REPORT SAMSO-TR-76-197

Operating Frequencies for the NAVSTAR/ Global Positioning System

Systems Engineering Operations
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30 July 1976

Final Report

APPROVED FOR PUBLIC RELEASE;
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Prepared for

SPACE AND MISSILE SYSTEMS ORGANIZATION
AIR FORCE SYSTEMS COMMAND
Los Angeles Air Force Station
P.O. Box 92960, Worldway Postal Center
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Contract No. F04701-75-C-0076

This final report was submitted by The Aerospace Corporation, El Segundo CA 90245, under Contract F04701-75-C-0076 with the Space and Missile Systems Organization, Deputy for Space Communications Systems, P.O. Box 92960, Worldway Postal Center, Los Angeles CA 90009. It was reviewed and approved for The Aerospace Corporation by E. M. Lassiter, Systems Engineering Operations. Lt Col D. Smith, SAMSO/YEC, was the project engineer.

This report has been reviewed by the Information Office (IOS) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

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REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: SAMSO-TR-76-197
2. GOVT ACCESSION NO.:
3. RECIPIENT'S CATALOG NUMBER:
4. TITLE (and Subtitle): OPERATING FREQUENCIES FOR THE NAVSTAR/GLOBAL POSITIONING SYSTEM
5. TYPE OF REPORT & PERIOD COVERED: Final rept.
6. PERFORMING ORG. REPORT NUMBER: TR-0076(6474-01)-1
7. AUTHOR(s): Frank E. Butterfield
8. CONTRACT OR GRANT NUMBER(s): F04701-75-C-0076
9. PERFORMING ORGANIZATION NAME AND ADDRESS: The Aerospace Corporation, El Segundo, Calif. 90245
10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS:
11. CONTROLLING OFFICE NAME AND ADDRESS: HQ SAMSO/YEE, PO Box 92960, LA CA 90009
12. REPORT DATE: 30 July 1976
13. NUMBER OF PAGES: 46
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office): Space and Missile Systems Organization, Air Force Systems Command, Los Angeles Air Force Station, Los Angeles, Calif. 90009
15. SECURITY CLASS. (of this report): Unclassified
15a. DECLASSIFICATION/DOWNGRADING SCHEDULE:
16. DISTRIBUTION STATEMENT (of this Report): Distribution Statement A — Approved for public release; distribution unlimited
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report):
18. SUPPLEMENTARY NOTES:
19. KEY WORDS (Continue on reverse side if necessary and identify by block number):
Navigation
Ionosphere
Aeronautical Radionavigation
Satellites

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A new aeronautical radionavigation system is being established to provide accurate worldwide navigation. The system employs transmitters mounted in earth orbitting satellites. The choice of operating frequencies for this system is limited by system accuracy on the one hand and satellite cost on the other. The technical basis for frequency choices is given along with the regulatory circumstances, the system options which should be retained, and an explanation of radiated power requirements.

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I. GENERAL

A. PURPOSE

It is the purpose of this report to give the technical background for the choice of operating frequencies and incident power levels for the NAVSTAR/ Global Positioning System (GPS) and to indicate directions in which flexibility for future growth is important.

B. SCOPE

The report covers the required relationships between variables in the frequency assignment considerations without going into depth about the means by which the various characteristics are obtained. A brief system description is also included.

C. SUMMARY

The NAVSTAR/GPS navigation signal frequency choices are constrained on the low side by performance limitations and by frequency allocation actions of earlier years. They are limited on the upper side by the cost of satellites in orbit. Since GPS is now in its initial concept validation phase, some flexibility in its characteristics must be maintained to take advantage of test results that will be obtained over the next several years.

II. NAVSTAR/GLOBAL POSITIONING SYSTEM

A. INTRODUCTION

In December 1973, the United States began implementation of the Concept Validation Phase (Phase I) of the NAVSTAR/GPS. The initial apparatus for this new aeronautical radionavigation program, now nearing completion, consists of six satellites with launch vehicles, a ground operations or control network, and six types of user equipment. This equipment will be emplaced and operated in preparation for consideration for continuation into Phase II, the System Validation Phase. In this phase, a limited worldwide operational capability will be established by 1981 and will consist of nine orbiting satellites uniformly distributed in three orbit planes. Carried on into Phase III, the Production Phase, the system will contain (in 1983 or 1984) eight satellites in each of these three planes for a total of 24.

It is the aim of this system to provide accurate position, velocity, and time information instantaneously and continually to navigators with a wide range of requirements.

It is expected that the system will gain wide acceptance as have navigation systems of the past, and will make significant contributions to air navigation precision and safety.

B. SATELLITES

In Phase I the six satellites will be placed in nearly 12-hr circular orbits inclined 63 deg. Two planes will be used and three satellites will be placed in each plane with angular separations of 40 deg. The satellites in the two planes will be phased so that they converge over the navigation test area in the U.S. with the proper geometrical arrangement for accurate three-dimensional navigation. In Phase II, satellites will be added in a third orbit plane to extend the period of time this favorable geometry exists. Late in the phase, the satellites will be repositioned for uniform distribution in the orbit planes to provide more than two satellites visible at all times from all points on earth. This distribution will provide navigation capability in two dimensions to suitably-equipped users.

The satellites transmit navigation signals through a symmetrically-shaped beam antenna directed toward the earth. This antenna produces a slightly lower intensity at the center of the beam than at the extremities to compensate for the spherical shape of the earth. Consequently, the satellites serve users on the entire visible surface with approximately the same uniform power.

The navigation signals are modulated synchronously with predetermined bit streams of sufficient bandwidth to produce the necessary navigation precision without recourse to two-way transmissions or Doppler integration. The navigation signals are also modulated with ephemeris information so that the satellite's position can be communicated to the users.

At the power levels required with the frequencies chosen for operation, the RF power can be produced by the use of solid state amplifiers in these satellites.

C. CONTROL NETWORK

It is the function of the control network to (1) establish the satellite ephemerides, (2) establish the state of the satellite clocks, (3) command appropriate actions aboard the satellites to keep them synchronized and on proper stations in their orbits, and (4) introduce the necessary information on the satellite transmissions. These functions are performed through monitor stations at Guam, Hawaii, Alaska, and California, and a control station located in California. The observations will be made on the navigation signals. Command will take place through the authorized satellite control frequencies. Some satellite telemetry will also be accomplished by means of authorized satellite telemetry channels.

D. USER EQUIPMENT

User equipment consists of an antenna, a receiver designed for the navigation signals, a navigation computer, and display. By synchronizing locally-generated bit streams with those received from four satellites and then recovering the data contained in the transmissions, the user determines the radio propagation delay between the satellites and his receiver, his location, and finally system time. The radio propagation delay is the basic quantity measured in system operation. It is often termed a "range" since the time delay and distance are related by the speed of light.

In the event the user's location has been established by past measurements, system time can be determined by observation of one satellite.

In order to reduce the number of systems required to produce all the navigation capability needed by the user population, each new system must produce the most service possible for the most reasonable cost. In the aeronautical radionavigator population, both high and low performance aircraft are found; some demand much greater accuracy than others and also have different requirements on freedom from interference, frequency of fix, tolerable time to accomplish a fix, and many other variables.

It has seemed reasonable that NAVSTAR/GPS be capable of providing a navigation capability somewhat superior to Omega at the least cost and yet support a capability much superior to VOR DME, TACAN, and Loran. This service should be available for any attitude of flight, but also should not preclude all reasonable means for interference control, including directive user anter   .

The design process has resulted in the definition of a catalog of user equipments with a considerable range of capabilities and costs, as well as the definition of the radio signal characteristics.

E. REQUIREMENTS

1. SINGLE NAVIGATION TRANSMISSION FREQUENCY

It is an objective of NAVSTAR/GPS to provide economical navigation of reasonable accuracy to a wide range of users. Since the simplest equipment has the lowest cost, it follows that GPS must provide this basic service with a single navigation signal frequency. The fundamental limitation on this service is ionospheric propagation delay. While the effects of the ionosphere are predictable to some degree (and GPS contains provisions for using this characteristic), the effects themselves and the magnitude of unpredictable parts are proportional to the square of signal wavelength. Consequently, it is necessary to choose a primary operating frequency high enough that ionospheric uncertainties are tolerable to a large population of navigators.

Lawrence, et al.[1], gives the propagation time delay caused by ionospheric propagation (the group delay) as an equivalent excess path length,

$$\Delta \ell ' = \frac{1.6 \times 10^3}{f^2} \int_0^s N dl \qquad (1)$$

where N is the density of electrons (number per cubic meter) along the radio path. For typical condition and vertical penetration at 100 MHz, $\Delta \ell ' = 400$ m. This value increases for other angles of penetration and increases by a factor of at least 10 in periods of high ionization.

Many attempts have been made to construct and evaluate models of the ionosphere. It is apparent that at the present time the delay can be predicted with an uncertainty no less than 25 percent. With an allowance of 100 ft for measurement error from this cause, position errors can be restricted to less than 400 ft. Thus, $0.25 \Delta \ell ' \leq 33$ m.

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[1] R. S. Lawrence, et al., "A Survey of Ionospheric Effects Upon Earth-Space Radio Propagation," Proc. IEEE. 52, pp 4-27 (1964).

From the preceding data,

$$\Delta \ell'_{max} = \frac{400 \times 10}{f^2/100^2} F(\alpha)$$

where f is in MHz, and the line-of-sight elevation measured from the horizon is α. Navigators at the earth's surface will find $F(\alpha) \simeq 2.5$ for low angles. The frequency required to meet the criterion is 860 MHz.

Consequently, an operating frequency in the NAVSTAR/GPS must lie above 860 MHz.

2. SIMULTANEOUS OPERATION ON TWO NAVIGATION TRANSMISSION FREQUENCIES

While it is desirable to use a high primary frequency to reduce ionospheric delay uncertainty for single frequency use, it is also desirable to provide a second frequency by means of which the ionosphere delay can be determined by navigators who require greater precision than single frequency operation can provide. The ratio between the second frequency and the primary frequency is important.

