

GPS OVERVIEW AND USER EQUIPMENT ANTIJAM DESIGN

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ABSTRACT

The Global Positioning System (GPS) features an all-weather global coverage navigation sensor with 0.01-nmi positioning accuracy. In the following paper, GPS is described with emphasis on antijam considerations developed in the USAF AFAL Generalized Development Model, GDM. Section 1 provides an overview of the GPS ground, space, and user segments. Section 2 describes antijam issues and techniques applicable to GPS. Section 3 describes the GDM design with emphasis on antijam features. The objectives of the paper are thereby threefold. The first is to give an overview of GPS, how it works, its participants, and its status. The second is to provide a tutorial discussion of spread spectrum receiver design related to GPS (some knowledge of signal processing principles is therein assumed). The third is to provide an example of GPS receiver design which incorporates antijam features.

1. GPS OVERVIEW

GPS is a navigation system using satellite beacons. It is composed of three segments: the space segment (satellites), the satellite control segment (ground-based), and the user segment (navigation receivers). The program had its origin as the 621B Satellite Navigation Program, and this USAF concept was combined with USN requirements for TIMATION as GPS. It is a tri-service program administered by SAMSO. The Army, Navy, and Coast Guard are represented in its management. Additionally, because of the wide application to civil aviation, the FAA is expected to participate.

Following a system definition study (Phase Zero), concept validation (Phase I) contracts were awarded to Rockwell Space Division for the satellites, to General Dynamics for the ground control segment, and to Magnavox for the user equipments. These were followed by contracts to Texas Instruments and Rockwell-Collins for additional user equipment development. Other Phase I participants include Hughes and Teledyne for a tactical missile application and numerous smaller study and test contracts.

Figure 1 shows the overall program schedule beginning with Phase I. The DSARC's are high-level program-approval reviews and represent continue or stop decisions based on major milestones. At present, two satellite vehicles (SV) are in orbit, one has been launched, and one remains to be launched prior to concept testing at Yuma. Tests will continue with SV's 5 and 6. Some test data using three ground-based beacons and one SV have already been gathered on the Magnavox user sets.

1.1 Space Segment

When fully operational, the GPS space segment consists of 24 SV's as shown in Figure 2. The 24 SV's are in three orbital planes, each at 63° inclination. The 8 SV's in each plane are in a circular orbit and separated by 45° . The orbits are 10,898 nmi in altitude from earth surface, and the period for one circle is 11.96 hours. This configuration provides simultaneous visibility of 6 to 11 SV's by any user anywhere on earth.

The SV's radiate two modulated L-band signals (Figure 3). Two carrier frequencies are required to measure the ionospheric delay. The C/A-code is a 1023-chip binary sequence that repeats every millisecond. The P-code is a very long binary sequence keyed at 10.23 MHz. Each SV has a unique P- and C/A-code to distinguish its signal from that of other SV's. The same code generator hardware is uniquely wired to provide this feature. All SV's share the same L-band frequencies. The data modulation contains SV position and clock corrections. The SV's are infrequently positioned and time-set from the ground. Instead, the control segment up-links on S-band time and position correction data, which is modulated in the SV onto the L-band carriers.

The SV's are launched from Vandenberg AFB using an Atlas F booster. They fly a sequence of orbits, shown in Figure 4, prior to final positioning. About one month is required before the final orbit is achieved.

1.2 Control Segment

The control segment, shown in Figure 5, identifies the geographic location of the monitor and master control stations. All SV's are seen by the monitors at least once every 12 hours. While in view, the SV position and clock are determined by comparing the signal arrival times at each monitor. The monitor station positions and clocks thereby provide the position/time reference for the SV constellation. These data are processed by the master control station. SV ephemeris and clock correction data are computed. The data is uploaded to the SV on S-band for retransmission to the users on the SV L-band navigation signal. It is possible to alter the SV clock and ephemeris using the up-link telemetry, but this requirement is infrequent.

1.3 User Segment

The community of users navigates from the SV L-band signals. Applications include all military air, land, and sea vehicles with an accurate positioning requirement as well as civil aviation and surveying. Given the existence of the planned space and control segments, L-band signals will continuously provide 50-ft position accuracy, 1-f/s velocity accuracy, and time within 10 ns anywhere on Earth in any weather. The ultimate applications of these performance capabilities are almost unbounded.

User equipments vary in design depending on the dynamics of the user and the signal-to-noise margin required, especially in a hostile, jammed environment. Present-day set designs are largely digital, thereby allowing for the use of future cost reductions in digital computer circuitry. Present equipment cost estimates based on today's technology range from \$5K to \$30K, depending on the set type. Forecasts for the military see about 30,000 sets in the 1990 time frame.

The top-level partitioning of a GPS user set, shown in Figure 6, indicates a receiving function and a navigation function. The former acquires the signals and measures ranges along the line-of-sight to the satellites; the latter manages the overall system and projects the measured range data into the user's navigation coordinate frame. GPS is a one-way ranging system wherein the user determines his position by processing range measurements to each of four separate satellites. The receiver is intended to measure the path delay between the user and each satellite but, because its clock is not in synchronism with the mutually synchronized satellite clocks (GPS system time), the time delay which the receiver actually measures includes the user clock time offset with respect to the system time contained in each SV. Because the measurements include this clock error, they are called pseudoranges. By properly processing these four measurements, the user is able to determine his 3-position coordinates and correct his own clock error.

The receiver measures pseudorange by correlating a locally generated replica of the P- or C/A-code with the incoming signal, thereby collapsing the 20-MHz spectrum of the received signal into the 50-Hz bandwidth associated with the 50-b/s down-link data. Further processing by a carrier tracking loop detects the 50-b/s data and reconstructs the carrier. Because the received signal level is so low, signal-to-noise ratios adequate to make the needed range measurements can be achieved only with system bandwidths of a few hertz.

Thus, since the combined effect of satellite and vehicle dynamics can create doppler shifts as large as 10 kHz, tracking loops are used in the receiver. The carrier tracking loop centers the reconstructed carrier frequency, and the code loop tracks the correlation peak by controlling the locally generated P- or C/A-code based on a comparison of early and

late correlations. Each of these loops can be thought of as a position servo tracking an input signal which varies with the dynamics of the vehicle and the satellite.

1.3.1 User Receiver Processing – Figure 7 shows a block diagram of a 1-SV channel user receiver which incorporates the rf processing, signal acquisition, correlation, carrier and code tracking, and data detection. Depending on the dynamics of the user, four SV channels may be used, or it may be possible to time-share one SV channel sequentially on four SV signals. For stationary users, reception of one SV signal at several points in orbit will yield accurate position data.

Following the antenna, rf gain, and first mixer, each SV signal is detected by multiplying the signal by a local replica of its C/A- or P-code, filtering the output, and performing carrier tracking. Early and late code replicas are used to center the “prompt” code replica through the code-tracking loop. As shown in Figure 7, most of the signal-processing functions are mechanized in software following a/d conversion of the baseband signal.

The functions required of the receiver are as follows:

- a. A time and frequency search for a selected SV is implemented for acquisition. The processor successively increments both the carrier frequency and the code generator until the amplitude of the received signal exceeds a threshold. Unless position and system time are known within a few tens of microseconds, this search is performed on the C/A-code. The C/A-code repeats each millisecond and has 1,023 possible time positions. Since the P-code does not repeat and its rate is 10.23 MHz, to search it over only 1,023 positions would require knowledge of system time and range to within 100 μ s. P-code acquisition is therefore used only when accurate system time is available. Its advantage is a 10-dB improvement in jamming margin.
- b. Following acquisition, the processor enables the code- and carrier-tracking loops and demodulates the 50-b/s data. The data includes system time which allows the receiver to switch over from C/A- to P-code operation.
- c. In the process of acquisition and tracking, the code generator is offset from the position that would have been maintained without the code search, reset for P-code handover, and code-tracking adjustments. This offset is the pseudorange measurement of satellite to user clock. Four such measurements allow the navigation computer to determine 3D position and system time (local clock error). To do this, however, also requires accurate knowledge of the SV positions and clock errors; this information is in the 50-b/s data.
- d. The receiver processor measures the carrier frequency and/or phase to close the carrier tracking loop. This process is necessary to keep the signal centered in the receiver filters. The frequency measurements are proportional to the SV to user line-of-sight velocity, and this data is used in the navigation computer.

The velocity measurements are also used to aid the code loop. Since the same dynamics apply to both loops and since the code rates and carrier frequencies are integrally related, the recovered carrier frequency is divided (by 154 for L1 and P-code operation) and used as the code generator clock. However, the code loop corrections are still necessary to remove slowly changing delay variations between signal modulation and signal phase in the media and to remove the effects of integrating the oscillator phase noise on the carrier frequency measurements into large position errors. This aiding of the code loop by the carrier loop removes the short-term dynamics seen by the code loop and allows its tracking bandwidth to be narrowed.

