCUE

This discussion relates to the Coast Guard requirements stated in Ref. 3, which appear to be representative of any search and rescue user. Four general guidelines, or factors, which influence the development of a navigation-satellite-aided search and rescue system are extracted from Appendix D of Ref. 3:

a) The Coast Guard is bound in most areas of its responsibilities to use the same navigation and communication facilities carried and employed by the activities that the Coast Guard serves.

b) Additionally, Coast Guard aircraft for navigation and for communications are required to carry the instrumentation prescribed by the national and international aeronautical organizations.

c) The field of search and rescue is unique in that it presents requirements for 2° of accuracy. The required absolute accuracy of navigation is specified. Once the search has commenced, however, absolute accuracy is not a consideration. Relative accuracy (i.e., the relative positions of the search units or the position of a search unit with respect to its previous search track) becomes the paramount consideration.

d) The Coast Guard will expend necessary funds to provide its units with navigation and communication equipment of the highest quality compatible with those systems in common use.

The first point clearly indicates that a search and rescue craft must be able to converse with a craft in distress and find that distressed craft when given information in terms of the latter's navigation system. The Navigation/Traffic Control system may or may not prove helpful in this case.

The second point is clearly appropriate for a user such as the Coast Guard. It also immediately relates the Coast Guard craft with all other national and international aeronautical organizations in precisely the way indicated in Item (a). Presumably, navigation and communication satellite equipment will apply here.

Item (c) is very important to this discussion since NAVSTAR will provide very-high-accuracy navigation capabilities as indicated in the foregoing paragraph and reflected in Table XXXV. It should be noted that the proposed system meets all requirements other than those for communication. Further, the required communication channels can easily be added to the proposed design (see subsec. 4.2 of vol. IV).

A worldwide Coast Guard search and rescue capability represents a smaller aircraft population than the New York ATC problem worked previously, and if a sophisticated system like the automatic position reporting system described there were provided, the total costs seem reasonable compared with the services offered. Furthermore, the use of worldwide communication satellites opens up the possibility of a worldwide search and rescue force which could make use of a Central

TABLE XXXV

AIR/SEA RESCUE REQUIREMENTS VS NAVSTAR CAPABILITIES

Air/Sea Rescue	NAVSTAR Capabilities
1) GENERAL	
a) The systems of navigation and communication must be in common use by the marine and air interests of the United States and other nations.	It will certainly be available and cost-effective, and hence its general use can be predicted.
b) The system must be capable of evolutionary implementation and expansion.	It will be.
c) Facilities and services must be available 24 hr/day.	They will be.
d) Navigational system must be available to all users simultaneously.	It will be.
2) SPECIFIC	
a) Navigation: It is desirable that the system indicates present position on a chart automatically and provide additional readout of course, ground speed, distance to go, angle and distance to track for both air and marine use.	The user hardware can be so designed.
b) Communication: The system should	
• Provide communications for operational control from base and on-scene.	Can be provided.
• Provide communications for interchange of position and weather information over both long and short distances.	Can be provided.
3) DETAILED REQUIREMENTS	
a) Search and Rescue:	
• Navigation: 1975 Absolute: One mi at 10-min intervals world-wide;	More than adequate

TABLE XXXV (Continued)

Air/Sea Rescue			NAVSTAR Capabilities
		Relative: 1,000 ft continuous within areas of primary Coast Guard responsibility; 1,000 yd, world-wide	More than adequate
	• Communications:	3-voice channels, world-wide, less polar regions.	Can be provided.
b)	Ocean stations.		
	• Navigation:	1965: 2 mi at 1-hr intervals - North Atlantic and North Pacific;	More than adequate.
		1975: 1 mi at 1-hr intervals - world-wide, less polar regions.	
	• Communications:	6-voice channels, world-wide, less polar regions.	Can be easily provided to this system.
c)	Ice Patrol		
	• Navigation:	North Atlantic (aircraft)	
		1965: 2 mi at 15-min intervals;	More than adequate.
		1975: 1/2 mi at 10-min intervals.	
	• Communications:	Vessels - 1-channel, North Atlantic;	Easily provided.
		Aircraft - per international aeronautical standards.	
d)	Oceanography:	Navigation and communication as agreed nationally and internationally.	

