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INDUSTRIAL TIME SERVICE STUDY

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This study examines options for delivery of accurate time and frequency information to industrial users. The study is sponsored by the Bonneville Power Administration (BPA) who finds a need for accurate timing to the one microsecond level. Prospective existing and future dissemination methods (Loran-C, GOES, USRDSS, GPS, etc.) are discussed in detail. The study produces a system architecture and preliminary design for a new time service using the widely available U.S. fixed satellite service (FSS) in which customers shall assume full costs of its operation through subscriber fees.

The study elaborates on three viable options: (1) FSS, (2) GPS, and (3) USRDSS. Based on this study, conclusions can be drawn regarding a timing system which will most satisfactorily meet the long range goals of most industrial users.

Key words: accuracy; frequency; satellite; time; time broadcast services; time dissemination

INDUSTRIAL TIME SERVICE STUDY

INTRODUCTION

This report is a comprehensive study of accurate time dissemination options which can satisfy present and future requirements for the Bonneville Power Administration (BPA). Over the years, the BPA has explored the use of precise time synchronization as a means of better fault location and improved system stability. In addition to its own continuing analyses, BPA contracted with the National Bureau of Standards, Time and Frequency Division, to study suitable time distribution systems and asked NBS to make recommendations based on the study.

Many of the existing time services are unsatisfactory solutions to the BPA for reasons discussed in this study. Furthermore, the future communication and navigation services, which directly affect prospective options for solving the time transfer problem for the BPA, are in a state of continuing technical and policy changes at this time. Nevertheless, the study has done a useful evaluation of what can be done for the BPA.

The report consists of four phases of study. It starts (Phase I) with a brief review of requirements for the BPA and NBS. That is followed by general discussions of any and all viable or closely viable timing systems (Phase II). Since no system will be a perfect solution, this phase narrows the options to those which have the least risk and fewest problems. Considerably more detail is presented concerning three possible options in the following phase (Phase 111). The report then concludes with a summary.

This study has gone into great detail in some areas, particularly Phase 111, which itself has three parts. This was done because Phase III presents three separate and viable options in enough detail that the sponsor (BPA) could arrive at its own conclusions. In addition, a preliminary design for a timing system using the Fixed Satellite Service (FSS) is extensively discussed. A combination of market demands, technical advances, FCC policy changes, and satellite receiver cost reductions led to further investigation of a FSS-based system.

A. PHASE I INTRODUCTION AND OBJECTIVES

The following is a statement of requirements for the "high accuracy time and frequency system" as provided for in the Agreement between the National Bureau of Standards (NBS) and the Bonneville Power Administration (BPA) - Agreement No. DE-AI79-84BP19476. The statements of requirements are divided into two parts -- a policy section and a functional section. The policy section outlines those requirements imposed upon services provided by government by administration policy and by NBS management to control unexpected financial liability. The functional requirements are a composite derived from those requirements by BPA for such a service as provided in the agreement, by NBS technical considerations given its experience with similar systems, and through long term and extensive contacts between time and frequency users and NBS.

Throughout this document the system of interest will be referred to as the Industrial Time Service or the ITS.

B. POLICY REQUIREMENTS

Certain administration requirements must be met in order for the NBS to enter into a time and frequency service such as the ITS.

1. The ITS must generate through user charges sufficient funds to completely recover all costs associated with the establishment, operation and maintenance of the service.

2. The ITS must be designed, implemented and operated in such a manner that no significant potential exists for large, unexpected cost to be incurred through failures or other uncontrollable events.

3. The ITS must be configured so that, at the discretion of NBS, direct NBS involvement may be substituted by contract to or transfer to the private sector.

These are policy matters which protect NBS from any financial risk and inability to control the service. Short term funding is needed to start the service, but it is the long term projections of operating funds which must be in line with NBS expenses.

Policy requirements as they are do not restrict the development of the ITS in any way given adequate demand, and hence funding, for such a service. Policy is in place to reduce financial risk and assure that the benefitting sector of the economy bears the cost of service received. NBS expertise and history are precisely in the area of time and frequency generation and dissemination, and all efforts will go toward proper implementation of the ITS.

With regard to item 3, ideally the removal of NBS involvement would not seriously affect the continuing operation of the ITS and service to its users. It must be pointed out that financial considerations alone do not affect the decision concerning ongoing involvement by NBS. NBS must maintain full control of its' own resources, and its ongoing direct involvement cannot be guaranteed. Again, this does not take anything away from development of the service.

C. FUNCTIONAL AND OTHER TECHNICAL REQUIREMENTS

The following are functional and technical requirements for the ITS. Specific receiver requirements as provided by BPA in the Agreement can be guaranteed by these requirements and conventional and economical receiver design.

1. PROVISIONS OF THE ITS

a. Time of Year information in the form of a time code repeated at a rate of at least once per minute.

b. The ITS shall provide synchronization to UTC(NBS) throughout CONUS to a precision of 0.1 µs or better.

c. The ITS shall operate continuously with availability of 99.7% averaged over one year.

d. The ITS shall provide information relating to the differences between UTC(NBS) and UT1 and shall provide notification of a leap second during the month of occurence.

e. The ITS shall require the use of an antenna no greater than 1 meter in any dimension to achieve all stated requirements.

f. The ITS shall require of the user no operator or other assistance once a properly set up receiving system is in place (outside of user equipment failure).

PHASE 11: A REVIEW OF
POSSIBLE TIME SERVICES

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D. PHASE II INTRODUCTION AND OBJECTIVES

The purpose of this phase of the study is to examine systems that have the potential of meeting some or all of the requirements for the Industrial Time Service (ITS). The system or systems that appear to meet all requirements for the ITS will be identified and will be the subject of more study and development in the next phase of this study. The systems under examination include those existing, under physical development, or in the planning stages. These systems either already provide signals intended for time dissemination, signals that inherently contain synchronization information that can be related to the NBS time scale, or systems to which time dissemination service can easily be added. These systems include navigation or position location systems, data transmission systems and broadcast systems. The results of this phase of the study are summarized at the conclusion section of this report as well as in Table 1.

Many of the options discussed in this phase for the industrial time service are developed to a degree that allows a fair evaluation of their capabilities. Such systems are Loran-C, OMEGA, Transit and GPS. However, important options for the ITS involve the use of geostationary satellites, and in this area there is considerable change and growth in markets. As a result of future needs a new segment in communications is emerging at a rapid rate. This is the Radiodetermination Satellite Service (RDSS). RDSS based systems are discussed in this phase but in a preliminary manner. RDSS systems appear to be in only a planning stage, and no such systems may evolve. In addition, if such services evolve, they may not be able to carry appropriate time and frequency information for any one of several reasons. Therefore the discussion of RDSS-based ITS is exemplary only. The RDSS for the United States is described in preliminary form in Appendix 11, CCIR Study Draft of 518-3, April, 1985.

Except for RDSS systems, well developed ITS options are discussed in this phase of work. Each will be described and compared against the technical and operational requirements determined in Phase I of this study.