- e. The same tracking processing is applied to the L2 carrier. Typically, simultaneous pseudorange measurements are made on both L2 and L1 sequentially on each of four SV's. The delay difference from L1 to L2 calibrates the ionospheric transmission delay, known to be inversely proportional to the square of the carrier frequency. This measurement provides a 10- to 50-ft improvement in positioning over that obtained using an ionospheric model. The expense is the rf hardware needed to convert L2 to if and the extra processing capability.

When the equipment contains a stable clock (about 10^{-9} per day), the local clock errors determined in the navigation solution are valid for several minutes. It is therefore possible to track only three SV's for a position solution for short intervals and to use the fourth channel for L2 measurements. In GDM, however, a fifth channel was provided for this purpose.

- f. When one of the SV's being tracked is about to go out of view, the navigation processor provides the receiver with a replacement SV and with accurate position, velocity, and time corrections for the new SV. The updated almanac data for all satellites is continually broadcast by each SV. The receiver then ceases tracking the old SV and starts the acquisition process on the replacement. In this case, P-code acquisition can be used since the pseudorange is known within a few tens of microseconds from the fresh almanac data.
- g. For civil users where antijam is not an issue and where moderately degraded position accuracy is acceptable (about 100 ft instead of 50 ft), the receiver can be operated on the C/A-code without handover to the P-code. Because of its higher rate (10.23 MHz) and long code (7 days), the P-code portion of the code generator requires considerable hardware. An austere user can avoid this expense by navigating with the C/A-code only.

1.3.2 User Navigation Processing – As shown in Figure 6, the navigation processor performs the functions of coordinate conversion, position and velocity measurement filtering, and SV selection based on stored almanac data. The measurement filtering is generally implemented with a recursive (Kalman) filter to optimize measurement

weighting. For a stand-alone system, a maximum of 11 states are required, clock phase and frequency, and acceleration, velocity, and position in each of three dimensions. If the navigation solution is aided by other user sensors, such as an inertial navigation system (INS), then the acceleration states are dropped and error models of the aiding sensors are included. Complete data does not exist on the merits of model complexity versus system accuracy, although many specific simulations have been performed.

The position solution requires good arithmetic capability in the processor and at least 32-bit precision. Presently, for high-dynamic systems, a computer with an average capability of about 500,000 operations per second (500 KOPS) and a memory of about 50K 16-bit words appears suitable. This sizing varies dramatically, depending on ancillary functions such as an INS mechanization, antenna attitude control, area navigation with waypoints, and reference coordinate system conversions. The software structure for the GDM data processor, which, except for the HPAA (antenna) control, is representative of an inertially aided GPS set mechanization, is shown in Figure 8.

Utilization of external on-board sensors, such as an INS, can materially enhance the anti-jam performance of a GPS receiver. Furthermore, GPS can be used to continuously calibrate out the sensor measurement errors. The external sensors can aid GPS in several ways, all of which result from reducing the dynamics which the GPS receiver must track.

- a. For steered antennas, an on-board attitude sensor can maintain beam pointing to the SV's.
- b. Velocity and position sensors can interpolate between GPS position solutions, thereby reducing the solution rate.
- c. Velocity and position sensors can be used to correct the carrier and code frequencies in the receiver in an open-loop mode, thereby reducing the tracking errors and allowing reduced tracking loop bandwidths.

Additionally, the navigation processor plays a significant role in initial acquisition prior to navigation. It selects, from almanac data and a rough estimate of present position, the SV's to be acquired, and it estimates the frequency range to be searched, based on the relative velocity to the SV.

2. GPS ANTIJAM CONSIDERATIONS

The GPS signal format, pseudonoise (pn) spread spectrum modulation, was chosen specifically for its anti-jam capability. This modulation requires precise synchronization in the receiver to generate the local pn code replica, and this information is exactly appropriate to time-of-arrival ranging measurements. Tone ranging and pulse ranging, while potentially applicable, do not inherently have the desired aj features.

The manner in which the signal format and detection process accomplish jammer suppression is shown in Figure 9. At the SV's, a narrow-band (50-b/s modulated) carrier is multiplied by a pn code; for GPS, this is the P-code. The (essentially) line spectrum of the carrier is thereby spread to the 20-MHz spectrum shown. During transmission, a jamming signal nearly centered on the carrier frequency is added (with white noise not shown). At the receiver, the signal plus jammer plus noise is multiplied by the local code replica. Following this multiplication, the jammer and the signal spectra are interchanged; the signal spectrum is collapsed back into a narrow band, and the jammer is spread into a 20-MHz broadband. The noise is essentially unaltered. The code multiplier is followed by narrowband filtering which passes all of the signal but only a small fraction of the spread spectrum jammer power. The receiver "gain" versus the jammer is the ratio of jammer power at the multiplier output to that which passes the detection filtering. This is called the processing gain. Without the pn modulation and demodulation, the jammer could apply all its power through the detection filtering. The pn processing reduces this by the processing gain which is the ratio of the spread spectrum bandwidth to the detection filter bandwidth. The jammer could transmit broadband noise. However, with or without the pn demodulation process, only that fraction centered on the detection filtering would affect the system. The spread spectrum technique is considered successful if the jammer is equated to broadband noise.

Given a predetermined spread spectrum bandwidth, the pn sequence rate of 10.23 MHz for GPS, the receiver designer can improve performance by reducing the detection bandwidth. Prior to nonlinear processing (such as frequency doubling or amplitude detection), the detection bandwidth is 50 Hz, to pass the 50-b/s data modulation. Doppler modulation due to dynamics is removed by the carrier-tracking loops. Following the removal of data by nonlinear processing, the bandwidth required is necessary to track out the carrier doppler. Reduction of either predetection or postdetection bandwidths improves performance.

The independent performance variable for all detection processes is C/N_0 , the total signal power divided by the noise power in a 1-Hz bandwidth. Actual predetection and postdetection bandwidths are included with C/N_0 in the performance formulas. For a spread spectrum system subject to jamming, all significant noise in the detection bandwidth is due to jamming. The noise spectral density due to jamming is the total jammer power divided by the pn sequence rate, 10.23 MHz for GPS. For strong jammers, the C/N_0 seen by the receiver is the jammer power to signal power ratio divided by 10.23 million, or $C/N_0 = S/J + 70$ dB. This is shown in Figures 10 and 11.

2.1 Tracking Loop Performance

The four noise-dependent performance requirements in a GPS-type receiver are acquisition, data detection, carrier tracking, and code tracking. Given previous acquisition

in a benign environment and given that SV ephemeris and clock data received at that time remain valid (about 1 hour), the critical navigation operations are carrier tracking and code tracking. For a stationary system, formulas and graphs of the performance of these loops are given in Figures 10 and 11. As discussed above, the required bandwidths show clearly as significant parameters.

The loss-of-lock thresholds for the code- and carrier-tracking loops are also shown in these figures. These are the C/No ratios where the loops fail to operate. In terms of peak tracking errors, they may be defined as follows:

- a. Carrier phase tracking - $1/8$ wavelength, equal to about one inch.
- b. Code tracking - $1/2$ chip (pn modulation element), equal to about 50 feet.

The thresholds are so small in terms of position accuracy that there is only a small improvement in system accuracy with improvement in C/No above threshold. The aj design issue, therefore, is to extend the tracking thresholds of the carrier and code loops.

In addition to noise, the tracking loops are subject to tracking errors due to failure to precisely follow the input dynamics. In phase lock loop theory, these are the modulation tracking errors in contrast to the additive noise errors shown in Figures 10 and 11. More simply, a servo-loop can follow inputs only at a frequency within its loop bandwidth. The magnitude of the tracking errors plus the noise errors must be held within the tracking thresholds listed above. It is convenient to separate the two and to allow a margin for the combination.

In order to quantify the tracking errors, it is useful to define a spectrum for the input dynamics. In lieu of a purely stochastic approach, it is assumed the worst-case dynamics are sinusoidal. Maximum acceleration, A, and jerk, J, are specified by user vehicle. They are then assumed to result from sinusoidal position variations between the vehicle and the satellites.