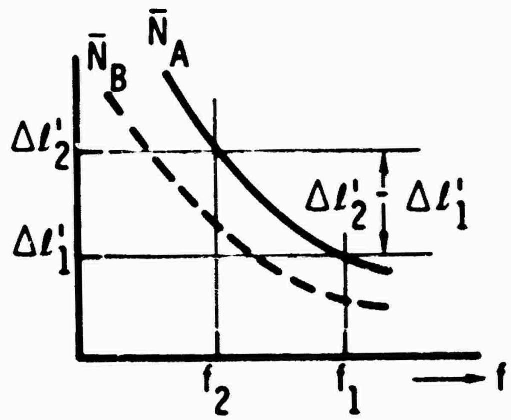

Figure 1. Ionospheric Propagation Delay as a Function of Frequency

Figure 1 shows the propagation delay function for two values of $\overline{N}$ where $\overline{N} = \int_0^s N dl$. In the operation of GPS, the magnitude of $\overline{N}$ is generally unknown and the observations at two frequencies are intended to find it, or more perticularly to find $\Delta \ell'_1$. The quantity $\Delta \ell'_2 - \Delta \ell'_1$ can be obtained from the range measurements on the two frequencies, f_1 and f_2. However, these measurements can be made only to a precision governed by the received signal-to-noise ratio and the degree to which the transmissions are synchronized when they leave the satellites. Consequently, the difference $\Delta \ell'_2 - \Delta \ell'_1$ must be recognized to be uncertain by $\sqrt{\delta_2^2 + \delta_1^2}$ where δ_2 and δ_1 are measurement errors associated with the respective frequencies.

From Eq. (1),

$$\Delta \ell'_1 = \frac{K}{f_1^2} \quad , \quad \Delta \ell'_2 = \frac{K}{f_2^2}$$

$$\Delta \ell'_2 - \Delta \ell'_1 = K\left[\frac{1}{f_2^2} - \frac{1}{f_1^2}\right] = D$$

$$K = D\left[\frac{f_1^2 f_2^2}{f_1^2 - f_2^2}\right]$$

and

$$\Delta \ell'_1 = \frac{D}{f_1^2}\left[\frac{f_1^2 f_2^2}{f_1^2 - f_2^2}\right] = D\left[\frac{1}{\left(\frac{f_1}{f_2}\right)^2 - 1}\right]$$

The error in determining $\Delta \ell_1'$, then, is greater than the error caused by receiver noise in measuring a single range by the factor

$$M = \sqrt{2}\left[\frac{1}{\left(\frac{f_1}{f_2}\right)^2 - 1}\right]$$

M is plotted in Figure 2 as a function of $\frac{f_2}{f_1}$.

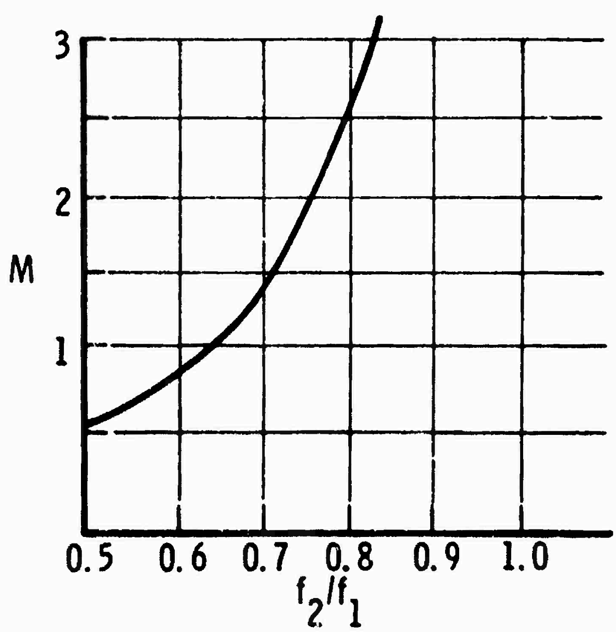

Figure 2. Error Multiplier in Ionospheric Delay Determination

In the GPS system, the range measurement error budget is roughly equally allocated to receiver noise, atmospheric uncertainties (ionosphere plus troposphere), space vehicle ephemerides and time uncertainties, and multipath uncertainties. To use a value of $M > 2$ raises the RMS value of the total range measurement by more than 25 percent and seriously compromises accuracy. It is clear that a value of f_2/f_1 like 0.63 would be desirable, giving $M = 1$. However, if the ratio becomes too small, it is inconvenient to accommodate f_1 and f_2 in the same antenna and preamplifier, and the expense of user equipment increases. A ratio of 0.7 is about the limit permitted by the current "state of the art."

The preceding analysis was performed on the principal terms in the full expression for $\Delta \ell'$. There remain bias terms that amount to approximately 3 percent of $\Delta \ell'$. That is, the two frequencies cannot be chosen so low that $0.03\, \Delta \ell'$ exceeds the tolerable uncertain bias. Table I[2] gives the expected system measurement error budget for precise navigation. It is clear that an additional bias-like error component in excess of 8 ft would seriously affect system performance. Then $\Delta \ell'$ is constrained to about 80 m

$$\Delta \ell' \le 80 \text{ m}$$

$$\frac{400 \times 10 \times 2.5}{f^2/100^2} \le 80 \text{ m}$$

$$1120 \le f$$

and carrier frequency has to exceed 1120 MHz. Consequently, one operating frequency must lie above 1120 MHz and the ratio of the frequencies should lie between 0.7 and 0.78.

3. OPERATION WITH TWO SIGNAL BANDWIDTHS AND APPROPRIATE POWER LEVELS

The precise navigation error budget of Table I is inconsistent with the less precise navigation discussed in Section II. E. 1 in connection with limits on ionosphere delay models. The cost of a user equipment built to Table I

[2] SAMSO System Specification for the NAVSTAR/GPS Phase I, SS-GPS-101B, Space and Missile Systems Organization, USAF (15 April 1974).

Table I. GPS Error Budget

All Values 1σ	
Space Vehicle Ephemeris	5 ft (nsec)
Atmosphere	8 to 17[a]
Space Vehicle Group Delay	3
Receiver Noise	5[b]
Multipath	4 to 9[c]
RSS	12 to 21

[a]8 ft - night, zenith penetration, ionosphere modeled plus troposphere

17 ft - two-frequency measurement plus troposphere

[b]In interference

[c]4 ft - typical of aircraft

9 ft - ground navigator

but performing the task described in Section II. E. 1 would be excessive. For less precise navigation, with its large ionosphere delay errors, more multipath and receiver noise uncertainty is also tolerable. It is also possible that the less precise navigation takes place in an environment of less intense interference. The following sections will show that precise navigation with small multipath errors, small receiver noise errors, and great interference rejection requires greater signal bandwidth than does the less precise navigation. Since the generation, control, and maintenance (through amplifier stages) of the wider bandwidth is more costly than the same functions for narrower bandwidth, a pair of signal bandwidths is found to be consistent with the aim of a low cost, low precision navigation service and simultaneously a high precision, high performance service. Consequently, the GPS signal on f_1, the primary frequency, has this duality of bandwidth. It is described in detail in Section III. A, "Navigation Signals."

The narrowband component, called the C/A signal, conveniently complements the P or precision signal, the wideband component, by functioning as a P signal acquisition aid. Because of this relationship, it is convenient to make these signal components synchronous in several ways and to make the P signal bandwidth precisely ten times the C/A signal bandwidth.

The quality of service provided navigators in GPS depends upon the power delivered as well as the operating frequency and bandwidth. There is one GPS function related solely to received power and that is the "data recovery" function.

The GPS signal includes data modulation at 50 bps which must be received with low error rate. Consequently, signal level must exceed noise density by about 30 dB as a minimum. A margin of 9 dB has been deemed a reasonable value to account for user equipment variations and to permit the wide bandwidths required during signal acquisition.

GPS is generally designed to permit the simplest practical navigating equipment and to constrain the navigator as little as possible. It is most convenient for the navigator to use an essentially omnidirectional antenna that has an effective area of $\lambda^2/4\pi$ sq m. It is also convenient for the navigator to use a simple amplifier for the first stage of his receiver that produces a noise level of about -199 dBW/Hz. The dependence of the user antenna effective area on λ^2 suggests a corresponding f^2 dependence for transmitted power.

However, it is impossible to maintain capability at higher frequencies by only increasing power. The reason is that higher carrier frequencies imply greater carrier frequency uncertainty caused by the limited stability of natural frequency sources, and by the higher Doppler components that result from dynamics. This carrier frequency uncertainty is reflected in necessarily greater bandwidths in user equipment, and correspondingly further increased requirements for power.

The Doppler effects of dynamics can be accommodated by increasing user tracking loop bandwidths and transmitter power by the factor $f^{1/2}$ for second order loops and $f^{1/3}$ for third order loops. Choosing the first, satellite power is then required to follow the relationship.

$$P_{f_b} = P_{f_a}\left(\frac{f_b}{f_a}\right)^{5/2}$$

With these factors in mind, Figure 3 has been computed, which gives the minimum values deemed us .e for incident power and peak power density at the earth's surface. To obtain transmitter power output required of a satellite, multiply these values by the projected area of the earth ($10^{14.1}$ sq m), spacecraft antenna loss, and any margins for correlation loss, undesired variations, and safety factors.

These minimum values m. .st be delivered by satellites through antennas whose patterns cannot be absolutely uniform, from effective distances between 11,000 and 13,000 nmi, through ionospheric scintillations, tropospheric absorption, at the beginning and end of satellite life. A reasonable margin for these variables is 10 dB (i.e., at 1575 MHz the GPS system should not be restricted to power density less than -149 dBW/sq m/4 kHz if it is to serve its worldwide population of users reliably).