By itself, the market for precise time and frequency distribution is limited. However, a large market exists for systems which allow precise navigation and a variety of navigation systems are in service or are proposed. Future high accuracy navigation systems are directed toward techniques involving precise time distribution from several locations in order to do position location. The better services for time and frequency distribution are usually linked to some sort of navigation system. Since the two disciplines work together, the fact that proposed time and frequency distribution systems are actually derived from radio navigation systems adds uncertainty to the long term viability of a time and frequency distribution service. This is so because the objective of the radio systems is navigation first with only secondary regard for the timekeeping capability to the end user of such systems. In fact, the need to periodically coordinate with some form of time reference is considered an added maintenance function for navigation systems. Unfortunately radio navigation systems find it counterproductive to service the time and frequency users because of the limited market and added maintenance of time coordination with a reference such as NBS or USNO. One concludes then that the most suitable kind of industrial time service is one specifically designed for time and frequency distribution which is technically workable and at the lowest possible cost overall.

The systems examined in this study are evaluated against some of the requirements and other parameters relevant to choosing between various system options for the ITS. The requirements of major importance are shown in the first column of Table I. They include:

D1. ACCURACY

Accuracy is the measure of how closely the system will deliver UTC(NBS) time to the user. This specification has been set at one microsecond as minimum acceptable performance. This level applies under all operating conditions or requirements that follow; i.e. on a continuous basis, over the CONUS, using a receiving system costing $3,000 or less, etc. In cases where a manufacturer or system operator quotes an accuracy figure, that figure is used for this aspect of the study.

D2. UNAMBIGUOUS UTC TIME CODE

This provision requires that the system transmits a time code giving the date including days, hours, minutes and seconds that is unambiguous to at least one year. It must be a uniform time code in that discontinuities such as the leap second do not occur without prior notification in the code during the month of its occurrence.

D3. COVERAGE

The coverage of the signal must be the continental United States (CONUS) as a minimum with greater than 99% availability.

D4. STATUS

The "status" is not a requirement but is simply a comment giving information about a system's capability to provide its intended purpose and when.

D5. OPERATIONAL TIME

The operational time is the time that the system can perform and deliver all of its applicable characteristics and specifications. The ITS requirement calls for full time operation with a small allowance for signal loss for any reason (<1% on the average and always less than a few hours at the worst at any one time).

D6. RECEIVER SYSTEM COSTS

Receiver system costs include the costs for antenna, preamplifier, cables, receiver and external oscillator if required. It represents an estimate of the complete cost of the receiver hardware reflecting current prices.

D7. OPERATOR

The operator is the organization responsible for the operation of the source or delivery portion of a system. The objective of a system may or may not include time and frequency dissemination. A second operator may be required to operate any time and frequency capability or subsystem. For example, this is the situation for GOES, where NBS is responsible for the operation of the time code and NOAA, Department of Commerce, is responsible for the overall operation of the satellites and its uplinking facilities. A similar situation would exist for the FSS and BSS entries.

D8. ANTENNA PACKAGE

This description includes the weight and physical size of the antenna system. Many of the antennas used in the systems discussed must be mounted on masts or similar structures. The dimensions of all supporting structures are not included here.

D9. NBS OPERATION AND MAINTENANCE COSTS FOR ITS

The annual costs for operating the time and frequency portion of the system are estimated here. For most systems, the time and frequency information is a by-product of a navigation system and is available at essentially no cost to the user. In many cases, the cost is not separable from the costs of operating the navigation portion of the system. This aspect *is* important to this study only when NBS or another such agency provides the time and frequency function.

D10. SUBSCRIBER FEES

If the private sector provides time-and-frequency information, it must recover costs plus profit through subscriber fees. It is policy now that government also realize full cost recovery through user fees. This will apply to new and proposed time and frequency services. At present no time and frequency broadcasts have user fees associated with them mainly because of the difficulty in denying access to those who do not pay any fees. New systems, however, can be designed to make charges possible to specific users with no access available to non-users.

D11. LONG TERM PROSPECTS

Presented here are brief comments on the viability of each system and on where and what the system may be in the foreseeable future. The ITS study requires a reasonable expectation that the system have a lifetime of 20 years. In some situations this lifetime refers to the principal service of the system assuming that the addition of a time and frequency capability is always possible throughout that lifetime. For instance, this is true with regard to the lease of a channel on a domestic communications satellite (the FSS option).

Table 1. Compari of Time Services

SYSTEM ISSUE	Study Requirements	Fixed Satellite Service (FSS)	Broadcast Satellite Service (BSS)	Loran-C	Navy Navigation Satellite System (Transit)	Geostationary Operational Enviromental Satellite (GOES)	NAVSTAR Global Positioning System (GPS)	Radio Determination Satellite Service (RDSS)
ACCURACY	1 μs	100 ns	10 μs	1 μs	25 μs	100 μs	100 ns	10 ns
UNAMBIGUOUS UTC TIME CODE	Yes	Yes (feasible)	Yes	None	No	Yes	Yes	Yes
COVERAGE	CONUS	CONUS +	CONUS + HI, AK, PR	CONUS +	Global	Western Hemisphere	Global	CONUS +
STATUS	NA	FSS extensively developed -- many independent operators. T/F undeveloped.	BSS just being brought into service. T/F undeveloped.	Extensive development including synchronization to UTC capabilities	Fully developed	Fully developed	Partially developed. Fully operational by 1988.	Satellite system under development. Time and Frequency Service being discussed as option.
OPERATIONAL TIME	Continuous	Continuous	May not be available during early morning hours.	Continuous	20 minute passes every few hours-requires internal clock to "flywheel" when satellite not in view	Continuous	14-18 hours per day -- will be continuous when fully operational.	Continuous when operation in 1987 or 1988
RECEIVER SYSTEM COSTS	< $3000	~ $2500	$1500	$12,000	$12,000 - 21,000	$2500 - 5000	$20000 -- cost expected to decline significantly during next 5-10 years.	> $1000
OPERATOR	NA	~25 independent operators	5 independent operators for BSS	Department of Transportation	Department of Defense	U.S. Department of Commerce/NBS	Department of Defense	4 private sector entries expected
ANTENNA PACKAGE SIZE	Maximum dimension 1 meter	dish < 1 meter in diameter	dish < 1 meter in diameter	loop 1 meter in diameter or whip	whip < 1 meter	< 1 meter^2	6" high 37" diameter, 3 pounds 15.2cm x 94cm diameter	
NBS OPERATIONAL MAINTENANCE COSTS FOR THIS SERVICE	Recoverable through user fees if NBS involved.	may be recovered through user fees -- encrypted data	may be recovered through user fees -- encrypted	None -- primarily a navigation system	None -- primarily a navigation system	1/3 man-year + $20,000/yr	None - DoD support navigation system	Small costs associated with maintaining time to UTC(NBS)
SUBSCRIBER FEES	Sufficient to cover O&M costs -- $300/yr. thought to be adequate	~ $300/yr.	~ $300/yr.	None	None	None	None expected -- has been discussed however.	Undetermined service charge
LONG TERM PROSPECTS	20 year lifetime	Excellent	Excellent for BSS	GAO recommends use of GPS instead	Likely phase out due to GPS (when operational)	Good	Questionable -- may be degraded or denied during national emergencies.	RDSS approved by FCC

E. FIXED SATELLITE SERVICE

The Fixed Satellite Service is a radio communication service between earth stations at specified fixed points where one or more satellites are used. In some cases this service includes satellite-to-satellite links which may be configured in the intersatellite service. The fixed satellite service may also include feeder links for other space radio communication services.

This service is mainly for telephone, telegraph, telegram and telex trunk services as well as television distribution. More recently, new services have included high speed transmission of documents, data transmission between computers, audio, and video teleconferencing.