Figure 12 shows the peak input sinusoidal position variations as a function of frequency for a fighter-type aircraft where A(max) is 5 g, and J(max) is 10 g/s. Also shown are the tracking errors for a BL = 1 Hz second-order and third-order position-tracking loop as function of frequency when subjected to the input spectrum. For GPS, the position-tracking loops are designed to follow dynamics at all frequencies out to the point where the peak input variations are less than the loop-tracking thresholds. To do this, the required loop noise bandwidths are about 20 Hz for carrier tracking and 1 Hz for code tracking if no aiding is available. Code tracking, however, is aided by carrier tracking when above threshold and BL = 0.1 Hz is then appropriate,

The use of inertially derived range rate to aid both carrier- and code-tracking loops can substantially reduce loop bandwidths without the penalty of increased dynamic tracking errors. A generalized block diagram of an inertially aided tracking loop that is applicable for analysis of either carrier or code loops is shown in Figure 13. Actual signal dynamics along the selected line-of-sight are described by the acceleration $A(s)$. The velocity-aiding signal (the dashed lines), although an imperfect measure of the true dynamics, drives the loop vco in an open-loop sense. The transfer function,

$$\frac{1-K}{\tau s + 1},$$

represents the imperfections in the measurement process, where K is scale factor error and τ models sensor or processing lags. Without aiding, the loop transfer function is:

$$\frac{E(s)}{A(s)} = \frac{1}{s^2 + sF(s)}.$$

With velocity aiding, it becomes:

$$\frac{E(s)}{A(s)} = \frac{1}{s^2 + sF(s)} \frac{\tau s + K}{\tau s + 1}.$$

Thus, the effect of aiding is to modify the loop transfer function by the attenuation factor,

$$\frac{\tau s + K}{\tau s + 1}$$

With perfect aiding ($\tau = 0, K = 0$), the loop tracks all dynamics without error, thereby implying that bandwidths can become arbitrarily narrow. However, a more interesting and useful consideration is to ask how tracking bandwidths vary as a function of imperfect aiding. Specifically, assuming that the delay parameter, τ , is negligible, both carrier and code loop bandwidth variations as a function of scale factor error K have been analyzed.

Figures 14 and 15 show the results for carrier and code loops respectively. A sinusoidal dynamics model was used employing the peak values given in Figure 12. The curves are normalized to the unaided case, that is, $K = 1$. For the carrier loop, $K = 0.001$ reduces the bandwidth needed for full dynamic capability from about 20 Hz to on the order of 2 Hz. For the code loop, $K = 0.001$ reduces the necessary bandwidth from 1 Hz to about 0.03 Hz. $K = 0.001$ is roughly the level of performance of today's 1-nmi/hr inertial systems without special calibration. Thus, today's typical inertial systems, by virtue of the loop bandwidth reductions they permit due to aiding, improve antijamming performance on the order of 10 to 15 dB. Special calibration methods could reduce the scale factor error further, but it is unlikely that an order of magnitude improvement can be attained. Even if such a reduction in scale factor error were possible, other error sources would limit

bandwidth. Although a detailed discussion is beyond the scope of this paper, these include gyro bias, random gyro drift, inertial axis misalignments, frequency standard phase noise, and frequency standard g sensitivity. Theoretically, all of these errors can be compensated via Kalman estimation techniques; however, practical considerations related to modeling errors and implementation complexity suggest that the lower limit on code and carrier loop bandwidths is on the order of 0.01 Hz and 1 Hz respectively.

2.2 Antennas

The general antenna requirements for GPS user equipment mainly provide uniform coverage over the upper hemisphere, since satellites must be tracked anywhere from the horizon to the zenith. However, if maximum use is made of known user-to-satellite geometries and known or deducible jammer locations, antennas can be a very effective form of spatial filtering by providing selective directional responses. Two quite different antenna approaches that can be used are beam steering and adaptive null steering.

Beam steering involves developing and pointing beams toward each satellite being tracked, thereby providing gain to the desired signals and discrimination against all out-of-beam sources. Figure 16 displays the beam characteristics. Direction cosine commands, based on user-to-satellite geometries, control each beam. The antenna array would normally lie in the horizontal plane with its aperture facing upward. As the figure shows, beams at or near zenith have a circular cross-section, while those near the horizon are elongated in the elevation plane. Beam steering has two disadvantages: (1) Large-array apertures are needed to form narrow beams at L-band. (2) Because beams must be spatially stabilized, beam-steering computations for a high-performance vehicle can become a substantial computational task. Figure 17 shows the set of beam patterns for the GDM antenna, an 18-inch x 18-inch array. The 3-dB width of the beams near zenith is approximately 30 degrees, and the first side lobes are down about 15 dB. Thus, a jamming source anywhere outside the primary beam would be suppressed 15 dB or more with respect to the desired signal by this antenna. A larger array would be needed to achieve still narrower beams and lower side lobes. In a manner similar to that described below, it is possible to offset the beam pointing in such a way that a jammer is moved from a side-lobe peak to a null on the directive antenna pattern. In GDM, an adaptive algorithm minimizes received jammer power in this way by dithering the main beam $\pm 8^\circ$ from center.

The pn-modulated GPS signal is about 30 dB below thermal noise. In the 20-MHz bandwidth, which precedes correction, the total powers for noise and signal are, respectively, about -130 dB W and -160 dB W. Therefore, any receiver input that rises above receiver front-end noise must be interference. Adaptive null-steering antennas use this fact to place nulls over strong interference sources. As shown in Figure 18, the outputs of several individual antenna elements are adaptively combined through phase and

amplitude controls to minimize the total input power to the receiver system. This approach effectively drives a strong jammer down to the thermal noise level. Adaptive antennas need neither large aperture arrays nor computed pointing commands and consequently are potentially simpler and lower in cost than beam-steering units. However, they can create spurious nulls which may suppress the desired signal, and only a small number of jammers can be nulled simultaneously. Figure 19 shows the characteristic behavior of an adaptive-array. A jammer is located 21 degrees off boresight. The adaptive algorithm places the jammer in a deep null while maintaining the boresight gain. Circuit element tolerances and dynamics limit the suppression to about 40 dB. However, any one of the other deep nulls which are also present could suppress the desired signal as well. This potential difficulty occurs because the adaptive system does not know the direction of the desired signal. If the line-of-sight vector to the satellite is provided, the adaptive algorithm can impose gain constraints which keep the spurious nulls from falling on the desired signal.

2.3 Special Processing

Certain special processing techniques can be used to enhance GPS user equipment performance. These methods apply in special situations or to special types of interference as contrasted to the general applicability of antenna techniques and inertial aiding. Data aiding applies when the user knows the 50-b/s data being transmitted by the satellites so that it can be multiplied off, thereby allowing the 50-Hz predetection bandwidth to be narrowed. Since switching from satellite to satellite occurs frequently, due to continuously varying geometry, and since data must be detected for each newly acquired satellite before data aiding can be employed, the technique can be used for only brief periods, for example to extend system operation another 5 or 6 dB during a weapons delivery run against a target defended by a jammer.

Other processing techniques improve performance by operating on known waveform and spectral characteristics of jammers. These work by estimating the jammer based on an a priori model, correlating this estimate with the signal plus jammer, and adjusting the estimation parameter to minimize the correlation. One example is an adaptive notch filter which is effective against a narrow-band jammer. The implementation of this technique can be visualized by replacing the antenna inputs to Figure 18 with taps on a delay line spaced by one-chip intervals. A second technique, also effective against narrow-band jamming, clips narrow-band spectral peaks generated by a frequency domain transform operation. An essential system requirement, when mechanizing any of these special processing algorithms, is that no significant performance loss occurs when the jammer differs from the a priori model.

3. GENERALIZED DEVELOPMENTAL MODEL OF GPS

GDM is an exploratory model of GPS designed to evaluate antijamming techniques. It is now installed on the C-141 GPS test aircraft and will be flight-tested at the Yuma test range with the Texas instrument and Magnavox models. Figure 20 shows the total GDM test system including operator station, USAF-provided pallet, and instrumentation system. Figure 21 shows a block diagram of the hardware. The elements are:

- a. A 4-beam directive antenna.
- b. An 8-channel rf assembly used for L1 and L2 reception from four SV's, including an 8 x 5 if switch.
- c. Five signal channel processors used to provide correlation demodulation of four SV L1 signals and one L2 signal (sequentially).
- d. A Collins CAPS-4 receiver processor used to control the SCP tracking vco's and code generators and to provide data demodulation, search and acquisition processing, code and carrier tracking loop filtering, and pseudorange and range-rate measurement processing.
- e. An IBM AP-101 data processor for navigation and an IBM bus controller for the 1553 data bus.
- f. An instrumentation system including TTY, magnetic tape storage, and a PDP-11/05 processor.
- g. An inertial measurement assembly, including battery standby, a Singer/Kearfott IMU, and IMU control circuits. The IMU is remote from the pallet and located as near as possible to the antenna to minimize moment arm effects between the inertial measurements and GPS measurements.
- h. An interface assembly and CRT control display unit.

The receiver processor is interconnected with the receiver hardware by a parallel data bus; the data processor interfaces all system elements via the 1553A serial data bus. The data processor obtains attitude information from the inertial system, converts it to line-of-sight coordinates, and points the antenna beams. Additionally, inertial velocity data are used to aid the carrier and code tracking in the manner described in Section 2.