4. DISCRIMINATION AGAINST MULTIPATH

Propagation of radio waves by reflections from the navigating aircraft itself or the ground, in addition to the direct line of sight, limits every radionavigation system. In many systems, the interference from reflected waves results in measurement errors of both signs, which causes the observed range to be greater or less than the true range. The magnitude of such

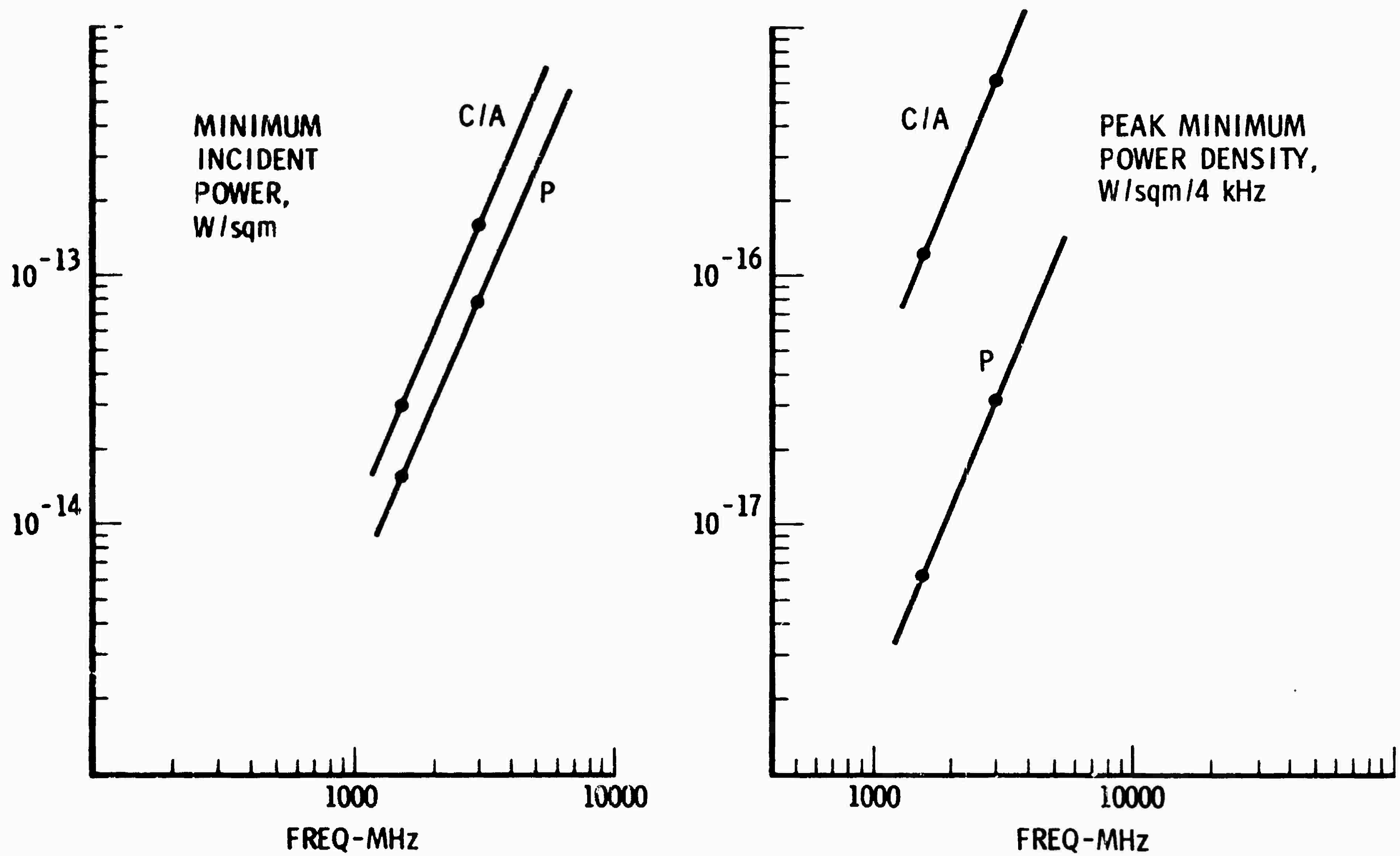

Figure 3. Minimum Power Density Acceptable for Operation with Omnidirectional Antennas; Add 10 dB for Spacecraft and Propagation Margin

errors depends in a complicated way upon the amount of excess delay represented by the reflection path.

Multipath propagation effects are most easily assessed by examination of the correlation function, $R(\tau)$, for the transmitted waveform. The effects are minimized when significant values of the correlation function are restricted to small multipath delays, τ.

Properly designed pseudo-noise (PN) waveforms exhibit excellent correlation functions in this regard and consequently have been chosen for GPS. The Phase I GPS uses PN codes that have a single main autocorrelation peak for each code period as shown in Figure 4.

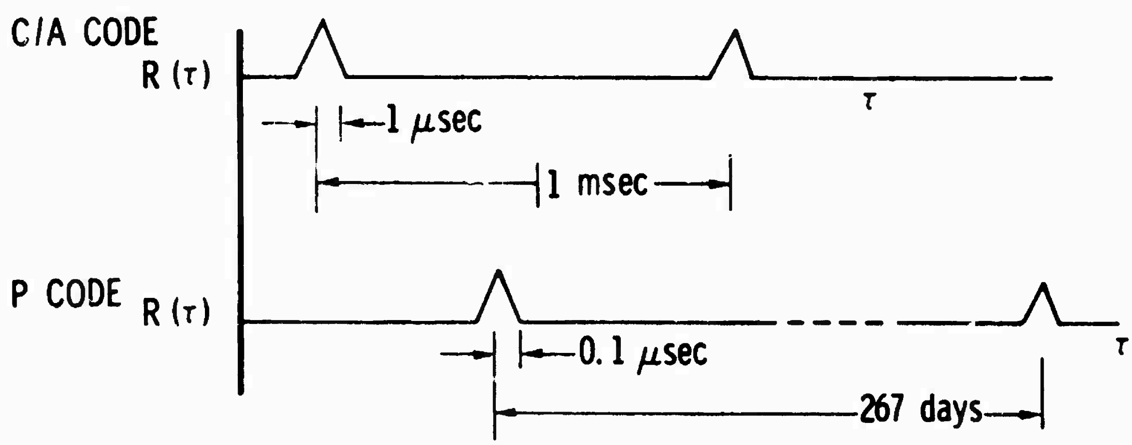

Figure 4. Autocorrelation Functions

Consequently, a receiver that is tracking these signals is insensitive to multipath signals that arrive more than 2 or 0.2 μsec delayed, respectively. These correlation properties are a result of the signal bit rates and thus the signal bandwidths. For operations near the ground, where short delays are encountered, even greater bandwidths are desirable. The GPS bandwidths have been chosen for simplicity in equipment, and only test experience will disclose if they are adequate.

5. DELIVERY OF ACCURATE RESULTS IN FACE OF INTERFERENCE

An expression which succinctly represents receiver performance is the one for measurement error in the code tracking loop. For a coherent detection receiver[3]

$$\sigma_\tau = \Delta \left[\frac{B_L N_d}{2C} \right]^{1/2} \qquad (2)$$

where

σ_τ = standard deviation of measurement, sec

Δ = length of shortest modulation interval, sec

$= \frac{1}{\text{bit rate}} = \frac{2}{\text{RF bandwidth}}$

B_L = code tracking loop bandwidth, Hz

C = carrier signal, W

N_d = noise density, W/Hz

First, measurement error is seen to be inversely proportional to RF bandwidth. Second, since there is a lower limit on N_d, the thermal noise density, there is a lower limit on received signal power. Once that power level is exceeded, accuracy improves, or alternatively, noise which is the consequence of interference can be tolerated. Good design requires sufficient power so that thermal noise can be exceeded by at least an order of magnitude, and in operation at rated accuracy, N_d can be almost entirely the result of interference. In the correlator, which precedes the code tracking loop, CW interference is converted to a spectrum identical to the GPS transmitted spectrum.

[3] C. R. Cahn, Spread Spectrum Applications and State of the Art Equipments, Report MX-TM-3134-72, Magnavox Research Laboratory.

while the reverse occurs with regard to the signal. Thus the maximum magnitude of N_d is equal to the interference power, I, divided by 1/2 the RF bandwidth of the signal, or

$$N_d = I\Delta$$

If this is substituted into Eq. (2)

$$\sigma_\tau = \Delta\left[\frac{B_L I\Delta}{2C}\right]^{1/2} \tag{3}$$

and

$$I = 2C\,\sigma_\tau^2/B_L \cdot \Delta^3$$

Tolerable interference is thus directly proportional to received power and to the third power of bandwidth. This strong dependence of tolerable interference on bandwidth is the reason that GPS Phase I design calls for P signal bandwidth between first spectral nulls of 20 MHz. This strong dependence is also the reason that GPS should have some flexibility to use higher code rates when it becomes economical to implement them in hardware. If frequency hopping is involved, the Δ's outside and inside the brackets in Eq. (3) are not the same. Frequency hopping in addition to PN modulation can be used for interference rejection without influencing accuracy.

Of course, Eq. (2) is not the only criterion. Present receivers tolerate only limited values of σ/Δ without losing lock. Besides measuring accurately, receivers must also recover carrier and data, and these functions also impose limitations on noise which are generally of the same nature but differ in magnitude.

RF bandwidth is also important in keeping GPS from interfering with other services, since GPS radiated power spectral density is lower for wider bands.

It is not obvious that widening the spectrum is advantageous when the ground transmitting neighbors of GPS are considered. They are sure to include some powerful pulse transmitters. Spectrum control notwithstanding, sidebands of these transmissions lie in the GPS passband and GPS receivers incorporate pulse clippers to cope with them. But GPS selectivity is limited also, and neighboring transmissions appear at GPS first mixers with finite amplitudes. The GPS correlator has a wideband local reference that converts strong out-of-band signals into weak interference that competes with legitimate satellite signals. The correlator local reference input amplitude distribution is shown in Figure 5. Correlator output is proportional to these amplitudes for CW signals at the frequencies shown. As the figure illustrates, doubling the bit rate reduces the output from interference in the central 20 MHz, but increases the output from interference just outside that range. It may not be a wise step if the band is "hemmed in" by strong neighbors, especially if the RF filter has to be widened much to preserve the correlation properties of legitimate signals.

In conclusion, to provide accuracy and resist interference, it is important for GPS to maintain options to increase power and bandwidth but they must be exercised carefully. Even if they are exercised on only one frequency they can ultimately add significant margin against purposeful interference.

6. ADHERENCE TO ITU REGULATIONS AND USAF/KRCF GUIDANCE

With reference to the "Revision of the Table of Frequency Allocations" Series B13, amended, as approved at the second reading at the 11th Plenary Meeting on 16 July 1971, the following frequency bands are identified as allocated to use for aeronautical radio-navigation involving satellites:*

149.9 - 150.5 MHz
(328.6 - 335.4 MHz) (not specifically allocated to satellites)
399.90 - 400.05 MHz
1558.5 - 1636.5 MHz

*Stanford Research Institute published a report entitled "Study of Frequency Selection for Com/Nav Satellite Systems" (SRI No. CSD-69-101/3) in April 1969. This report was an antecedent of the frequency allocation.