International examples of the use of the FSS are INTELSAT and INTER-SPUTNIK. Neither of these international systems provide CONUS coverage from one satellite. Furthermore, CONUS coverage is not possible with either system using any number of their operational satellites.

A number of domestic satellite communication systems have been put into operation since its inception in the U.S. in 1975. Many more are planned for the future. Table 2 shows the presently authorized FSS systems serving the U.S. and Table 3 shows those that applied with the FCC before the November 1983 cutoff. More systems are expected to be added once the backlog of applicants from the 1983 action has been acted upon.

TABLE 2.

AUTHORIZED SYSTEMS (FIXED)

- Advanced Business Communications Inc.
- American Satellite Company
- American Telephone and Telegraph
- GTE Satellite/Spacenet
- Hughes Communications
- Mobile Satellite Corporation
- Rainbow Satellite Inc.
- RCA Americom
- Satellite Business Systems
- United States Satellite Systems
- Western Union

TABLE 3.

PROPOSED SYSTEMS AND SATELLITES

(November 1983 Applicants)

General

Alascomn, Inc.

American Satellite

American Telephone & Telegraph

Cablesat General Corp.

Columbia Communications Corp.

Comsat General Corp.

Digital Telesat

Equatorial Communications Systems

Federal Express

Ford Aerospace Satellite Services Corp.

GTE Satellite Corp.

GTE Spacenet Corp.

Hughes Communications Galaxy, Inc.

Martin Marietta Communications Systems, Inc.

Mobile Satellite Corp.

National Exchange, Inc.

Rainbow Satellite, Inc.

RCA Americom

Satellite Business Systems

Systematics General Corp.

The FSS is a service intended to support the point-to-point transmission of communications on a bulk basis. It is not intended for broadcast services, although recent applications are using it for broadcast service. No time services exist today using the FSS although some audio services do carry time information on a par with the typical time-and-temperature messages available on the telephone in urban areas accompanied by either commercial messages or operated on a pay basis, typically 25 cents per call.

Satellites operating in the other services have been used both experimentally and operationally for time and frequency dissemination with very acceptable levels of performance. In the early 1970's an experimental NASA satellite, ATS-3, was used to transmit a slightly modified WWV format to large geographical areas of the Western Hemisphere with results for the first time demonstrating superior time performance related to accuracy, reliability of signal transmission, simplicity, low cost of user equipment, and signal recovery. These early experiments led to the GOES service (discussed elsewhere in this report) which has been providing a full time code to the Western Hemisphere since 1975. Both of these examples illustrate the use of dedicated facilities for which there is very limited or no backup (redundancy).

The use of the FSS is much like the simple lease of a telephone line. The FSS has many operators competing for users' business including long term protected leases. This means a time service can be implemented through a long term lease of a channel on someone's existing satellite. The lease can be the result of a competitive procurement guaranteeing the lowest price for a specified level of service. No special equipment needs to be designed or placed into orbit over what is already there in abundance.

Through (1) a careful examination of the technical characteristics of the FSS transponders, (2) a review of work done on satellite tracking techniques applicable to a time service concept, (3) noting the existing telecommunications and broadcasting applications now implemented in the FSS, (4) a review of equipment costs and trends, and (5) past experiences with implementing satellite services, we at NBS feel, with reasonable certainty, that the performances summarized in Table 1 for a time service using the FSS can be achieved. These expectations do, however, require detailed study and experimentation to verify, some of which will be done in the next phase of this study assuming enough merit in the FSS option relative to the other options is found to continue.

The FSS provides facilities for telecommunications activities. These facilities are highly reliable and can be provided on a continuous basis even during periods when the sun would be eclipsed by the earth, thereby cutting off the source of energy from the satellite's solar collectors. All satellites in the FSS serving the U.S. provide at the minimum CONUS coverage with many giving additional coverage of Hawaii, Puerto Rico and Alaska. Since the antenna pattern cannot provide sharp cutoffs in its pattern, parts of Canada and Mexico can also experience similar signal levels near our borders with decreasing levels as one moves away from these boundaries. Continuity of service is guaranteed by use of backup satellite circuitry and, if necessary, a backup satellite.

The principal accuracy of this time signal is a matter of final signal-to-noise ratio in the user's receiver and accurate information on the position of the FSS satellite. (Equipment systematics can be calibrated and are comparatively small.) Preliminary calculations have shown that sufficient S/N ratios can be achieved for certain signal structures to yield better than one tenth microsecond precision using antennas of less than one meter in diameter. These calculations hold true for both the C band and the KU band of the FSS. Recent NBS analysis of tracking experiments done by General Electric, under contract to NASA, on some of NASA's Applied Technology Satellites (ATS) in the 1970's indicate that adequate tracking can be accomplished by a tracking system suitable for the ITS concept and mode of operation. This analysis coupled with more recent filtering techniques leads the authors to believe a low cost, simple, and reliable tracking system can be developed for the ITS to guarantee nearly 0.1 microsecond delivery accuracy. Preliminary examination of the use of the Data Encryption Standard (DES) in the ITS to deny delivery of time to nonpaying users has been favorable. The DES has been implemented on a single chip costing twenty to fifty dollars (depending upon speed) to which a "key" (decode authorization) can be sold periodically to each user, thus making cost recovery feasible. The number of customers one can reasonably expect remains unanswered and is certainly a function of overall annual costs. We think that for a receiver costing $2500, a 10% annual charge of $250 per year would be acceptable to most users. The GOES broadcast has nearly 2000 receivers in the field without any NBS promotion for its use. A similar number of ITS customers should be possible with active NBS promotion of its use especially considering that the service will be meeting many more users' needs.

F. BROADCAST SATELLITE SERVICE (BSS)

The Broadcast Satellite Service is a system of direct broadcast of signals to the general public. Signals are relayed by satellites generally at geostationary orbital altitude and intended for direct reception to the recipient. In the BSS, signals may either be received directly by individuals or may be received by a community receiver for distribution to other recipients. In the literature this system is also referred to as the Direct Broadcasting Satellite Service or DBS Service. These systems are generally designed to handle NTSC video signals since the primary objective is to provide information and entertainment program services. Given the wide available bandwidth other signals may be added (multiplexed) with the normal video and audio transmissions on a noninterfering basis given appropriate approvals. Thus an opportunity exists for additional transmission of a time code.

For home reception the receiver antenna will be small for aesthetic, structural, and cost reasons. A home antenna of less than 1 meter in diameter is the system goal. With a small receiver antenna a burden is placed on the relay satellite to produce enough transmitted power so that the energy incident upon receiving antenna is sufficient for full reception. Larger receiving antennas may be used in other situations. For example a community receiver may be used to distribute a signal to more than one individual. In this way the costs are spread over the number of recipients and there is more flexibility in choosing an optimum antenna location. Community receivers may be used in cable systems, educational facilities, and hotels or apartment houses.

Although considerable groundwork has been laid in the development of a specific BSS planned for the CONUS, there is no routine service in place now. Small systems have been used in the United States to validate concepts. Operational systems do exist in Japan and parts of Europe, however. A specific BSS planned for the United States would have the following major aspects based on the primary objectives of the system. (Other planned systems may have somewhat different characteristics.) Independently programmable satellites would be used for each of the four time zones of the contiguous U.S. The four operating satellites would provide downlink transmissions in the 12 GHz BSS band with a typical EIRP of 57 dBW. Uplinks are in the 17 GHz BSS band. Satellite orbital locations would be selected to maximize relay capacity and spectrum use while retaining acceptable eclipse times and elevation angles. Operationally, additional satellites would be in orbit as spares in a full nationwide implementation of the BSS. The spares would allow restoration of service within a few minutes to highly populated areas if any primary satellite failure should occur. The spares would be maintained in such a way that they could be relocated and reoriented to provide full backup to any failed satellite.