The GDM system incorporates, as shown, the antijam features of multiple-pointed antenna beams directed by attitude sensing and squinted by adaptive processing. Inertial aiding is used, which allows the carrier-tracking loop bandwidth to be 1 Hz and the code-loop bandwidth to be 1/30th Hz. The inertial measurements provide velocity information sufficiently accurate to allow code tracking after even the extended carrier-tracking capability is overcome by jamming. Overall, the GDM mechanization extends the antijamming capability of a GPS receiver by about 40 dB over a set without these features. A 20-dB result is obtained from the directive, squinted antenna operation, and 20 dB

results from extended narrow-band code tracking without carrier tracking. Narrow-band operation with aiding extends the carrier-tracking capability 10 dB beyond the conventional wide-band mechanization but falls 10 dB short of the aided code-tracking threshold.

The flexible software implementation of the GDM system allows for future inclusion of special antijam processing. Notch filtering and data aiding are two candidates under consideration. Also, the tactics of satellite selection and change as a function of performance monitoring in conjunction with the separately controlled and rf-processed antenna signals can provide protection against jammers coaligned with an SV. This is in contrast to a set with a single antenna and rf amplifier where all SV signals see the same jamming level.

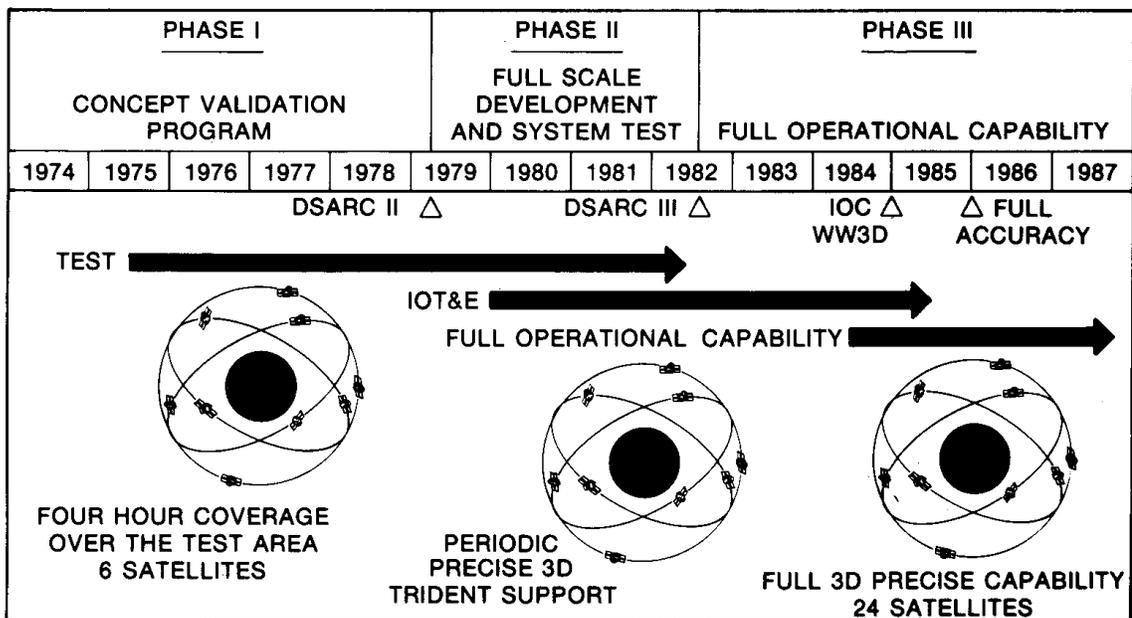


Figure 1. Navstar Global Positioning System Schedule.

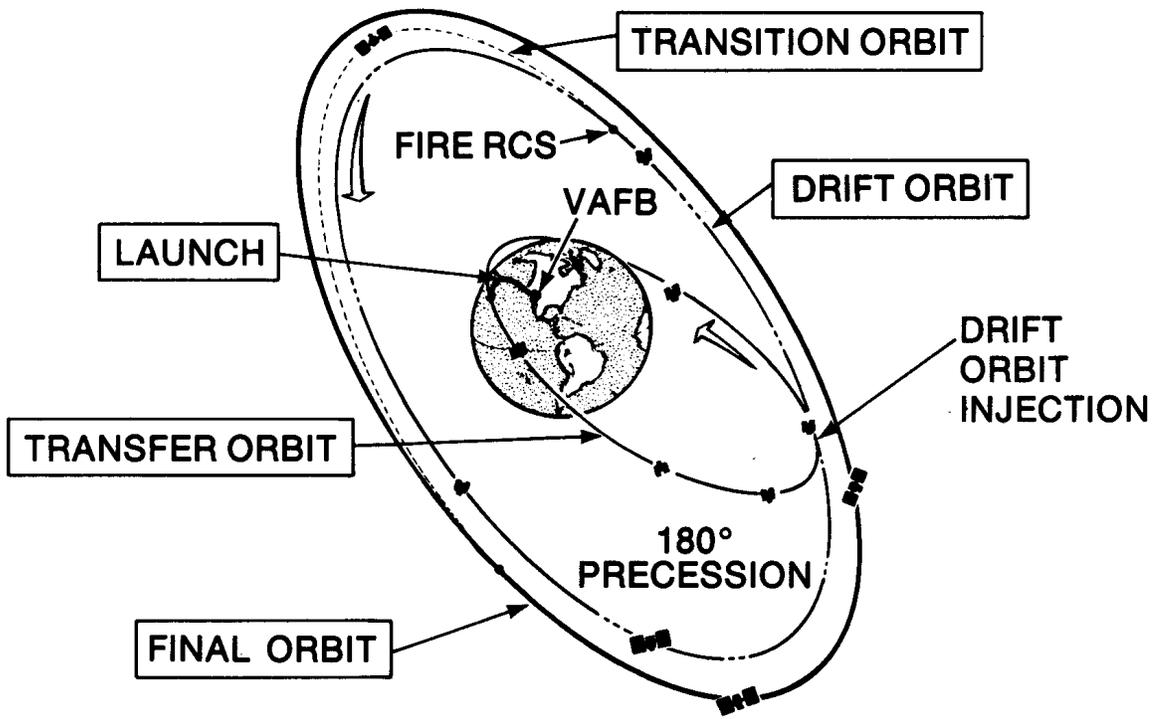


Figure 4. Mission Operations.

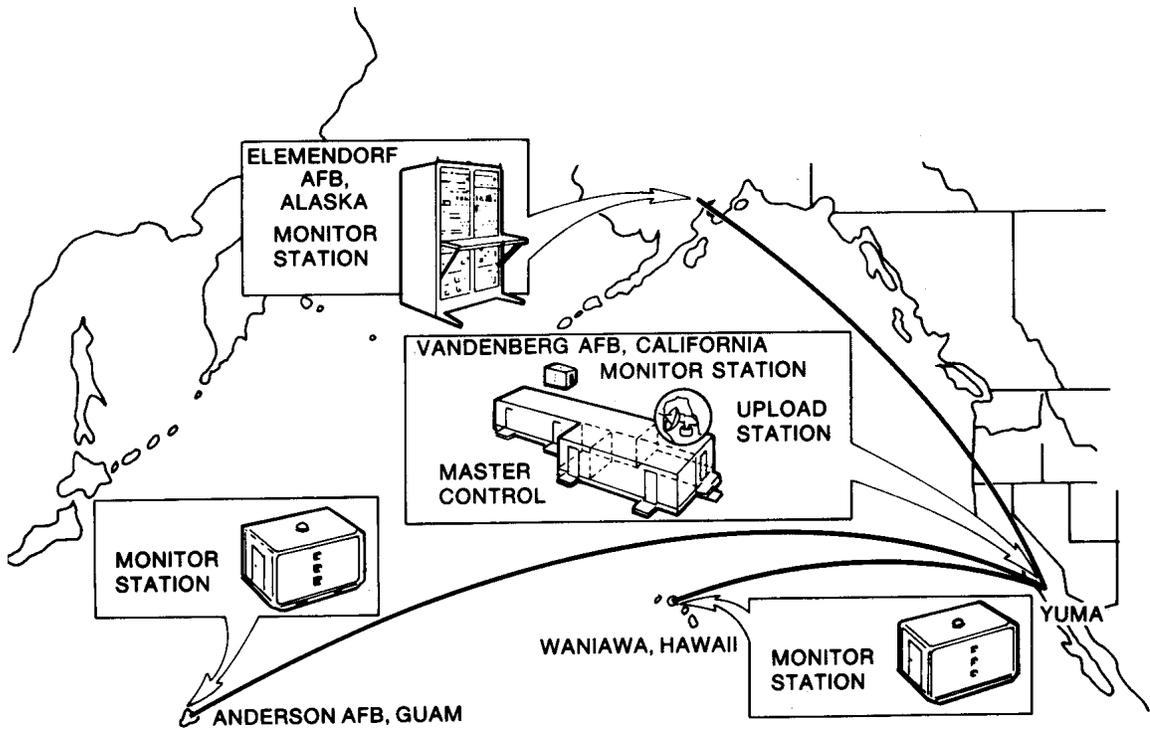


Figure 5. GPS Control Segment.