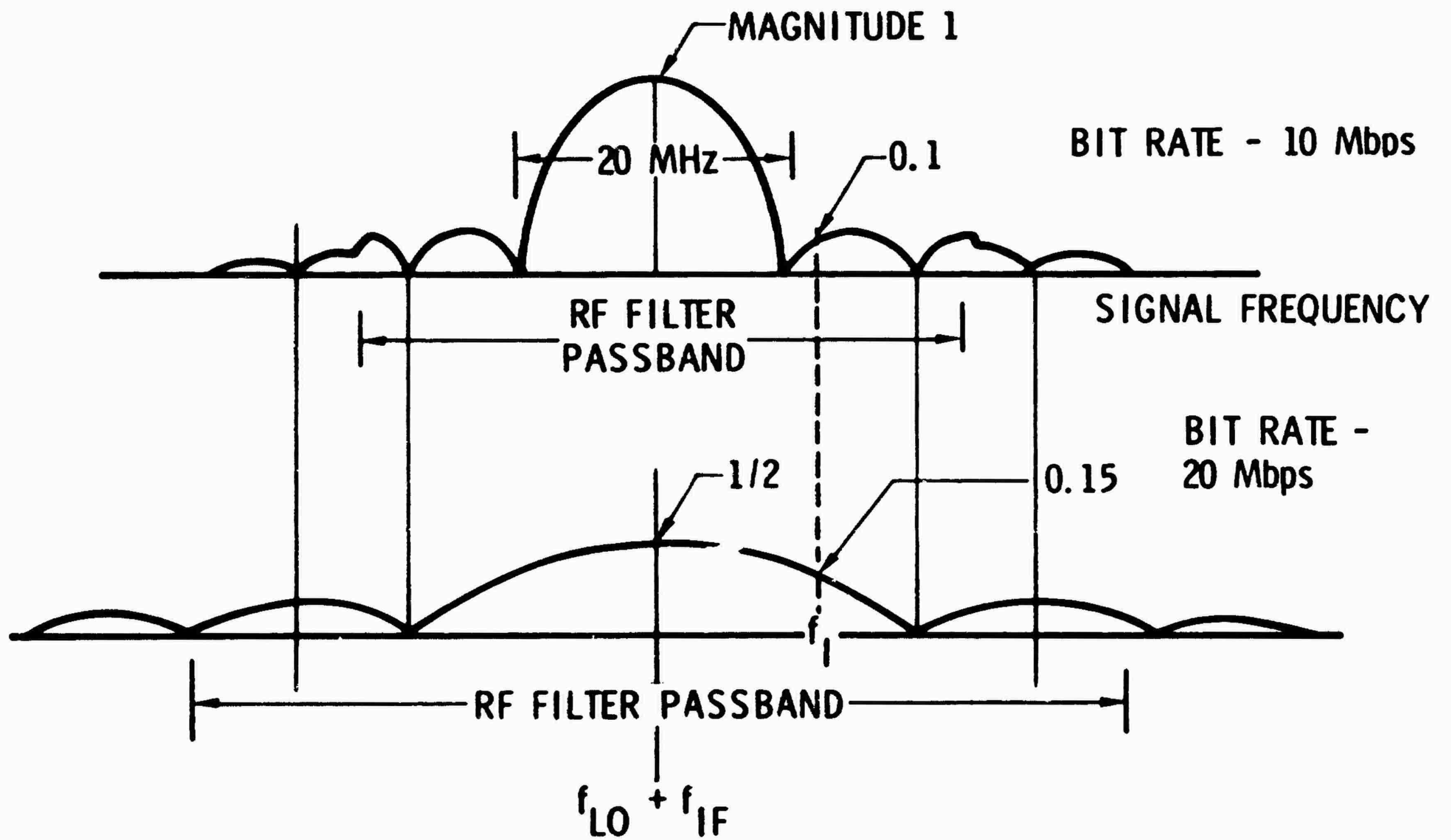

Figure 5. Correlator Output for Uncorrelated Input Signals

4200 - 4400 MHz

5000 - 5250 MHz

15.4 - 15.7 GHz

Guidance provided by the Frequency Management office in 1972 was to the effect that the primary frequency be chosen in the allocated 1558 - 1636 MHz band, and the secondary frequency be chosen in the 1215 - 1250 MHz band.

For reference, Appendix A contains the regulations and notes applicable to these frequency bands. It is interesting to note the difference in wording between notes G111, 112 and the earlier notes such as 470 NE which specified incident power limits in other frequency bands to be a function of incidence angle.

7. OTHER INFLUENCES

a. Antenna Directivity

The NAVSTAR/GPS uses antenna directivity to obtain or optimize some of its characteristics. The satellite employs an array that produces a pattern shaped to make the power density at the earth uniform over the surface. Some user equipments employ directivity to discriminate against interference. These functions are more easily produced at higher frequencies and the influence is for higher frequency choices in all circumstances. For example, the simple antenna that produces 20 dB of suppression of an interference signal when operated at one frequency produces only 5 dB of suppression when operated at half that frequency.

b. Radio Noise

The radio noise incident on the antenna of GPS users is of considerable concern to the system designers. While it is a highly variable quantity, it generally diminishes as the operating frequency increases. A great deal of data has been published[4,5] on the subject and generally indicates that

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[4]ITT, Reference Data for Radio Eng ieers, Fourth Edition, 763.

[5]E. N. Skomal, "Man-Made Noise in t e M/W Frequency Range," The Microwave Journal, 18, (1) (January 1 75).

manmade noise is the predominant constituent at frequencies above 100 MHz. Further, man-made noise at the present time is an important source of interference below 1000 MHz. This factor influences operating frequency choices for GPS to be made above this value.

c. Atmospheric Attenuation

Both computed results and experience show atmospheric attenuation (predominantly the result of moisture of one form or another) to be significant at frequencies higher than 3000 MHz. Consequently, exceeding this value in choosing a frequency for GPS penalizes the system and requires additional power to provide operating margin.

d. Ionospheric Scintillation

Serious scintillation of signals propagating through the ionosphere has been observed, particularly at certain latitudes. Since the observations are limited, any real dependence on frequency has not been established. Furthermore, effects on group delay have not been measured. Consequently, at the present time, the only accommodation the GPS can make to this phenomenon is to make allowance in the power margin provided in the system.

e. Ionospheric Dispersion

Equation (1) indicates the dispersive nature of the ionospheric propagation medium. For a wideband signal width, this characteristic leads to distortion and loss of performance. Jones and Leong[6] have computed the effects of distortion on the correlation function for the GPS waveform. They show a correlation loss corresponding to 2 dB for a linear variation of delay of 67 m across the signal bandwidth. By using the values of Section II. E. 6 for high ionization and zenith penetration,

[6] J. J. Jones, and W. K. S. Leong, Filter Distortion Effects on Correlation Detection and Ranging Accuracy, Technical Memo 216, Communications Sciences Dept., Philco Ford Corporation, Western Development Laboratory.

$$\Delta \ell ' = \frac{400 \times 10 \text{ m}}{f^2/100^2}$$

where f is in MHz. If f_+ is taken to be the upper edge of the transmitted frequency band, $f_+ = f + 10$ for the 20 MHz bandwidth of GPS.

$$\Delta \ell'_f - \Delta \ell'_{f_+} \leq \frac{67}{2}$$

$$4 \times 10^7 \left[\frac{1}{f^2} - \frac{1}{(f + 10)^2} \right] \leq 38$$

$$4 \times 10^7 \left[\frac{f^2 + 20f + 100 - f^2}{f^2 \left(f^2 + 20f + 100 \right)} \right] \leq 38$$

Then, approximately, $f \geq \sqrt[3]{20} \times 10^2$ or 280 MHz, in order that dispersive effects be less than 2 dB for vertical penetration and greater for other angles. Cahn has estimated the frequency limit at 400 MHz.[7]

[7] C. R. Cahn, Timation Modulation Study, Report 4439, Magnavox Research Laboratory (31 August 1972).

III. PHASE I DESIGN

A. NAVIGATION SIGNALS

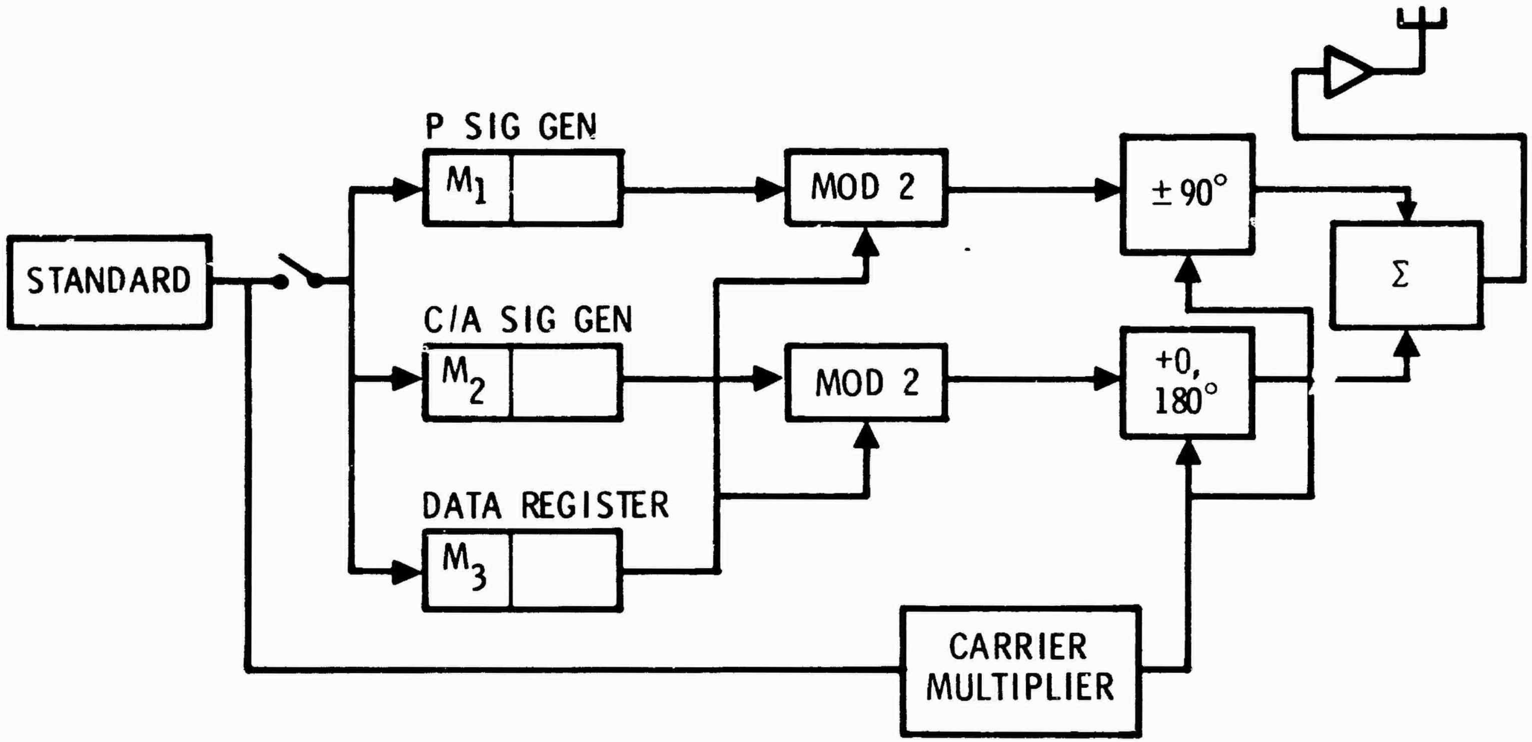
Satellite navigation transmissions are stable, phase-modulated carriers. At 1575.42 MHz, two modulations are used simultaneously. The first is one long pseudo-random binary sequence with shortest interval of 98 nsec deviating a carrier component ± 90 deg. The second is a periodic pseudo-random binary sequence with shortest interval of 980 nsec and repetition rate of 1000 complete sequences per sec. The second binary sequence deviates a second carrier component 0 and 180 deg. The first sequence is called the P sequence, the second the C/A sequence. Their transitions are simultaneous and their epochs are common. Daily ephemeris and clock state estimates are added in binary form (modulo 2) to both the P and C/A sequences at 50 bps. The carrier components are combined prior to transmission. Conceptually, the process is illustrated in Figure 6.