A central uplink location would be used for the majority of transmitted programs. Although it is possible to have multiple access it is not entirely desirable during high viewing periods. Multiple access may be used during low viewing periods. The most favorable plan calls for all access to the BSS to be done through a central dispatch. Real time programming outside the central location could be linked via other satellites (i.e., FSS) or terrestrial microwave links.

Although the BSS calls for telemetry tracking and command control of its relay satellites, only very coarse positioning information will be provided. The BSS is not deemed as any sort of navigation facility. Its emphasis in command and control is for system testing, activating home equipment of subscribers, changing levels of programming to existing customers, and coordinating customer subscriber billing functions. Because of the subscription nature of the video program material, broadcast transmissions from satellites are scrambled for security purposes. The purpose of the security scrambling is to discourage piracy and to filter out nonpaying customers. Normal decoding information will be done in real time over the air by periodic transmission of the unique data key for recipients. In addition special scrambling techniques suitable for special programs or special interest material will be on line.

Standard broadcast transmissions of video signals use a single sideband amplitude modulated scheme for the video information and frequency modulation (FM) for the audio portion. To minimize costs the BSS will use only FM in the transmission of video and audio information. Not only cost, but system complexity are also reduced. The overall signal transmission parameters for the BSS are outlined in Table 4.

TABLE 4.

Video Baseband:	CCIR Standard M with **NTSC** color
Audio/Control Subcarrier:	
Inputs:	**1** ea. Basic Program; Audio Bandwidth = **13** kHz
	1 ea. Stereo or Second Language; Audio Bandwidth = **13** kHz
	1 ea. Access Control Channel; Bit Rate = 62 kbps
Audio Encoding:	PCM, Bit Rate = **315** kbps/channel
Composite Bit Rate:	**692** kbps
Modulation:	QPSK
Frequency:	5.5MHz
Amplitude:	0.12 volts r.m.s. before emphasis at **1** volt **p-p** video reference point
Emphasis:	**525** line per CCIR **Rec. 405-1**
Video Deviation:	10 MHz p-p
IF Bandwidth:	**16** MHz
Uplink Frequency:	In the band **17.3 - 18.1** GHz
Downlink Frequency:	In the band **12.2 - 12.7** GHz

Because of the higher output power needed by the BSS satellites, the onboard battery power system is insufficient for full time operation. Periods when the satellite solar panels are not receiving solar power (eclipse periods) exist for the satellites and cause periods in which operation is not possible. This is a serious limitation in view of the ITS requirement for full time unattended reception of an accurate time signal. In addition to this limitation the BSS is not fundamentally a navigation system and satellite position information will not be calculated to a precise enough level. It is possible for the ITS to bear the full burden of precise satellite position information. However, the principle mission of the BSS allows for scrambled video signals and there is no direct provision for a "clear" channel available for time and position information which needs to be relayed. Since non-BSS signals are not a provision of the BSS service the addition of time and frequency dissemination at the 1 µs level is more complicated.

On the surface there appear to be some benefits available from the use of the BSS for time-and-frequency distribution. However, the BSS must be ruled out on two key issues. The first is that transmission is not available on a full time basis (full time is not needed to meet the goals of the BSS). Secondly, the spectrum allocation in the 12 GHz frequency range is strictly assigned for meeting the objectives of the BSS, and no provisions exist for other signals. This would make the plan to distribute a time and frequency signal complicated by unknown factors at this point since none of the approved BSS applications are in service.

G. NAVSTAR GPS

The NAVSTAR Global Positioning System (GPS) is a worldwide navigation system using satellites and has been under development since 1973. GPS is a Department of Defense (DoD) program intended to satisfy DoD requirements. During the past few years the use of GPS by non-DoD applications has been encouraged by the DoD. The system is expected to be fully operational by 1988 or 1989 and will provide worldwide continuous navigation capabilities to all users. Only six satellites are in orbit (May 1985) now and provide less than continuous worldwide coverage.

Position fixing with GPS is accomplished as follows. The satellites broadcast a precisely timed signal modulated with a ranging code and a navigation message consisting of statements on where the satellite was at the time of broadcast. A receiver performs a trilateration to three separated satellites, computing satellite range from the ranging code and decoding satellite location from the navigation message. The range to one satellite establishes a sphere around the satellite upon which the user is located. Range to two satellites defines a circle of intersection of two spheres on which the user is located. A third satellite range reduces the user's location to two points one of which can be rejected as impossible. The final key element to this position location procedure is that to perform accurate ranging, the user must determine the time of reception which he differences with the broadcast time of transmission (given in the satellite message). The user's receiver clock is not synchronized with the satellite clock (each satellite carries atomic clocks, all mutually synchronized). This lack of synchronization adds a clock bias (range bias) to each satellite signal as it arrives. The bias is resolved by ranging to a fourth satellite and in effect produces four equations involving four unknowns (the user's three dimensions of position and the user's clock bias).

When fully operational the satellite constellation will consist of 18 satellites in low eccentricity (20,169 kilometer) orbits inclined at 55 degrees with 6 satellites equally spaced within three orbit planes each equally spaced at 120 degrees around the equatorial plane. The satellites are at half-synchronous altitude making two revolutions of the earth each sidereal day (23 hour, 56 minutes and 4.09 seconds).

The GPS satellites broadcast continuous navigation messages at approximately 1575 and 1228 MHz called the L1 and L2 frequencies respectively. The L1 frequency is modulated by two codes called the P code or precise code and the C/A code or coarse acquisition code. The L2 frequency has only the P code. The P code runs at a rate of 10.23 Mbit/s and the C/A code at 1.023 Mbit/s. The P code is very long, repeating every 267 days. The P code sequence is changed every seven days for the purpose of transmission security. The P code is intended for the highest precision work and will be available only to the DoD and other users approved for use on the basis of "national security interests." The C/A code is shorter, with a one millisecond period, and has been stated by DoD to be available to the general public. Each satellite has a unique C/A and P code.

There are plans by the DoD to degrade the accuracy of the CIA code and limit the navigation accuracy to 100 meters. Present performance without degradation is much better.

As mentioned before, each GPS satellite carries an atomic clock synchronized to a time scale called GPS time. The message from the satellite provides the relationship between GPS time and UTC time and therefore provides the means of UTC time dissemination. The time transfer process is as follows. The position of the satellite is given in the transmitted message as a function of time. The position of the user's receiver is known either as a result of the user entering a position or as a result of the receiver operating in the navigation mode with the GPS system. These two pieces of information provide the distance between the satellite and the user's receiver as a function of time (it is assumed that the user's receiver is stationary). The propagation delay is determined using the velocity of light. The user's clock can then be synchronized to UTC through simple calculations handled by the receiver itself.

A commercial, relatively low cost GPS timing receiver has been used to evaluate the GPS system for satisfying the requirements of the ITS. The system was found capable of synchronizing external clocks to within 0.1 microsecond. The receiver costs $25,000, but significant cost reductions are expected over the next 10 years after GPS becomes operational. The antenna is small and lightweight, and requires no pointing. Although subscriber fees have been mentioned, the most recent statements by the DoD on GPS policy have indicated that DoD will allow free access to the C/A code.