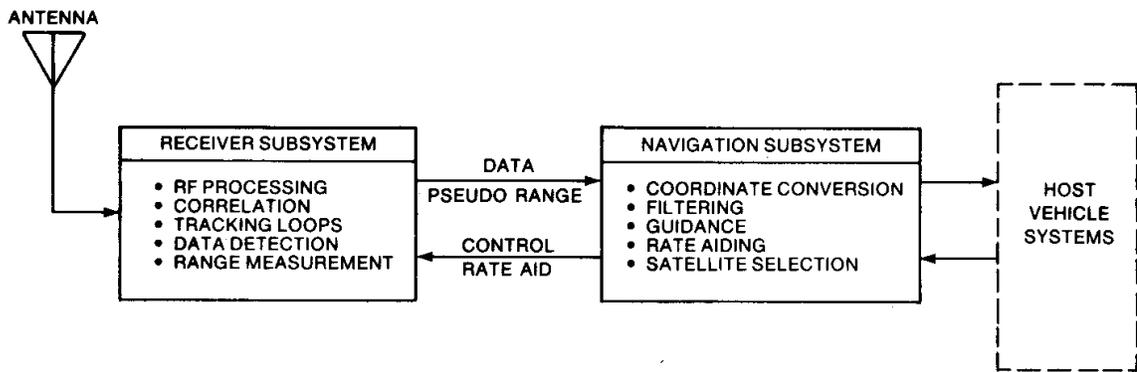


Figure 6. GPS User Equipment Functional Diagram.

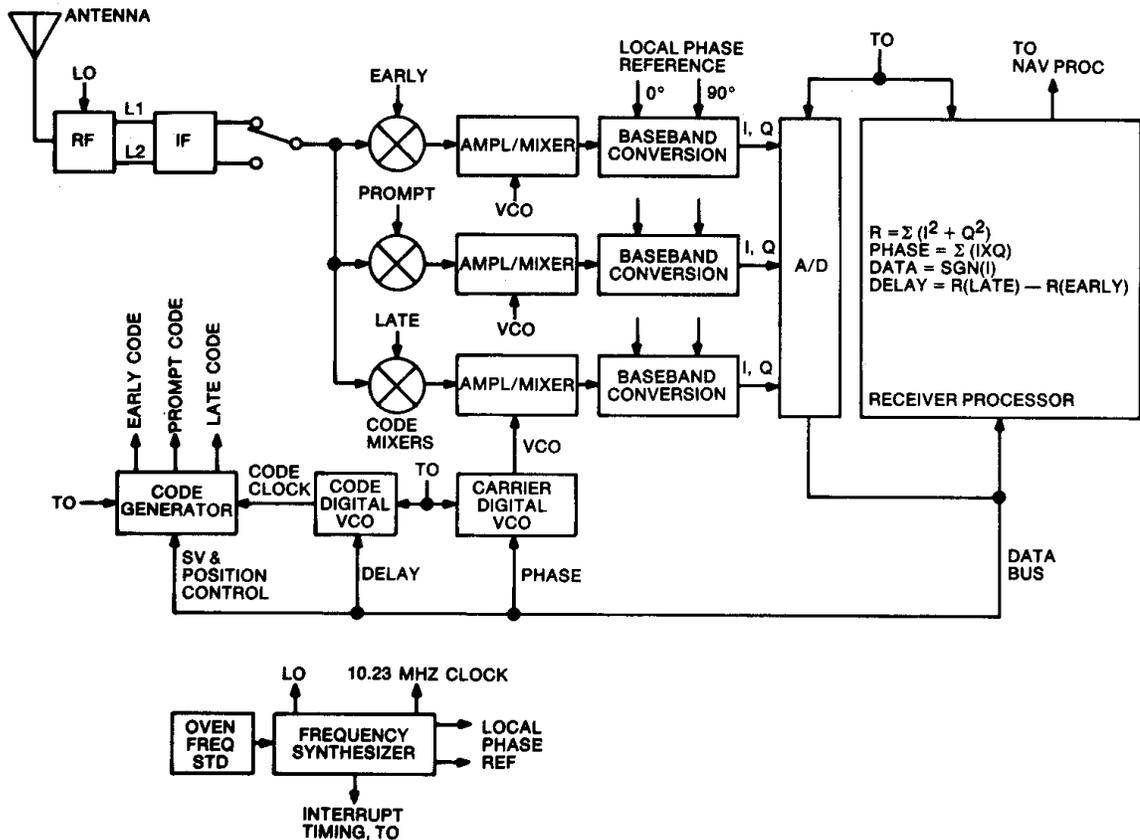


Figure 7. SV Receiver.

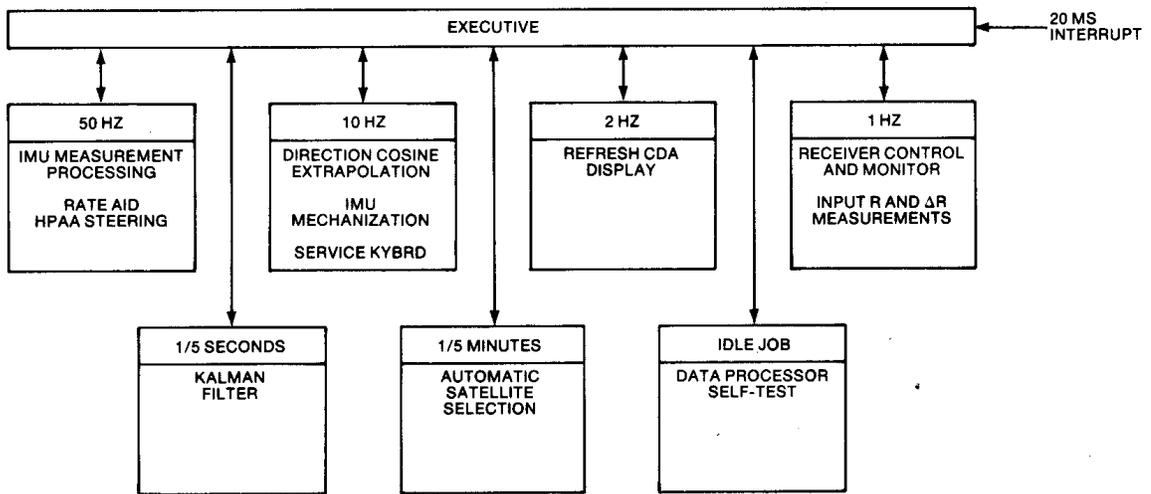


Figure 8. Data Processor Software.

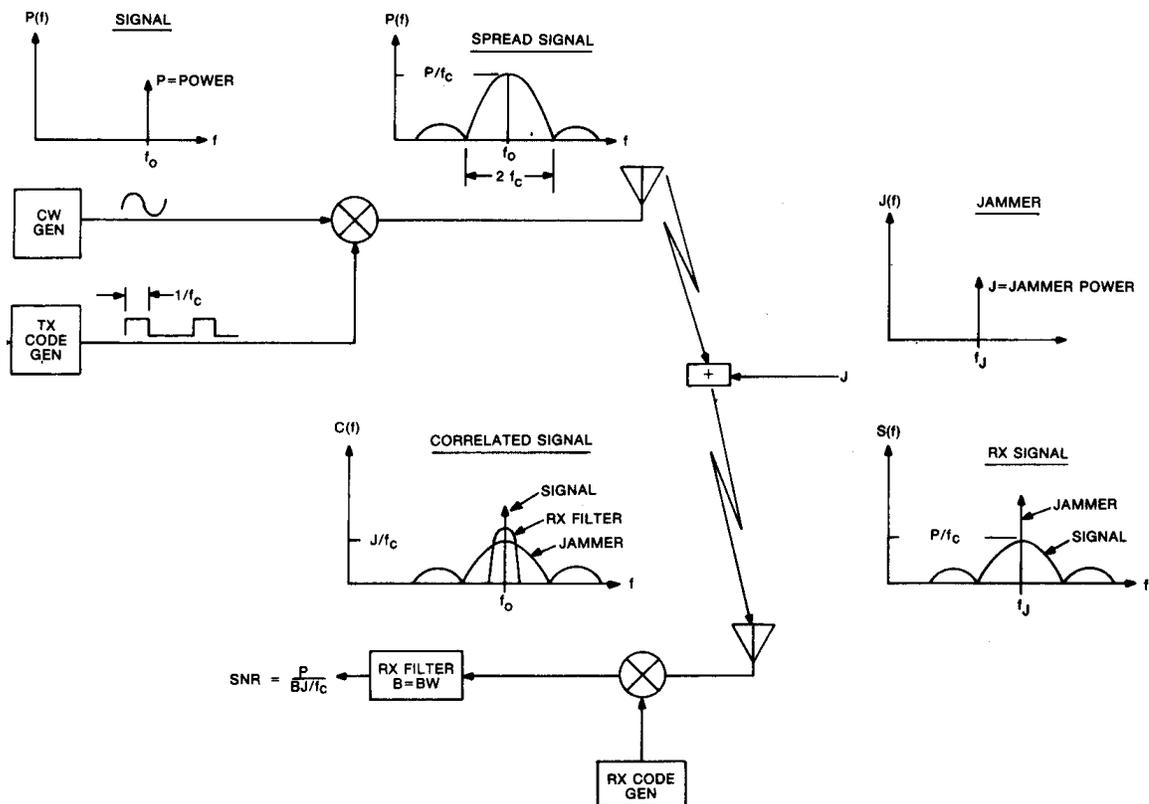


Figure 9. Spectrum Transformations in PN Spread Spectrum.