TABLE XXXV (Continued)

Air/Sea Rescue	NAVSTAR Capabilities
e) Aids to Navigation	
• Navigation: 50 yd or better within waters of U. S., its territories, and its possessions.	~100 ft (1σ)
• Communications: No operational requirement.	
f) Ice Breaking	
• Navigation: Polar and subpolar regions; 1965: 2 mi at 1-hr intervals; 1975: 2 mi at 1-hr intervals.	More than adequate.
• Communications: 6 channels, world-wide.	Can be provided.
g) Pleasure Boating (from Search and Rescue Viewpoint)	
• Navigation: World-wide, less polar region; 1965: 1 mi at 1-hr intervals; 1975: 1 mi at 1-hr intervals.	More than adequate.
• Communications: 3 channels, world-wide, less polar regions.	Can be provided.

Operations room or Command Center similar to the Manned Spacecraft Center at Houston or the Air Force Satellite Control Facility at Sunnyvale.

8.5 TERMINAL PROXIMITY DETECTION

From some rather extensive work relating the use of navigation satellites to the problem of collision avoidance, it is clear that satellites offer some definite advantages in the overall collision-avoidance area. In addition to the use of the navigation satellite technique discussed so far, two different approaches examined in collision-avoidance systems using satellites are described in Refs. 5 and 6.

9. TESTING

The objectives of the Navigation Satellite Test Program are to:

- Identify functional items which may require proof of principle subsequent to a feasibility analysis.
- Specify basic test units needed to test functional components and appropriately incorporate the results of tests into subsystems.
- Specify test vehicles appropriate to the simulation of the system wherein the basic test units may be exercised in an environment similar to that experienced by the system itself, but not necessarily as complete nor as complex and certainly not as expensive. Construct a program plan, schedules, costs, and critical paths that would culminate in system development at a time when all problems of a technical nature had been appropriately analyzed and tested in an environment giving a reasonable level of confidence of system success for the developer.

Functions performed in the navigation loops (i. e., ground stations ⇆ satellites ⇆ users) may be classified as follows:

- Signal generation
- Modulation
- Transmission
- Propagation
- Reception
- Processing
- Display

Not all of these functions will require testing to any great extent since state-of-the-art techniques and off-the-shelf hardware components may be completely adequate in some cases, with some functions entering only into the test program as required for subsystems and/or integrated system test.

9.1 SIGNAL GENERATION

The heart of the multiple satellite-ranging-measurement method is the derivation of a suitable signal of sufficient stability to ensure that satellite transmissions are originated and properly synchronized by reference to a stable oscillator on board the spacecraft.

The use of a crystal oscillator simplifies the satellite hardware and improves reliability figures. Existing laboratory test data indicate adequate accuracy. It is, however, necessary to correct the frequency drifts due to aging over the 5-year period. Thermal and radiation effects at orbital altitude should also be tested. The necessary degree of contr,ol will require investigation of reset methods and confirmation of the authenticity of the oscillator model that will be used in the ephemeral computation.

9.2 MODULATION

Data on satellite ephemeris oscillator drift, etc., are to be transmitted by the satellite to the user. It is preferred that the data transmission be combined with the ranging signal on one RF carrier. Therefore, the ranging signal design should be compatible with the efficient transmission of data on the same carrier.

Several ranging systems have been analyzed and tradeoffs have been done among the factors affecting the selection. The BINOR code has been tentatively selected at this time. However, until such time as its utility for the NAVSTAR application can be demonstrated, some parallel efforts should continue with other techniques, particularly a compressed pulse. The initial minimum requirement is the fabrication of a time base unit and BINOR code generator in order to test the code generation and time devision multiplexing with the data. Two such units could serve as prototypes for satellite-user link tests, for future flight articles for systems tests, and for command data-ranging timing sequencing and synchronization.