H. RADIODETERMINATION SATELLITE SERVICE

The Radiodetermination Satellite Service is a radiocommunication service for the purpose of radiodetermination involving the use of one of more space stations. The radiodetermination satellite service for the United States, USRDSS, is being developed to provide position and navigation information and a limited digital message capability to users with small, low cost transceivers. The system is intended to be used for maritime, aeronautical, and land based mobile applications. Four companies have now revealed plans to launch satellites to handle services ranging from locating and navigating trucks, boats, and planes to handling nationwide cellular radio, paging and digital messages.

Several companies have applied to the FCC to launch a radiodetermination system. Geostar Corporation was the first to file with the FCC (March 1983) and has made some proposals of particular interest to this study. Geostar is in fact the only system at this time for which we know details on its future plans. It will therefore be used to further discuss what the RDSS is and how it might be useful to the ITS. The system proposes to provide the following functions: positioning, directional guidance, collision and terrain voidance for aircraft and boats, position reporting to fleet dispatch centers, sending messages, receiving messages, and interconnection to the telephone system for all services that can be provided through a modem. Geostar will provide these services through the use of a ground station with a computer, two or more geostationary satellites, and transceivers carried by aircraft, surface vehicles, and possibly individuals.

In September 1984 the FCC issued a Notice of Proposed Rulemaking proposing the allocation of frequency bands in the microwave region in the United States for the RDSS. The FCC's final action in the RDSS will determine technical details and standards for the RDSS and which entities may begin business in the U.S. If the FCC acts in a timely manner, Geostar expects to begin service to CONUS in 1987.

Additional Geostar plans that have been advanced recently include time and frequency dissemination. Drawing directly from a report prepared for Geostar by the Systematics General Corporation we found Geostar's plans to be described as follows:

The USRDSS is a proposed system envisioned in the radiodetermination satellite service which will consist of a number of operational satellites in geostationary orbits, one or more fixed location control centers, and a large population of mobile users (subscribers) located within the system coverage zone. In the envisioned system, a periodic time reference PN code, originating at a control center, is relayed through one satellite to all user stations within a coverage zone. The user stations are expected to be relatively inexpensive, preprogrammed tranceivers designed to respond with uniquely identified signal bursts back to the control center via two of the satellites in the system. Responses may include messages for other users or requests for other services. The control center will determine the two associated roundtrip propagation path delays and, using a stored terrain map or altitude information from the user station, compute the precise location of the user station using redundant high speed computers. Computed positions along with pending messages are addressed and transmitted back to the appropriate user via the original signal containing the embedded periodic reference PN code. During operation, the system will be continuously calibrated using known, fixed location "benchmark" transceivers. Outbound links from a satellite to the user stations are planned for the frequency range 2483.5-2500.0 MHz while inbound links from the users to the satellites are planned for the frequency 1610.0-1626.5 MHz.

As a complementary by-product of its primary service of precision radiodetermination, the USRDSS System is expected to provide both general time dissemination to a large number of users and high accuracy time transfer. The capability for wide area coverage and the design emphasis on low cost, automated user transceivers enable a large user base for these functions. For general time dissemination the operational mode of the envisioned USRDSS includes corrections for the user position performed by a microprocessor within the user transceiver. Computed position parameters from the control center will be used and the estimated accuracy for users in this mode is 150 microseconds.

The operational mode for a high accuracy time transfer service with the envisioned USRDSS involves a method analogous to the simultaneous exchange of timing signals through a communications satellite link. Two users desiring to correlate their local clocks will respond to a specified epoch on the outbound USRDSS signal. The time of receipt of the epoch at the user station is labeled with the local clock value. The control center can estimate the difference in the outbound signal's time of arrival at the two stations by measuring the time difference in the arrival of their responses and incorporating calibration factors derived from the "benchmarks." By comparing the clock value labels and the calculated times of arrival of the outbound signals, the offset between the two user clocks can be determined. The estimated accuracy for this service is 10 nanoseconds.

A special case of the high accuracy time transfer service makes use of an accurate clock at the central control center. The clock is periodically recalibrated by transferring time from a reference standard clock such as that available at the United States National Bureau of Standards. The control center can then transfer precise time, upon request, to any user located within the system coverage zone. The estimated accuracy for this special case is also 10 nanoseconds.

The following Tables 5 and 6 that follow summarize the characteristics, costs and advantages to Geostar's plans for time dissemination.

TABLE 5

Selective Comparative Information for Satellite Alternatives

Satellite Alternative	Coverage	Accuracy Capability	User Cost Est. (US $, 1981)	Feasible for Onsite Use	Operation or Experimental
USRDSS Medium Precision Time Dissemination	United States	150 ><c	$500 (plus small monthly service charge)	Yes	Planned operational system starting 1987/1988.
USRDSS High Precision Time Transfer	United States	10 msec	$1000 (plus small monthly service charge)	Yes	Planned operational system starting 1987/1988.

TABLE 6.

Principal Advantages and Disadvantages of Satellite Alternatives

Satellite Alternative	Principal Advantages	Principal Disadvantages
USRDSS Medium Precision Time Dissemination	Low Cost. Portable User Transceiver Automatic system operation. Wide area geographic coverage.	System not available until 1987/1988.
USRDSS High Precision Time Transfer	Low Cost. Two-way technique provides high accuracy. Wide area geographic coverage. Onsite operation. System provides message links among users.	System not available until 1987/1988.

I. LORAN-C SYSTEM

Loran-C is a low frequency radio navigation service which operates at a frequency of 100 kHz. The bandwidth of all Loran-C transmissions with modulation is 20 kHz. Low frequency radio signals (long wavelength signals) have transmission characteristics which are stable for distribution of frequency and time as well as its intended purpose of navigation for the military. Because the radio signal follows the curvature of the earth, the usual HF skip conditions are reduced or eliminated. Low frequency radio transmissions propagate almost exclusively by ground wave characteristics.

For satisfying navigation needs Loran-C is made up of many synchronized transmitters forming a network or chain of stations. One station in each chain is a master station and it serves as the originator of frequency and timing information. The other transmitters in the network retransmit signals received from a master station. Retransmission from a slave station in the network occurs at a precisely delayed interval of time. A Loran-C navigation receiver requires reception from three transmitters (a master and two slaves, for example) to establish a position fix. For frequency and time reception only a single Loran-C transmitter needs to be used.

Loran-C is a well developed navigation system that has demonstrated time accuracy to the 1 microsecond level for measurements in long term (several days). Performance is not expected to exceed these numbers. For frequency dissemination the stability is of the order of 1×10^{-11} at one day averaging. One must realize that these performance characteristics are the best published and LORAN-C has been given very extensive development by large agencies such as the military. Indeed, given the signal-to-noise ratios typically available from Loran-C and the limited 20 kHz bandwidth, the performance specifications published represent remarkable results.

Table 7 shows the Loran-C network and other parameters of interest with respect to this study. Although Loran-C satisfies most of the prerequisites of the ITS a few issues are not satisfied. The most serious problem with the use of Loran-C is that its format does not transmit a time code. Time interval measurements are possible using Loran-C but no absolute time is actually transmitted. One could, of course, maintain coarse time at the receiver to resolve time ambiguity. But given a complete receiver failure, the receiver would not be able to automatically resynchronize. Some other method of received time would be necessary and would need to be downloaded to the coarse clock.