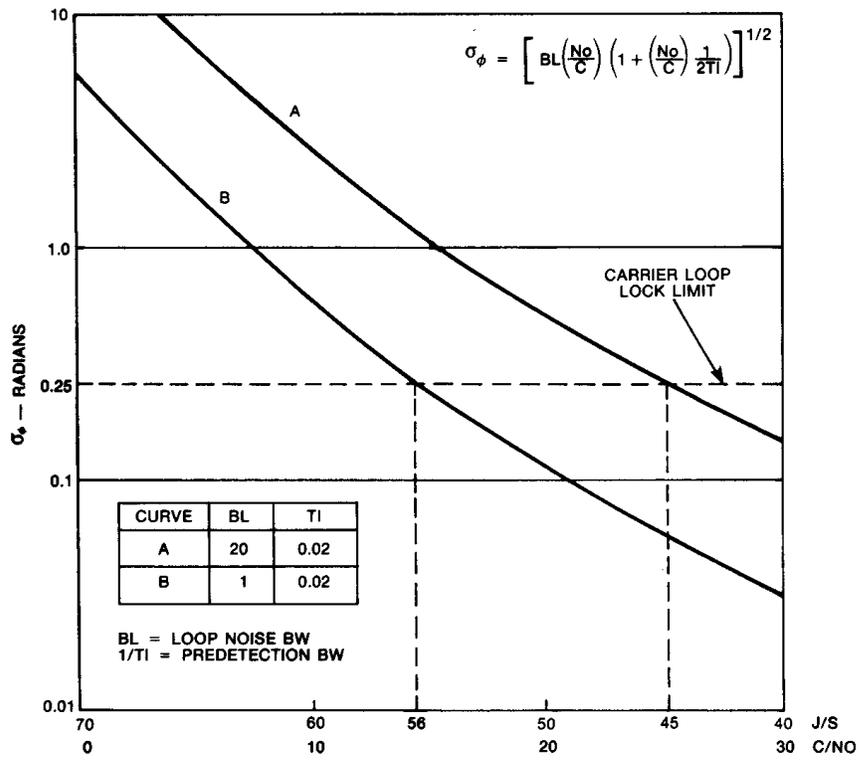


Figure 10. Carrier Loop Noise Response.

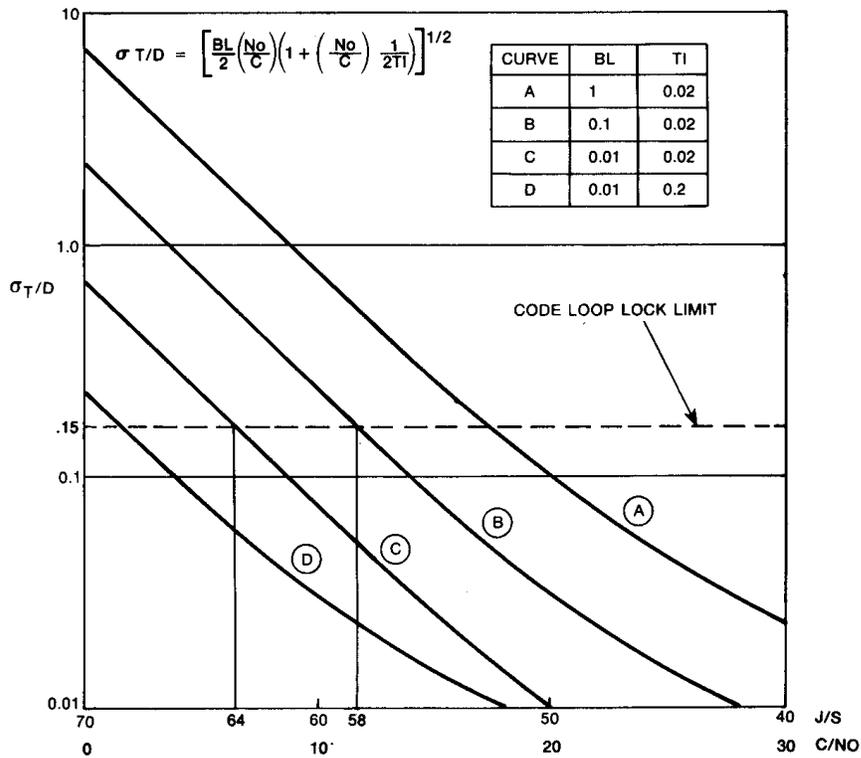


Figure 11. Code Loop Noise Response.

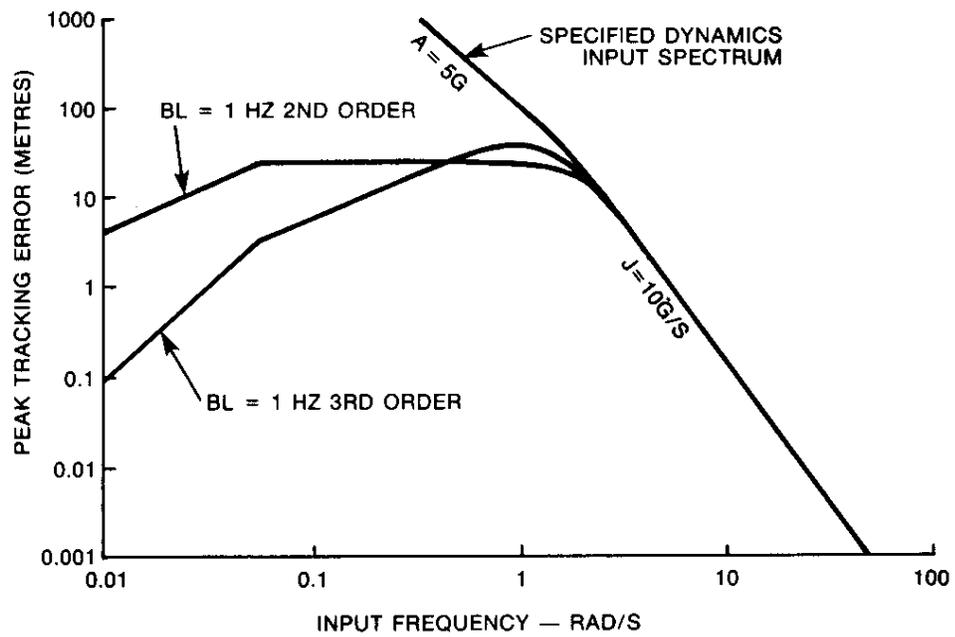


Figure 12. Code Loop Dynamic Tracking Error.

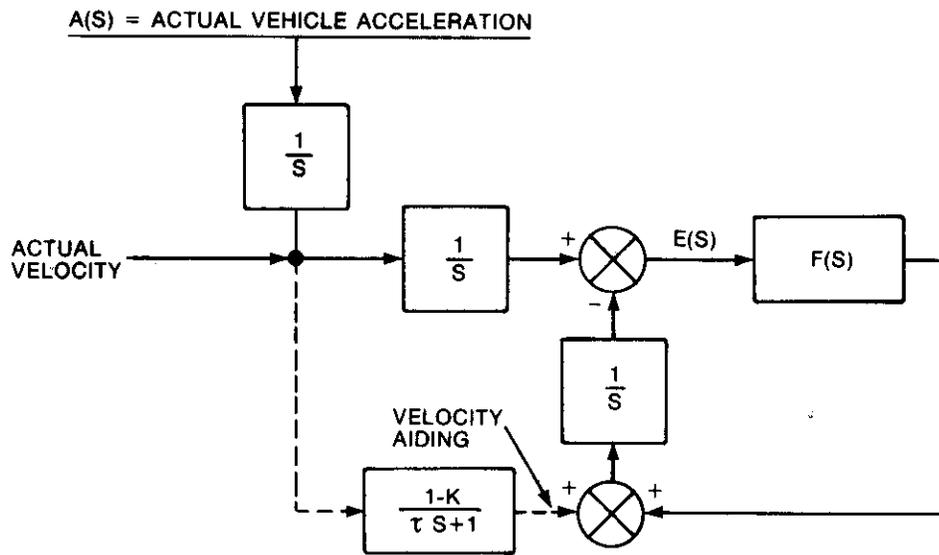


Figure 13. Aided Tracking Loop Model.