Only the P sequence and data are ordinarily applied to the 1227.6 MHz carrier in the Phase I satellites. Upon command, the C/A sequence can be substituted.

The satellites are required to produce the output shown in Table II from the antenna specified at all observation angles greater than 5 deg above the horizon.

Table II. Signal Levels from Linearly Polarized Antenna with 3 dB Gains

	Signal	
Channel	P	C/A
1575 MHz	-163 dBW and	-160 dBW
1227 MHz	-166 dBW or	-166 dBW
All transmissions are RHCP		



M_1, M_2, M_3 - FREQUENCY MULTIPLIERS

Figure 6. Signal Assembly and Modulation for 1575 MHz Carrier

The same levels are, of course, observed on omnidirectional, circularly-polarized antennas.

B. SATELLITE COST

The recurring cost per pound of manufactured articles, like satellites, is constant over a wide range. If relationships between the technical properties of GPS satellites and their weights can be established, then the relationship with cost follows directly.

The main function of Phase I GPS satellites is to convert DC energy developed by their solar arrays into RF power in the navigation signals.

Rockwell International engineers have established that around the GPS satellite design point, 1 W of RF output power requires 5 lb of satellite weight. That is, $W_{SV} = W_o + 5 \times P$

Section II. E. 3 shows the power density (and hence total power) requirements for GPS as a function of frequency. From that section,

$$W_{SV} = W_o + 5 \times P(f)$$

$$W_{SV_2} = W_o + 5 \times P_1 \left(\frac{f_2}{f_1}\right)^{5/2}$$

While the entire weight of the spacecraft is not directly connected with power conversion, even small changes in weight require changes in launch vehicles and these do not represent a continuum in cost or capability.

Figure 7 shows estimated costs of satellites "installed" on orbit, in relation to those of the Phase I satellites, as a function of operating frequency. Each of the cases shown is based on a different but reasonable launch arrangement. They all represent the increase in satellite weight as proportional to power output. Since these estimates were made without the benefit of complete designs, some uncertainty exists about them as represented by the vertical bars on Figure 7.

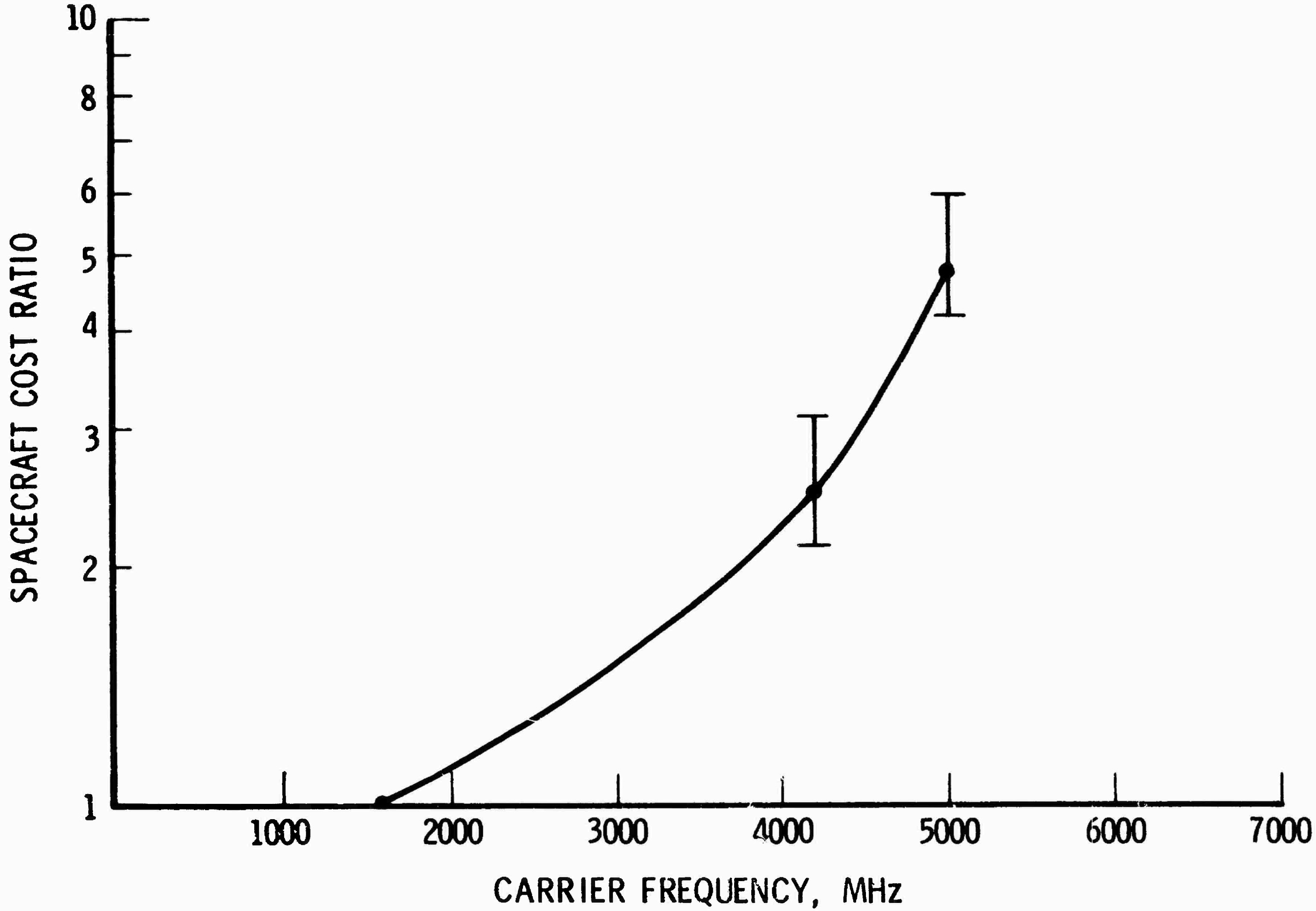


Figure 7. Satellite Costs Related to Phase I

In any event, doubling the cost of GPS satellites without improving the capability of the system, which is the case for both these estimates, is certainly to be avoided.

IV. INTERFERENCE

GPS occupies shared bands and is presently a secondary service in both. The 1215 - 1250 MHz band contains some radars, some TACAN and higher frequency radar side bands, and amateur service. The amateur service is entitled to protection.[8] The 1558 - 1660 MHz band includes radar altimeters, Aerosat, Marisat, perhaps collision avoidance systems, and undoubtedly harmonics of several lower frequency services. In Europe it also contains installations for Fixed Service which are entitled to protection. Finally there are radio-astronomy bands at 1400 - 1427, 1612, 1665, and 1720 MHz, all of which request or are entitled to protection.

TACAN and radar signals are accommodated by pulse limiting in GPS receivers. CW interference suffers the processing gain (loss) of the PN modulation. While actual performance of GPS in its environment is yet to be established, estimates have been made of all of the known circumstances. Many of these are a matter of record. Some of those which are not are given below.

A. AMATEUR SERVICE

The GPS Phase I incident power on the 1227 MHz transmission is -143 dBW/sq m and -177 dBW/sq m/4 kHz. With a 6 dB noise figure receiver the thermal noise in 4 kHz is -162 dBW. An amateur antenna of 1 sq m directed at the GPS satellites leaves the signal 15 dB below thermal noise.

B. FIXED SERVICE

The GPS Phase I incident power on the 1575 MHz transmission is -135 dBW/sq m on the C/A code and -138 dBW/sq m on the P code. These correspond to -159 dBW/sq m/4 kHz on C/A and -172 dBW/sq m/4 kHz on P, on the average. The C/A sequence is periodic, however, and exhibits spectral lines separated 1 kHz with amplitude of -165 dBW/sq m/line. They are not of constant frequency since they contain the Doppler component due to satellite motion. The line width is 100 Hz as the consequence of data modulation.

[8] Message RUEFHQA0301 171956z Oct. 74.

Consider the P signal where the energy is uniformly distributed like noise. Received on a 1 sq m antenna, its level is -208 dBW/Hz, well below the level that might be expected of a high quality, fixed service receiver. As for the C/A code, the line peak power density is about -165-17 = -182 dBW/Hz when received on a 1 sq m antenna. This would be discernible on a narrow spectrum analyzer if it were stable in frequency. The average energy near the carrier, however (-195 dBW/Hz), is only about equal to the expected receiver thermal noise. The average over a TV channel is about -198 dBW/Hz. The fleeting contacts between satellites and fixed service receivers are not expected to be more serious than an ordinary fade.