A second area of concern is the high cost (approximately $10,000) of a suitable automatic time receiver. Automatic in this sense means that the receiver can be operated completely unattended. Although Loran-C navigation receivers can be purchased for under $2,000, the need for the additional automation to make it a timing receiver (i.e., the ability to identify the proper cycle and decode pulse groups) adds considerably to the cost of the basic 100 kHz receiver.

Table 7.

LORAN-C NETWORK

CHAIN	GRI	TRANSMITTER	COORDINATES		TED (μSEC)	PWR (kw)
Central Pacific	49900	H Johnston Is., HI	16 44 44.0 N	169 30 31.2 W		275
		X Upolu, PT., HI	20 14 49.2 N	155 53 09.7 W	15972.23	275
		Y Kure Is., HI	28 23 41.8 N	178 17 30.2 W	34253.17	275
Canadian East coast	59300	M Caribou, HE	46 48 21.2 N	67 55 37.7 W		350
		X Nantucket, MA	41 15 11.9 N	€5 56 39.1 W	13131.88	275
		Y Cape Race, NFLD	46 46 32.2 N	53 10 28.2 W	28755.02	1500
Sea of Japan (Commando Lion)*	59700	M Pohang, Korea	36 11 02.1 N	129 20 25.8 E		30
		W Hokkaido, Japan	42 44 37.1 N	143 43 09.2 E	15783.68	1000
		X Kwang Ju, Korea	35 02 27.5 N	126 32 31.4 E	31947.02	30
		Y Gesashl. Okinawa	26 36 25.0 N	128 08 56.4 E	45565.56	1000
Canadian West Coast	59900	M williams Lake, BC	51 57 58.8 N	122 22 02.2 W		400
		X Shoal Cove, AK	55 26 20.9 N	131 15 19.7 W	13343.60	540
		Y George, WA	47 03 48.0 N	119 44 39.5 W	28927.36	1600
		Z Port Hardy, BC	50 36 29.7 N	127 21 29.0 W	42266.63	400
North Atlantic	79300	M Angissoq Greenland	59 59 17.3 N	45 10 27.5 W		760
		W Sandur, Iceland	64 54 26.6 N	23 55 21.8 W	15068.03	1500
		X Ejde, Faeroe Is., Denmark	62 17 59.6 N	07 04 26.1 W	27803.77	325
		2 Cape Race, NFLD	46 46 32.2 N	53 10 28.2 W	48212.20	1500
Gulf ot Alaska	79600	M Tok, AK	63 19 42.8 N	142 48 31.9 W		540
		X Narrow Cape, AK	57 26 20.2 N	152 22 11.3 W	13804.45	400
		Y Shoal Cove, AK	55 26 20.9 N	131 15 19.7 W	29651.14	540
Norwegian Sea	79700	M Ejde, Faerod Is., Denmark	62 17 59.6 N	07 04 26.1 W		325
		W Sylt, Germany	54 48 29.9 N	08 17 36.3 E	30065.64	275
		X BO, Norway	68 38 06.2 N	14 27 47.0 E	15048.10	165
		Y Sandur, Iceland	64 54 26.6 N	23 55 21.8 W	48944.53	1500
		2 Jan Mayen, Norway	70 54 52.6 N	08 43 58.7 W	63216.30	165
Southeast U.S.	79800	M Malone, FL	30 59 38.7 N	85 10 09.3 W		800
		W Grangeville, LA	30 43 33.0 N	90 49 43.6 W	12809.54	800
		X Raymondville, TX	26 31 55.0 N	97 50 00.1 W	27443.38	400
		Y Jupiter, FL	27 01 58.5 N	80 06 53.5 W	45201.88	275
		2 Carolina Be., NC	34 03 46.0 N	77 54 46.8 W	61542.72	550
Mediterranean Sea	79900	M Sellia Marina, It	38 52 20.6 N	16 43 06.2 E		165
		X Lampedusa, It	35 31 20.8 N	12 31 30.3 E	12755.98	325
		Y Kargabarun, Turk.	40 58 21.0 N	27 52 01.5 E	32273.30	165
		2 Estartit, Spain	42 03 36.5 N	03 12 15.5 E	50999.71	165
Great Lakes	89700	M Dana, IN	39 51 07.5 N	87 29 12.1 W		400
		W Malone, FL	30 59 38.7 N	85 10 09.3 W	14355.11	800
		X Sencca, NY	42 42 50.6 N	76 49 33.9 W	31162.06	800
		Y Baudette, MN	48 36 49.8 N	94 33 18.5 W	47753.74	500
West Coast U.S.	99400	M Fallon, NV	39 33 06.6 N	118 49 56.4 W		400
		W George, WA	47 a3 48.0 N	119 44 39.5 W	13796.90	1600
		X Middletown, CA	38 46 57.0 N	122 29 44.5 W	28094. SO	400
		Y Searchlight, NV	35 19 18.2 N	114 48 17.4 W	41967.30	540
Northeast U.S.	99600	M Sencca, NY	42 42 50.6 N	76 49 33.9 W		800
		W Caribou, ME	46 48 27.2 N	67 55 37.7 W	13797.20	350
		X Nantucket, MA	41 15 11.9 N	69 58 39.1 W	26969.93	275
		Y Carolina Be., NC	34 03 46.0 N	77 54 46.8 W	42221.65	550
		2 Dana, IN	39 51 07.5 N	87 29 12.1 W	57162.06	400
Northwest Pacific	99700	M Iwo Jima, Japan	24 48 03.6 N	141 19 30.3 E		1800
	**	W Marcus Is., Japan	24 17 07.9 N	153 58 53.2 E	15283.94	1800
		X Hokkaido, Japan	42 44 37.1 N	143 43 09.3 E	36685.12	1000
		Y Gesashi, Japan	26 36 25.0 N	128 08 56.5 E	59463.18	1000
		2 Yap Island, USA	09 32 45.8 N	138 09 55.0 E	80746.79	1000
North Pacific	99900	M St. Paul, AK	57 09 12.3 N	170 15 06.8 W		275
		X Attu, AK	52 49 44.0 N	173 10 49.0 E	14875.25	275
		Y pt. Clarence, AK	65 14 40.3 N	166 53 12.6 W	32068.95	1000
		7 Narrow Cape, AK	57 26 20.2 N	152 22 11.3 W	46590.45	400

CHAIN - The Loran-C transmitters and the basic chain configuration.
GRI - The Loran-C Group Repetition Interval (transmission rate) in microseconds.
TRANSMITTER - M = Master Transmitter of the Loran-C chain.
W-2 = Secondary Transmitter identification letter within a given chain.
COORDINATES - Location of transmitter antenna.
TED - Total emission delay. This is the sum of the coding delay and baseline length in microseconds.
PWR (kw) - Transmitter radiated power in kilowatts.
SOURCE - United States Coast Guard <u>Specification of the Transmitted Loran-C Signal</u> July 1981, COMDTINST f116562.4 (with the exception of Commando Lion).
* - Expected to be operational in 1981.
** - Chain reconfigures when M antenna is down for maintenance. This occurs approximately every 3-4 years for a 30-60 day period. Marcus Island becomes M and the GRI is temporarily changed to 79300. Last temporary rrconfiguration was FEB 1981.