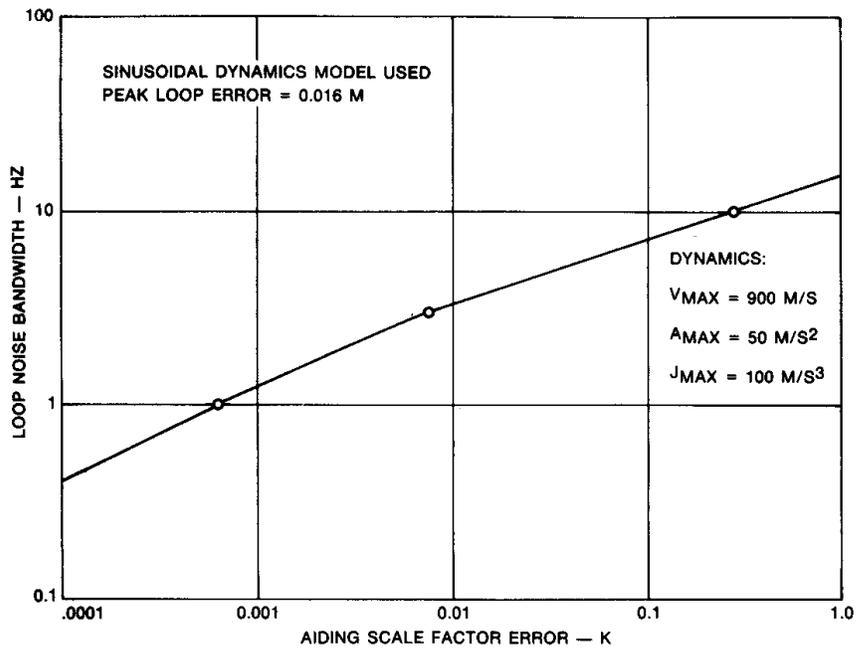


Figure 14. Carrier Bandwidth Vs Quality of Aid.

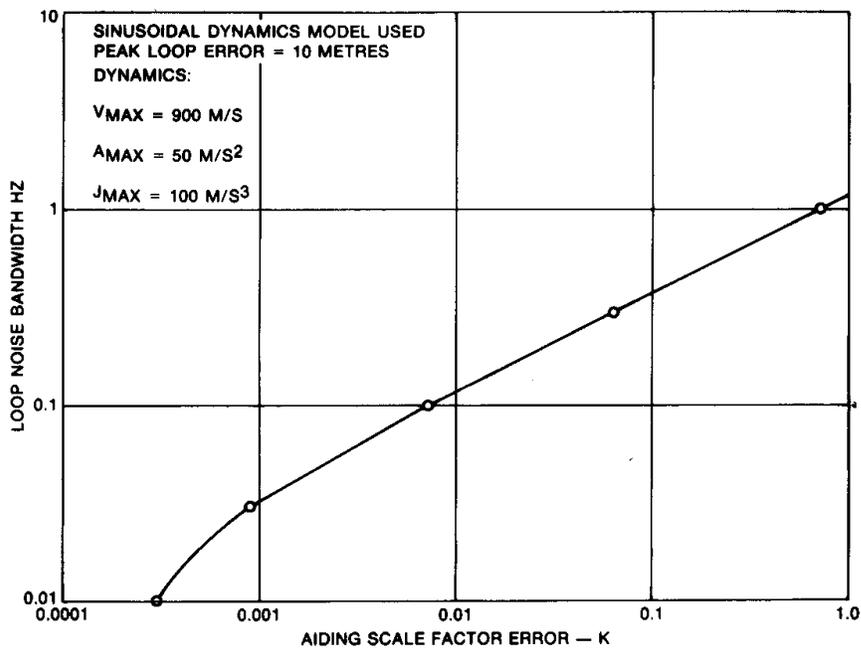


Figure 15. Code Bandwidth Vs Quality of Aid.

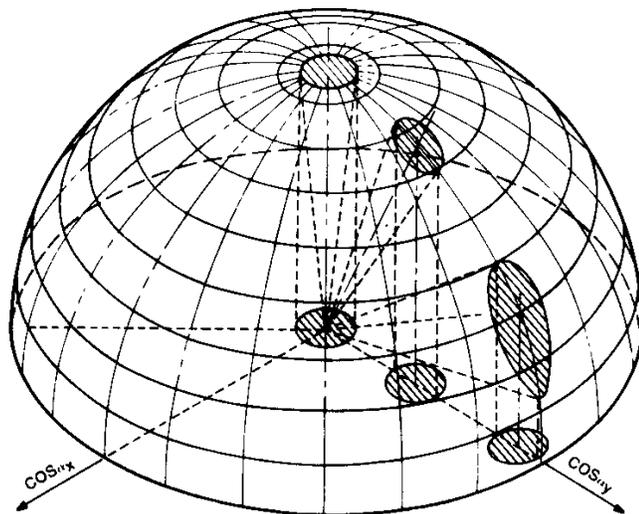
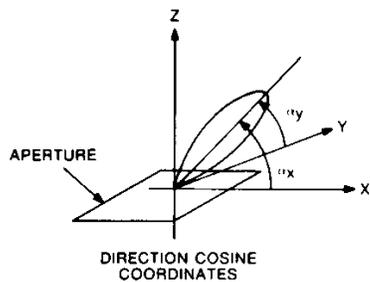


Figure 16 . Beam Steering Geometry.

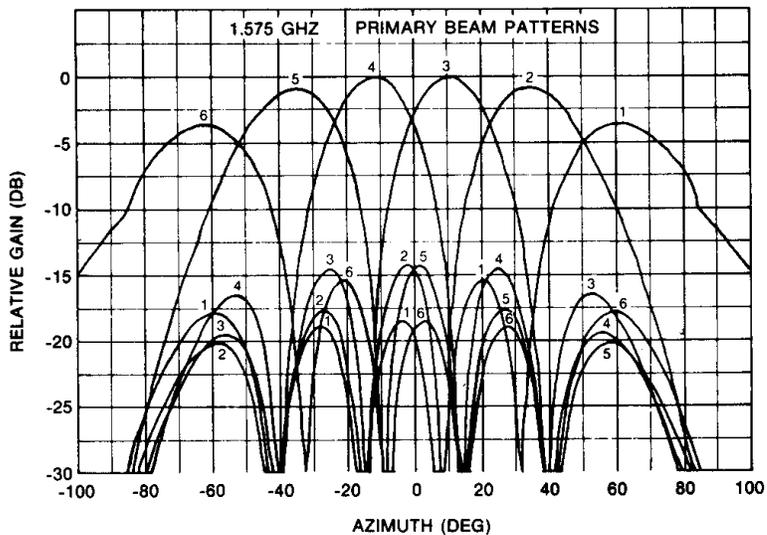


Figure 17. Steered Array Beam Patterns.

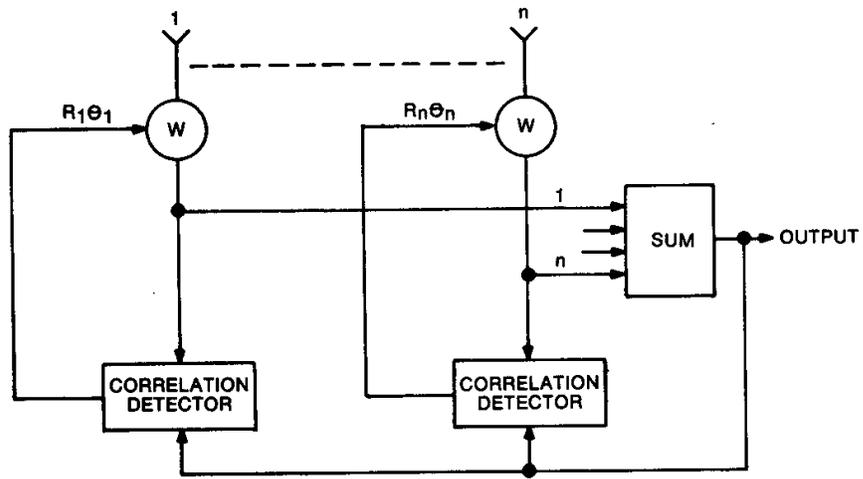


Figure 18. Adaptive Null Steered Antenna.