C. INTERFERENCE TO GPS BY FIXED SERVICE

To assess the effects of fixed service on GPS, some assumptions have to be made about transmission bandwidth, power, and directivity. If the service is taken to be 4 kHz voice channels operating at +40 dB S/N, each channel allocated 50 kHz of RF bandwidth, the distance is 30 mi, and the path is line of sight, then 1 sq m antennas with gain of 25 dB seem reasonable. The path loss from an omnidirectional antenna to a 1 sq m antenna is

$$4\pi(30)^2 \times (1852)^2 = 3.7 \times 10^{10}, \text{ or about } 106 \text{ dB}$$

With a receiver NF of 10, thermal noise in 4 kHz is -158 dBW and signal is -118 dBW. The effective radiated power (ERP) required is -12 dBW and transmitter power -37 dBW per channel. This energy is diminished in the GPS receiver by the processing gain to the carrier loop bandwidth of 20 Hz. For the P signal, the processing gain is 57 dB, so effective ERP is -69 dBW per channel. At 1 mi, path loss to a GPS omnidirectional antenna would be 76 + 25 = 101 dB, and power delivered to the carrier loop -170 dBW per channel, which is about the tolerable limit. Consequently, GPS will suffer interference when flying through the beam of fixed service stations at short range if the transmissions are close to the GPS carrier. The beamwidth of a 25 dB gain antenna is 10 deg. The GPS program includes several elements to combat such interference (integration with IMUs, antennas that discriminate against isolated and ground sources). The severity of interference will not be predictable until the population of fixed service stations is understood. In the 1558 - 1636 MHz band, GPS is not protected by regulation. In the 4200 - 4400 MHz band, commercial aircraft would be protected.

D. RADIO-ASTRONOMY

All users of the RF spectrum are obligated to plan for protection of certain frequency bands used for radio-astronomy. The guide used by GPS is "Annex 7-1" starting on page 223. This calls for protection for continuum observations at 1400 - 1427 MHz (page 233) and for line observation protection at 1420 and 1665 (Table 7-1-II and Appendix II, footnote 353A).

Figure 8 gives the average values for the GPS power spectrum, calculated from

$$SB = -10 \log[(n + 1/2)\pi]^2 + S_{peak\ density/Hz} - 3$$

where

SB = average sideband level in dBW/sq m/Hz

n = number of the sideband, counting from the carrier

$S_{peak\ density/Hz}$ = peak density of the signal in dBW/sq m/Hz

The term "-3" accounts for the fact that the average values of the power spectrum are, of course, 3 dB lower than the peak values.

The GPS Phase I spectrum levels meet the line observation interference criteria without filtering at 1420 and 1665 MHz.

The satellites contain a diplexer which is used to combine the 1227 and 1575 MHz modulated carriers into a common transmitting antenna. The selectivity of the filters in this diplexer has not yet been established

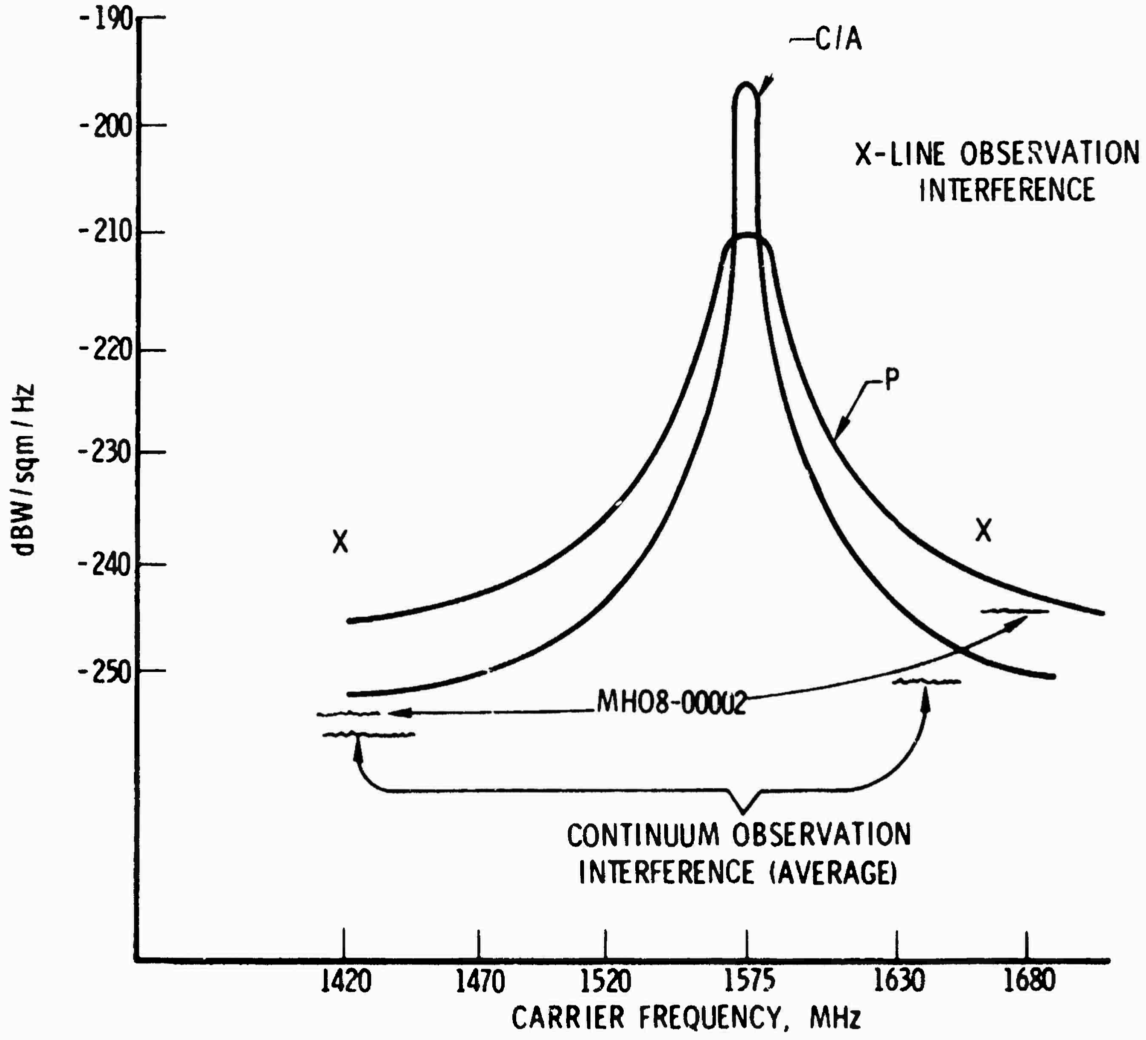


Figure 8. Average Sideband Levels for Phase I GPS[9]

[9] Space Vehicle Nav. System and NTS PRN Nav Assembly/User System Segment and Monitor Station Interface Control Document, MH08-00002-400, Rockwell International.

by test and it is too early to determine if the additional 9 dB required at 1420 and 1665 MHz to prevent interference to continuum observations will be obtained.

APPENDIX A

ITU REGULATIONS FOR GPS FREQUENCY BANDS

960-1215	AERONAUTICAL RADIONAVIGATION 341	960-1215	G, NG 341	AERONAUTICAL RADIONAVIGATION	AERONAUTICAL RADIONAVIGATION
1215-1300	RADIOLOCATION Amateur 342 343 344 345	1215-1300	G, NG US34	RADIOLOCATION G12 G55 G56 G111	Amateur
1300-1350	AERONAUTICAL RADIONAVIGATION 346 Radiolocation 347 348	1300-1350	G, NG 346	AERONAUTICAL RADIONAVIGATION Radiolocation G2	AERONAUTICAL RADIONAVIGATION

1535-1542.5	MARITIME MOBILE-SATELLITE 352 352D 352E	1535-1542.5	G, NG 352E US39	MARITIME MOBILE-SATELLITE	MARITIME MOBILE-SATELLITE
1542.5-1543.5	AERONAUTICAL MOBILE-SATELLITE (R) MARITIME MOBILE-SATELLITE 352 352D 352F	1542.5-1543.5	G, NG 352F US39	AERONAUTICAL MOBILE-SATELLITE (R) MARITIME MOBILE-SATELLITE	AERONAUTICAL MOBILE-SATELLITE (R) MARITIME MOBILE-SATELLITE
1543.5-1558.5	AERONAUTICAL MOBILE-SATELLITE (R) 352 352D 352G	1543.5-1558.5	G, NG 352G US39	AERONAUTICAL MOBILE-SATELLITE (R)	AERONAUTICAL MOBILE-SATELLITE (R)
1558.5-1636.5	AERONAUTICAL RADIONAVIGATION 352 352A 352B 352D 352K	1558.5-1636.5	G, NG 352A 352B US39 US39A US208	AERONAUTICAL RADIONAVIGATION G54 G112	AERONAUTICAL RADIONAVIGATION
1636.5-1644	MARITIME MOBILE-SATELLITE 352 352D 352H	1636.5-1644	G, NG 352H US39	MARITIME MOBILE-SATELLITE	MARITIME MOBILE-SATELLITE
1644-1645	AERONAUTICAL MOBILE-SATELLITE (R) MARITIME MOBILE-SATELLITE 352 352D 352I	1644-1645	G, NG 352. US39	AERONAUTICAL MOBILE-SATELLITE (R) MARITIME MOBILE-SATELLITE	AERONAUTICAL MOBILE-SATELLITE (R) MARITIME MOBILE-SATELLITE
1645-1660	AERONAUTICAL MOBILE-SATELLITE (R) 352 352D 352J	1645-1660	G, NG 352J US39	AERONAUTICAL MOBILE-SATELLITE (R)	AERONAUTICAL MOBILE-SATELLITE (R)

(International Footnotes)

332A Within the frequency band 620-790 MHz, assignments may be made to television stations using frequency modulation in the broadcasting-satellite service, subject to agreement between the administrations concerned and those having services, operating in accordance with the Table, which may be affected (see Resolutions Nos. Spa 2-2 and Spa 2-3). Such stations shall not produce a power flux density in excess of the value -129 dbW/m^2 for angles of arrival less than 20° (see Recommendation No. Spa 2-10) within the territories of other countries without the consent of the administrations of those countries.