Although the prospects for continued viability of Loran-C as a navigation system are good, other navigation systems of higher precision and generally better performance are now becoming available. This trend will generally take away from future technological upgrades of Loran-C. Loran-C represents the best that systems using radio propagation on the earth's surface can realize for precise timing. This otherwise good system suffers from only two major objections; the inability to receive unambiguous time and the high cost of a fully automatic receiver. The cost of the receiver may fall in time, but this is not a predictable trend, and the market size may not be sufficient to drive production up and cost down substantially.

J. TRANSIT

The U.S. Navy Navigation Satellite System called Transit became operational in 1964. It answered the need of the Polaris ballistic missile submarines for an accurate global navigation system. Transit provides intermittent position fixes in that the satellite is only in view of a fixed position on the earth for approximately 20 minutes.

There are usually five operational Transit satellites in orbit with many more on the ground, all ready for launch to replace failures in orbit. Each satellite transmits carrier frequencies, coherently derived from an onboard oscillator, at approximately 150 and 400 MHz. The transmitted signals provide, during a pass, a source of constant transmitted frequency, a navigation message, and timing information.

The navigation message is controlled to begin and end at the instant of every even minute. An updated navigation message and time correction is obtained periodically by uploading from the ground. The time correction data are stored in the satellite's memory and applied in steps as small as 9.7 microseconds.

The five satellites are in nearly circular polar orbit at an altitude of approximately 1075 kilometers. At this altitude the satellites and their orbits would look something like Figure 1. The earth rotates underneath the constellation of satellites. With a satellite above the horizon, one can make a position fix. The interval between fixes (passes of the

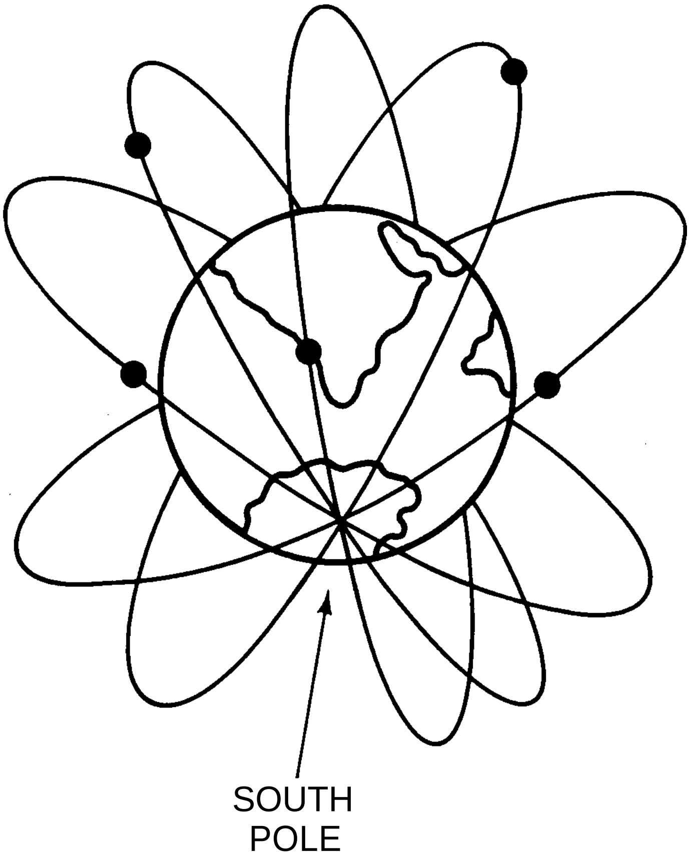


Fig. J1. Five Transit Satellites in Polar Orbit

satellite) can vary from a half hour to nearly two hours depending upon your position relative to the orbit planes.

The navigation message, transmitted every two minutes, begins on the even minute. The end of the message contains a synchronization word that identifies the time mark and beginning of the next two minute message. The satellite's orbital parameters in the first part of the message define an orbit from which the satellite's position can be calculated. To determine one's position on the earth, one has to relate his position to the known satellite orbit through the process of measuring the Doppler shift which is a unique function of the observer's position and motion relative to the satellite's motion through a known orbit.

The frequencies received from the satellite consist of the frequencies transmitted plus a Doppler frequency shift of up to plus or minus 8 kHz. The Doppler-shifted frequencies are due to the relative motion between the satellite's transmitter and the user's ground-based receiver. A position fix is obtained from the following process: (1) an informed estimate is made of the user's position; (2) the slant ranges from this position to the known satellite positions are computed; (3) the computed ranges are compared with the actual measured ranges; and (4) the assumed position is systematically varied and the process repeated until the sum of the squares of the residuals is minimized.

As is with any navigation system, there is a certain time order involved. In the case of Transit, a clock is involved, being carried in the satellite which can be used to synchronize clocks on the ground, a by-product of the navigation function.

A Transit timing receiver needs to only receive the Transit signal, demodulate it, and process the data and timing mark called the Fudical Timing Mark or simply the FTM as shown in Figure 2. The FTM is the timing mark at the end of the two minute Transit message that begins on the even minute. It is the transition from the synchronization word consisting of 23 consecutive 1's followed by a single 0 to the modulation burst of 400 Hz as shown on Figure 3. The timing mark and ephemeris data are handed to the micro computer which calculates the delay between the satellite and the receiver, corrects the arrival of the FTM, and sets an internal clock to agree approximately with UTC, including hours, minutes and seconds.

Commercial versions of this receiver usually have the ability to average the results over many passes of selected Transit satellites and to filter the data for poor quality due to signal level, low elevation angles, poor performance as stated through DoD bulletins or other criteria.

During most of 1979, NBS used two commercial Transit timing receivers to acquire the 400 MHz Transit signals. These receivers computed the path delays and corrected a 1 pps output to be in synchronization with the satellite clock. Reference to DoD bulletins were then used to reference the received time to UTC. The block diagram of Figure 4 indicates how the commercial TRANSIT receivers were used for these evaluations. Although