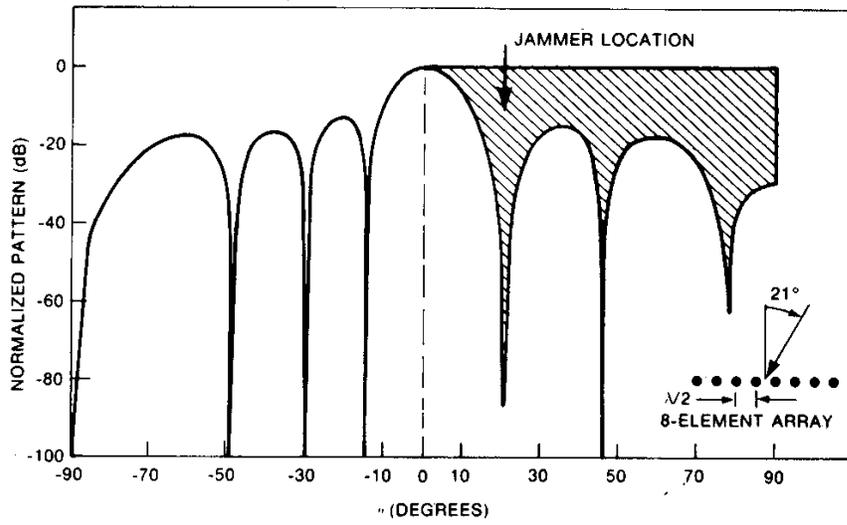


Figure 19. Adaptive Array Response Pattern.

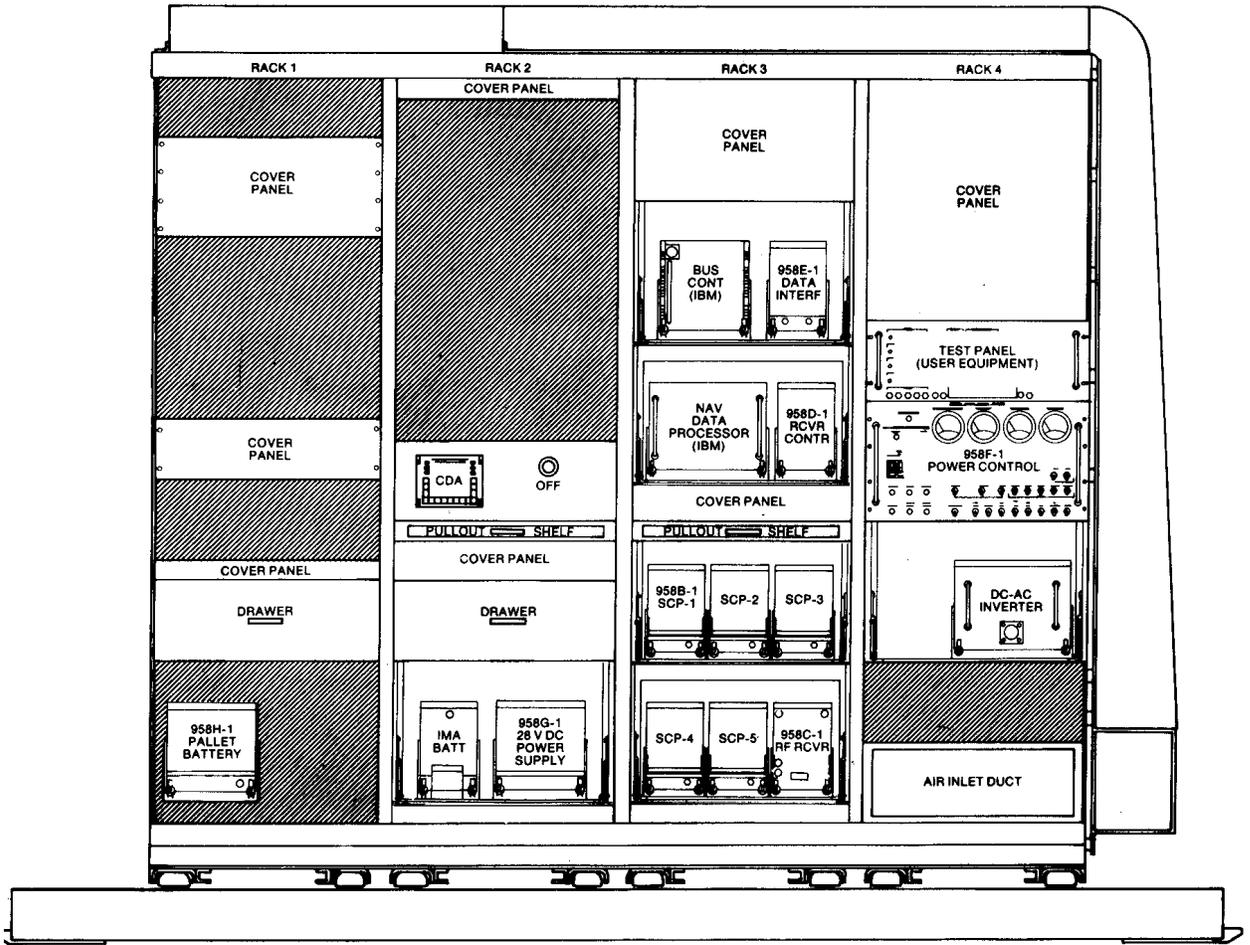


Figure 20. C-141 Pallet Design-Rack Assembly, User Equipment.

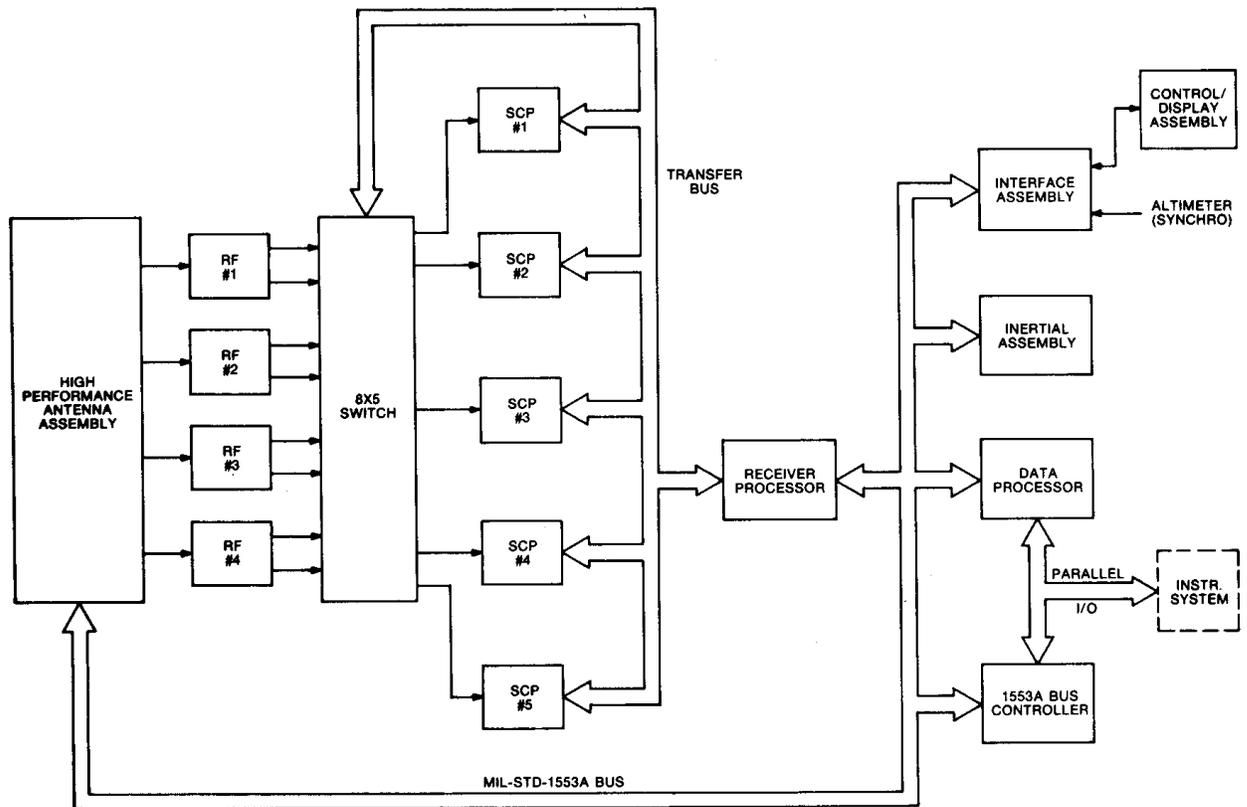


Figure 21. System Block Diagram.