9.3 TRANSMISSION

The proposed high-power, solid-state, L-band transmitter will require further analysis and subsequent breadboarding and test prior to fabrication. State-of-the-art of solid-state power generation at L-band indicates that the requirement is feasible in a 2-year development period.

For a 50-w design, the only part of the design that is limiting is the final tripler and available diodes.

A 100-w transmitter will probably require either a klystron, a TWT, or a parallel solid-state final amplifier in addition to the same solid-state low-level and drive circuitry of the 50-w design.

The mechanically despun satellite antenna is proven state-of-the-art, but exact gain measurements may require breadboarding and test. This antenna will be involved in the spacecraft test program as an integrated unit of the final spacecraft design.

9.4 PROPAGATION

Multipath effects are very important and should be the subject of detailed testing. Final confirmation of the effects of multipath will require a simulation of the satellite-user link with models of the actual user antennas in an environment that is as close as practicable to the final system.

Other propagation effects should be the subject of further analyses, which can be subsequently verified by test.

9.5 RECEPTION

Since the receivers in the proposed tracking stations and the user equipment are essentially equivalent, combined testing is very practical across the spectrum of reception. The following functional items are indicative of the requirements:

1) RF Receiver

   a) Acquisition time of carrier as a function of:

      Signal level
      Carrier doppler rate
      Loop acquisition bandwidth

   b) Tracking of carrier:

      Loop out of lock as a function of loop tracking bandwidth versus carrier doppler rate.

c) Test for loop staying in lock as receiver switches loop bandwidth from acquisition to tracking mode.

2) <u>Code Acquisition</u>

a) Acquisition properties:

Clock loop acquisition time versus SNR and loop bandwidth
Effects of pre- and post-detection filtering of code on measurement accuracy and acquisition.

3) <u>User Data Acquisition</u>

a) Acquisition time of demodulator synchronization loop

b) Bit error rate versus SNR

4) <u>Range Accuracy</u>

a) Measure phase accuracy of receiver versus:

Signal level
Doppler shift
Signal-to-noise ratio
Varying multipath-simulated

Any units fabricated in support of functional testing would be used as prototypes in later subsystem and system testing programs at fixed sites, in aircraft, or on board ships.

9.6 PROCESSING

At this state of conception, computation of the nature required for the NAVSTAR operation, either at the master computing center(s) or by the user (navigator), is not expected to dictate the need nor the development of any unique computing equipment (hardware). Undoubtedly, however, considerable savings in cost and complexity can be achieved through the well-conceived and tested development of supporting software. Accordingly, then, a development and test program for software and its adaption is required in orbital data processing, orbit improvement and prediction, and in the integration of the command and telemetry function into the overall ground system.

9.7 DISPLAY

Display requirements for the NAVSTAR Ground System command and control are expected to be met by state-of-the-art innovations which will have been proven in other applications. In user equipment, however, increased accuracy, coverage, and fix frequency afforded by NAVSTAR as expected may result in new concepts for presentation and display which, when coupled with the user's increased performance (e.g., SST) will require testing in a human-factor and man-computer interface sense. The minimum requirement appears to involve the integration of NAVSTAR results into the user's navigation and guidance system at several levels of sophistication, i.e., ships, submarines, and aircraft of several different types.

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APPENIX A

NEW TECHNOLOGY

Given the scope and depth of the new technologies described in this report, page-by-page identification of their discussions was precluded and identification has been made on a sectional basis.

- This interim report describes the synthesis of a high-accuracy, all-weather navigation system (NAVSTAR) providing nearly continuous earth coverage and developed to employ low-cost, highly reliable user hardware. (Covered in detail in secs. 2, 3, 5, and 6 of this volume plus appropriate references to further details in sections and subsections of the other three volumes comprising this interim report.)

- Corollary benefit from NAVSTAR is the provision of a high-accuracy time standard (self-evident from details presented in secs. 2, 3, 5, and 6 of this volume).

- Based upon the NAVSTAR system concept, there is a high degree of probability that a practical, low-cost, collision-avoidance subsystem can be developed.