333 In Region 1, stations of the fixed service using tropospheric scatter may operate in the band 790-960 MHz subject to agreements between the administrations concerned and affected. Such operations in the band 790-860 MHz shall be on a secondary basis to those of the broadcasting service.

334 In Belgium, France and Monaco, the band 790-860 MHz is allocated to the broadcasting service.

335 In Australia, the band 470-500 MHz is allocated to the fixed and mobile services.

336 In China, Korea, Japan and the Philippines, the band 585-610 MHz is also allocated to the broadcasting service.

337 In Australia, the band 585-610 MHz is allocated on a primary basis to the broadcasting service and on a secondary basis to the radionavigation service.

338 In Australia, the band 610-820 MHz is allocated to the broadcasting service; the bands 820-890 MHz and 942-960 MHz are allocated to the fixed service.

339 In India and Pakistan, the band 610-960 MHz is allocated to the broadcasting service.

339A Specific portions of the frequency band 900-960 MHz may also be used, on a secondary basis, for experimental purposes in connection with space research.

340 In Region 2, the frequency 915 MHz is designated for industrial, scientific and medical purposes. Emissions must be confined within the limits of ± 13 MHz of that frequency. Radiocommunication services operating within these limits must accept any harmful interference that may be experienced from the operation of industrial, scientific and medical equipment.

341 The band 960-1 215 MHz is reserved on a world-wide basis for the use and development of airborne electronic aids to air navigation and any directly associated ground-based facilities.

● 342 In Albania, Bulgaria, Hungary, Poland, Roumania, Czechoslovakia and the U.S.S.R., the band 1 215-1 300 MHz is also allocated to the fixed service.

● 343 In Belgium, France, Norway, the Netherlands, Portugal and Sweden, the band 1 215-1 300 MHz is also allocated to the radionavigation service.

● 344 In China, India, Indonesia, Japan, Pakistan, Portuguese Overseas Provinces in Region 1 south of the equator, and in Switzerland, the band 1 215-1 300 MHz is also allocated to the fixed and mobile services.

(International Footnotes Continued)

345 In the F.R. of Germany, the band 1 250-1 300 MHz is allocated to the amateur service.

346 The use of the bands 1 300-1 350 MHz, 2 700-2 900 MHz and 9 000-9 200 MHz by the aeronautical radionavigation service is restricted to ground-based radars and, in the future, to associated airborne transponders which transmit only on frequencies in these bands and only when actuated by radars operating in the same band.

347 In the United Kingdom, the band 1 300-1 350 MHz is allocated to the radiolocation service.

348 In Albania, Austria, Bulgaria, Hungary, Indonesia, Poland, Roumania, Sweden, Switzerland, Czechoslovakia and the U.S.S.R., the band 1 300-1 350 MHz is also allocated to the fixed and mobile services.

349 In Region 2 and Albania, Bulgaria, Hungary, Poland, Roumania, Czechoslovakia and the U.S.S.R., the existing installations of the radionavigation service may continue to operate, temporarily, in the band 1 350-1 400 MHz.

349A Radio astronomy observations on the Hydrogen line displaced towards lower frequencies are carried out in a number of countries under national arrangements. Administrations should bear in mind the needs of the radio astronomy service in their future planning of the band 1 350-1 400 MHz.

350A Space stations employing frequencies in the band 1 525-1 535 MHz for telemetering purposes may also transmit tracking signals in this band.

350B As regards the category of the fixed service, see Resolution No. Spa 3.

350C In Albania, Bulgaria, France, Hungary, Kuwait, Lebanon, Morocco, Poland, the United Arab Republic, Yugoslavia, Roumania, Czechoslovakia and the U.S.S.R., the band 1 525-1 535 MHz is also allocated, on a primary basis, to the mobile, except aeronautical mobile, service. As regards the category of this service, see Resolution No. Spa 3.

350D In Cuba, the band 1 525-1 535 MHz is also allocated, on a primary basis, to the mobile service.

● 352 In Albania, Bulgaria, Hungary, Poland, Roumania, Czechoslovakia and the U.S.S.R., the band 1 535-1 660 MHz is also allocated to the fixed service. As regards the category of the fixed service in the band 1 535-1 540 MHz, see Resolution No. Spa 3.

● 352A The bands 1 558.5-1 636.5 MHz, 4 200-4 400 MHz, 5 000-5 250 MHz and 15.4-15.7 GHz are reserved on a world-wide basis for the use and development of airborne electronic aids to air navigation and any directly associated ground-based or satellite-borne facilities.

● 352B The bands 1 558.5-1 636.5 MHz, 5 000-5 250 MHz and 15.4-15.7 GHz are also allocated to the aeronautical mobile (R) service for the use and development of systems using space radiocommunication techniques. Such use and development is subject to agreement and co-ordination between the administrations concerned and those having services operating in accordance with the Table, which may be affected.

● 352D In Austria, Indonesia and the F. R. of Germany, the band 1 540-1 660 MHz is also allocated to the fixed service.

(International Footnotes Continued)

352E The use of the band 1 535-1 542.5 MHz is limited to transmissions from space to earth stations in the maritime mobile-satellite service for communication and/or radiodetermination purposes. Transmissions from coast stations directly to ship stations, or between ship stations, are also authorized when such transmissions are used to extend or supplement the satellite-to-ship links.

352F The use of the band 1 542.5-1 543.5 MHz is limited to transmissions from space to earth stations in the aeronautical mobile-satellite (R) and maritime mobile-satellite services for communication and/or radiodetermination purposes. Transmissions from land stations directly to mobile stations, or between mobile stations, of the aeronautical mobile (R) and maritime mobile services, are also authorized. The utilization of this band is subject to prior operational co-ordination between the two services.

352G The use of the band 1 543.5-1 558.5 MHz is limited to transmissions from space to earth stations in the aeronautical mobile-satellite (R) service for communication and/or radiodetermination purposes. Transmissions from terrestrial aeronautical stations directly to aircraft stations, or between aircraft stations, in the aeronautical mobile (R) service are also authorized when such transmissions are used to extend or supplement the satellite-to-aircraft links.

352H The use of the band 1 636.5-1 644 MHz is limited to transmissions from earth to space stations in the maritime mobile-satellite service for communication and/or radiodetermination purposes. Transmissions from ship stations directly to coast stations or between ship stations, are also authorized when such transmissions are used to extend or supplement the ship-to-satellite links.

352I The use of the band 1 644-1 645 MHz is limited to transmissions from earth to space stations in the aeronautical mobile-satellite (R) and maritime mobile-satellite services for communication and/or radiodetermination purposes. Transmissions from mobile stations directly to land stations, or between mobile stations, of the aeronautical mobile (R) and maritime mobile services, are also authorized. The utilization of this band is subject to prior operational co-ordination between the two services.

352J The use of the band 1 645-1 660 MHz is limited to transmissions from earth to space stations in the aeronautical mobile-satellite (R) service for communication and/or radiodetermination purposes. Transmissions from aircraft stations in the aeronautical mobile (R) service directly to terrestrial aeronautical stations, or between aircraft stations, are also authorized when such transmissions are used to extend or supplement the aircraft-to-satellite links.

● 352K Radio astronomy observations on important spectral lines due to the hydroxyl radicle OH at frequencies 1 612.231 MHz and 1 720.530 MHz are carried out in a number of countries under national arrangements; the bands observed being 1 611.5-1 612.5 MHz and 1 720-1 721 MHz respectively. Administrations should bear in mind the needs of radio astronomy service in their future planning of the bands 1 558.5-1 636.5 MHz and 1 710-1 770 MHz.

● 353A In view of the successful detection by astronomers of two hydroxyl spectral lines in the regions of 1 665 MHz and 1 667 MHz, administrations are urged to give all practicable protection in the band 1 660-1 670 MHz for future research in radio astronomy particularly by eliminating air-to-ground transmissions in the meteorological aids service in the band 1 664.4-1 668.4 MHz as soon as practicable.

Government (G) Footnotes

(These footnotes, each consisting of the letter "G" followed by one or more digits, denote stipulations applicable only to the Government.)

G2 In the bands 216-225, 420-450, 1300-1400, 2300-2450, 2700-2900, 5650-5925 and 9000-9200 MHz, the Government radiolocation is limited to the military services.

G5 In the bands 162.0125-173.2, 173.4-174, 406.1-410 and 410-470 MHz, the fixed and mobile services are all allocated on a primary basis to the Government non-military agencies.

G6 Military tactical fixed and mobile operations may be conducted nationally on a secondary basis; (1) to the meteorological aids service in the band 403-406 MHz; and (2) to the radio astronomy service in the band 406.1-410 MHz. Such fixed and mobile operations are subject to local coordination to ensure that harmful interference will not be caused to the services to which the bands are allocated.

G8 Low power Government radio control operations are permitted in the band 420-450 MHz.

G11 Government fixed and mobile radio services, including low power radio control operations, are permitted in the band 902-928 MHz on a secondary basis.

● G12 The allocation for the band 1215-1300 MHz does not of itself necessarily preclude Government aeronautical radionavigation operations in this band in certain specific cases where necessary and where fully coordinated.

G15 Use of the band 2700-2900 MHz by the military fixed and shipborne air defense radiolocation installations will be fully coordinated with the meteorological aids and aeronautical radionavigation services. The military air defense installations will be moved from the band 2700-2900 MHz at the earliest practicable date. Until such time as military air defense installations can be accommodated satisfactorily elsewhere in the spectrum, such operations will, insofar as practicable, be adjusted to meet the requirements of the aeronautical radionavigation service.

G19 Use of the band 9000-9200 MHz by military fixed and shipborne air defense radiolocation installations will be fully coordinated with the aeronautical radionavigation service, recognizing fully the safety aspects of the latter. Military air defense installations will be accommodated ultimately outside this band. Until such time as military defense installations can be accommodated satisfactorily elsewhere in the spectrum such operations will, insofar as practicable, be adjusted to meet the requirements of the aeronautical radionavigation service.

G27 The fixed and mobile services are limited to the military services.

G29 In the band 2300-2400 MHz, the fixed and mobile services shall not cause harmful interference to the amateur service.

G30 In the bands 138-144, 148-149.9, 150.05-150.8, 225-328.6, 335.4-399.9, 1427-1429 and 1429-1435 MHz, the fixed and mobile services are limited primarily to operations by the military services.

G31 In the band 3300-3500 MHz, the Government radiolocation is limited to the military services, except as provided by footnote US108.

G32 Except for weather radars on meteorological satellites in the band 9975-10025 MHz and for Government survey operations (see footnote US108), Government radiolocation in the band 10000-10500 MHz is limited to the military services.

(Government Footnotes Continued)

G33 In the band 1715-1800 kHz, stations in the radiolocation service shall not cause harmful interference to stations of the aeronautical radio-navigation service.

G34 In the band 34.4-34.5 GHz, weather radars on board meteorological satellites for cloud detection are authorized to operate on the basis of equality with military radiolocation devices. All other non-military radiolocation in the band 33.4-36.0 GHz shall be secondary to the military services.

G35 In the bands 136-137 MHz and 31.5-31.8 GHz, no assignments are to be made except those that are in accordance with the Government Table of Frequency Allocations and those for experimentation that is consistent with the use for which the band is allocated.

G36 Except for weather radars on meteorological-satellites in the band 9975-10025 MHz, all Government non-military radiolocation in the band 9500-10000 MHz shall be secondary to the military services.

G41 No station will be authorized to transmit in the band 73.0-74.6 MHz except one holding a valid authorization on December 1, 1961.

G42 Space command, control, range and range rate systems for earth station transmission only (including installations on certain Navy ships) may be accommodated on a co-equal basis with the fixed and mobile services in the band 1761-1842 MHz. Specific frequencies required to be used at any location will be satisfied on a coordinated case-by-case basis.

● G43 Military fixed and mobile operations may continue in the band 149.9-150.05 MHz until required to be reaccommodated to meet the needs of the radionavigation-satellite service.

● G44 Military fixed and mobile operations may continue in the band 399.9-400 MHz until required to be reaccommodated to meet the needs of the radio-navigation-satellite service.

● G45 No stations will be authorized to transmit in the band 21850-21870 kHz, 1400-1427 MHz, 2690-2700 MHz, 4990-5000 MHz, 10.68-10.70 GHz, 15.35-15.40 GHz, 23.6-24.0 GHz, 31.2-31.5 GHz, 52-54.25 GHz, 58.2-59.0 GHz, 64-65 GHz, 86-92 GHz, 101-102 GHz, 130-140 GHz, 182-185 GHz and 230-240 GHz.

G51 In the bands 7250-7300 and 7975-8025 MHz, no assignments are to be made except those that are in accordance with the Government Table of Frequency Allocations and those for experimentation that is consistent with the use for which these bands are allocated. Existing assignments in the fixed service supporting the air traffic control function, which may continue on a secondary basis to the satellite service (fixed, transportable or located on board a ship or aircraft), will be discontinued as soon as practicable and not later than July 1, 1977.

● G54 Aeronautical mobile communications which are an integral part of aeronautical radionavigation systems may be satisfied in the band 1558.5-1636.6 MHz, 5000-5250 MHz and 15.4-15.7 GHz.

● G55 Authority to operate a joint-use radar (Air Defense/Air Traffic Control) in the band 216-225, 420-450, 1215-1300 and 2300-2500 MHz may be issued to the agency responsible for the technical operation and maintenance of that radar. Despite this dual usage, such radars shall be authorized in the radiolocation service. Present and future requirements for air defense needs shall take precedence over any secondary usage for air traffic control purposes.

● G56 Government radiolocation in the bands 1215-1300, 2900-3100, 5350-5650 and 9300-9500 MHz is primarily for the military services; however, limited secondary use is permitted by other Government agencies in support of experimentation and research programs.

(Government Footnotes Continued)

G57 Frequencies in the band 25.07-25.11 MHz may be authorized to Government ship stations for telegraphy, on the condition that harmful interference is not caused to non-Government land mobile service uses.

● G58 No stations will be authorized to transmit in the band 4200-4400 MHz except altimeter stations and experimental stations. Experimental stations will not be authorized to develop equipment for operational use in this band other than equipment related to altimeter stations.

G59 In the bands 902-928 MHz, 3100-3300 MHz, 3500-3700 MHz, 5250-5350 MHz, 8500-9000 MHz, 9200-9300 MHz, 13.4-14.0 GHz, 15.7-17.7 GHz and 24.05-24.25 GHz, all Government non-military radiolocation shall be secondary to military radiolocation.

G100 The mobile satellite service within the bands 240.0-328.6 and 335.4-399.9 MHz is limited to military systems.

G101 In the band 2200-2300 MHz, telemetering, tracking, ranging, analog/digital data and/or voice from operational space stations may be accommodated on a co-equal basis with fixed, mobile and space research services.

G102 In the band 8025-8400 MHz, Earth Resources Satellite (ERS) System earth stations (receiving) within the US&P will be limited in number. It may be necessary to operate fixed-satellite service earth stations (transmitting) within the coordination area of an ERS earth station. Such operations will be coordinated in accordance with established procedures.

G103 In the band 8175-8215 MHz, it may be necessary to operate meteorological-satellite earth stations (transmitting) within the coordination area of an Earth Resources Satellite (ERS) earth station (receiving). Such operations will be coordinated in accordance with established procedures.

G104 In the bands 7450-7550 and 8175-8215 MHz, it is agreed that although the military space radio communication systems, which include earth stations near the proposed meteorological-satellite installations will precede the meteorological-satellite installations, engineering adjustments to either the military or the meteorological-satellite systems or both will be made as mutually required to assure compatible operations of the systems concerned.

G105 In the band 420-460 MHz, Radio Altimeter operations are limited to the military services and to existing equipments which may continue to operate until January 1, 1978 on the condition that harmful interference is not caused to stations of services operating in accordance with the U. S. National Table of Frequency Allocations.

G106 The bands 2501-2502 kHz, 5003-5005 kHz, 10003-10005 kHz, 15005-15010 kHz, 19990-19995 kHz, 20005-20010 kHz and 25005-25010 kHz are also allocated, on a secondary basis, to the space research service. The space research transmissions are subject to immediate temporary or permanent shutdown in the event of interference to the reception of the standard frequency and time broadcasts.

G107 Military earth stations in the band 7250-7750 and 7900-8400 MHz and 20.2-21.2, 30-31, 92-93, 102-103, 140-141 and 150-151 GHz may be fixed, transportable or located on board a ship or aircraft.

G108 Planning and use of the bands 7300-7750, 7900-7975 and 8025-8400 MHz by mobile earth stations and the band 8025-8400 MHz by stations of earth resources satellite systems, necessitate the development of technical and/or operational sharing criteria to ensure the maximum degree of electromagnetic compatibility with existing and planned systems within these bands.

(Government Footnotes Continued)

G109 All assignments in the band 157.0375-157.1875 MHz are subject to adjustment to other frequencies in this band as long term U.S. maritime VHF planning develops, particularly that planning incident to support of the National VHF-FM Radiotelephone Safety and Distress System (See Doc. 15624/1-1.9.111/1.9.125).

G110 Government ground-based stations in the aeronautical radionavigation service may be authorized between 3500 and 3700 MHz where accommodation in the 2700-2900 MHz band is not technically and/or economically feasible.

G111 In the band 1215-1250 MHz, the frequency 1227.6 MHz with emissions limited to ± 12 MHz bandwidth, is also allocated to the Radionavigation Satellite Service, for satellite down link transmissions only. The power flux density at the earth's surface from such transmissions shall not exceed -152dBW/m^2/4kHz. The Radionavigation Satellite Service shall not cause harmful interference to the Amateur Service and shall accept any harmful interference that may be caused by the Amateur Service.

G112 In the band 1558.5-1636.5 MHz, the frequency 1575.42 MHz with emission limited to ±15 MHz bandwidth is also allocated to the Radionavigation Satellite Service for satellite down link transmissions only. The power flux density at the earth's surface from such transmissions shall not exceed -152dBW/m^2/4kHz.

ADD 470NE a) The power flux density at the earth's surface produced by emissions from a space station or reflected from a passive satellite for all conditions and for all methods of modulation shall not exceed the following values:

– 154 dBW/m^2 in any 4 kHz band for angles of arrival between 0 and 5 degrees above the horizontal plane;

$-154 + \frac{\delta - 5}{2}$ dBW/m^2 in any 4 kHz band for angles of arrival (δ) between 5 and 25 degrees above the horizontal plane;

– 144 dBW/m^2 in any 4 kHz band for angles of arrival between 25 and 90 degrees above the horizontal plane.

These limits relate to the power flux density which would be obtained under assumed free-space propagation conditions.

ADD 470NF b) The limits given in No. 470NE apply in the frequency bands listed in No. 470NG which are allocated to transmission by space stations in the following space radiocommunication services:

– Earth exploration-satellite service and in particular meteorological-satellite service (space-to-Earth)

– Space research service (space-to-Earth)

– Fixed-satellite service (space-to-Earth)

where these bands are shared with equal rights with the fixed or mobile services.

ADD 470NG

1 670 - 1 690 MHz
1 690 - 1 700 MHz (for the countries mentioned in No. 354A)
1 700 - 1 710 MHz
1 770 - 1 790 MHz (for the countries mentioned in No. 356AA)
2 200 - 2 290 MHz
2 290 - 2 300 MHz
2 500 - 2 535 MHz

ADD 470NGA c) The power flux density values given in No. 470NE are derived on the basis of protecting the fixed service using line-of-sight techniques. Where a fixed service using tropospheric scatter operates in the bands listed in No. 470NG and where there is insufficient frequency separation, there must be sufficient angular separation between the direction to the space station and the direction of maximum radiation of the antenna of the receiving station of the fixed service using tropospheric scatter to ensure that the interference power at the receiver input of the station of the fixed service does not exceed − 168 dBW in any 4 kHz band.

US 34 The only non-Government service permitted in the bands 220-225 MHz, 1215-1300 MHz, 2300-2450 MHz, and 5650-5925 MHz is the amateur service. The amateur service shall not cause harmful interference to the radiolocation service.

US 39 Within the band 1540-1660 MHz, radio altimeters are permitted to use only the portion 1600-1660 MHz and then only until such time as international standardization of other aeronautical radionavigation systems or devices requires the discontinuance of radio altimeters in this band.

US 39A The band 1592.5-1622.5 MHz is allotted provisionally, but on a primary basis, for the collision avoidance function, noting the continued use of existing altimeters in the band 1600-1660 MHz.

US 208 Planning and use of the band 1558.5-1636.5 MHz necessitate the development of satisfactory technical and/or operational sharing criteria to ensure the maximum degree of electromagnetic compatibility with existing and planned systems within the band.