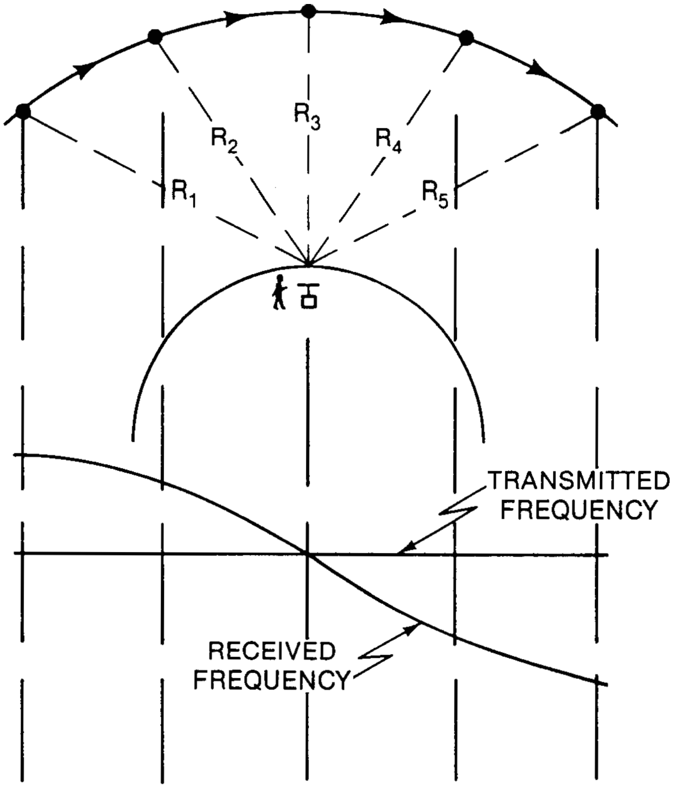


Fig. J2. A Position Fix Using a Transit Satellite

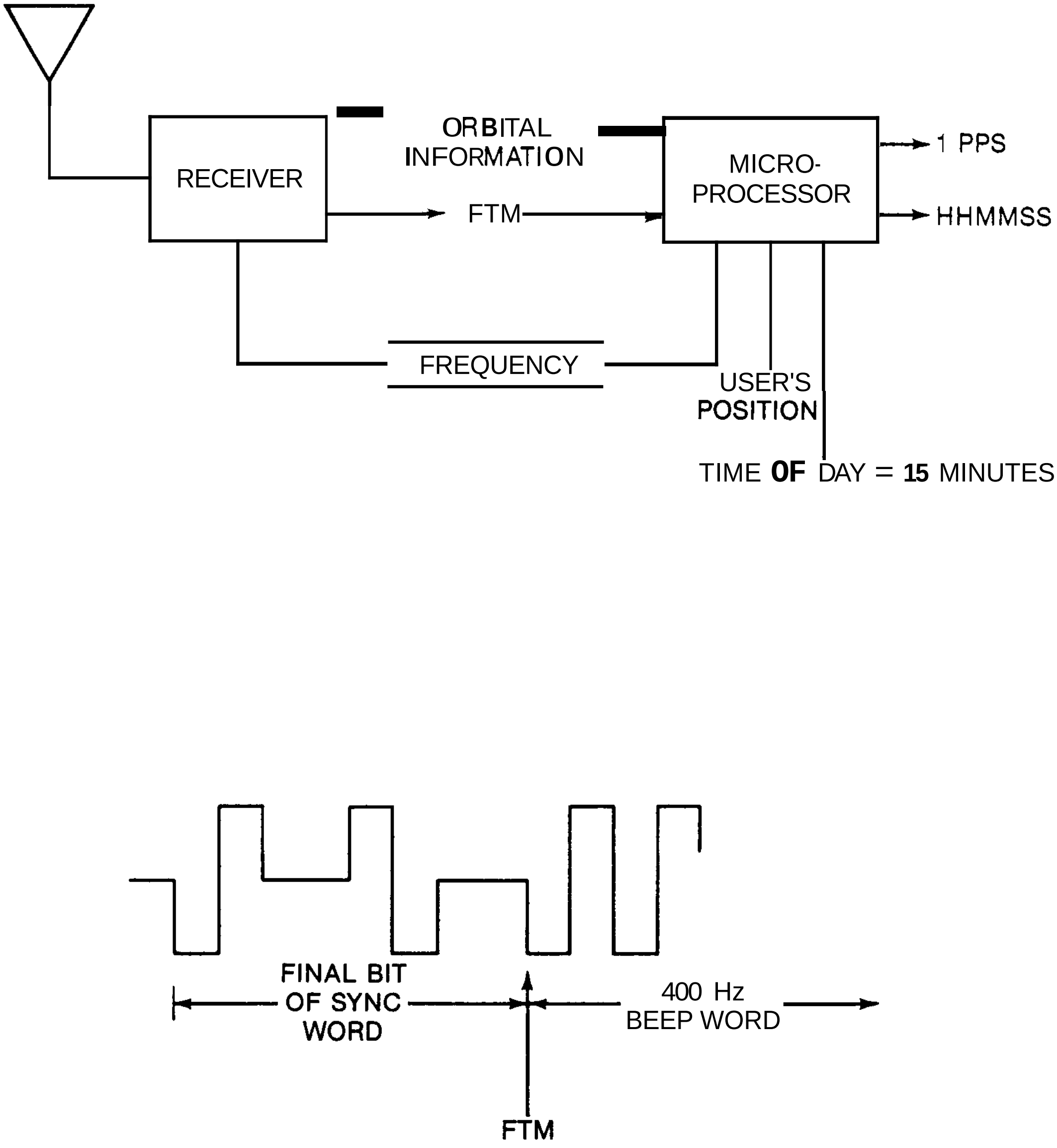


Fig. J3. Block Diagram of Transit Receiver and Transit Signal

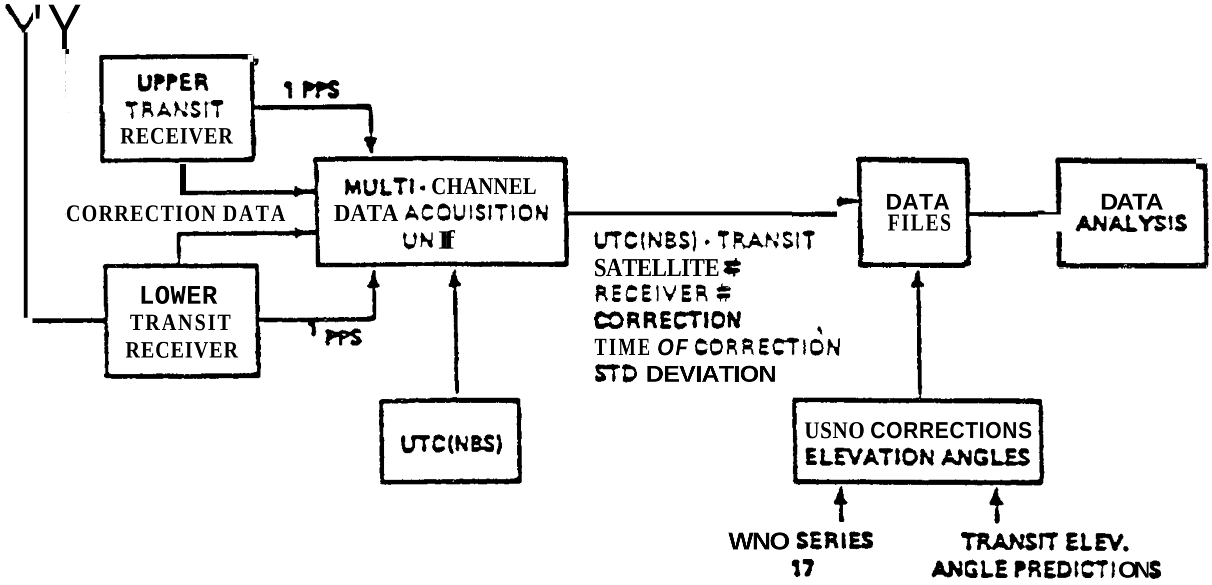


FIGURE J4. Block Diagram of Transit Monitoring System these particular receivers include capabilities for averaging over any number of satellite passes from 1 to 100 and for selectively deleting one or more of the 5 operating satellites from the ensemble used to correct the output 1 pps, NBS chose to use a multichannel data logger to accumulate data separately from each successful satellite pass. The data from each pass were recorded providing a measurement of the Transit receiver 1 pps relative to UTC(NBS), identification numbers for the particular satellite and receiver involved, the amount of correction computed and applied by the receiver, the data and time of correction, and the standard deviation of the individual 2 minute points as supplied by the receiver. After the fact the data file was completed by adding a "Transit clock-UTC(USNO)" correction as published by USNO and the elevation angle for each pass. These data were then analyzed in various ways to show the dependence on the particular satellite ensemble used, the number of passes averaged, the particular receivers used, the application of the USNO corrections, and satellite elevation angle.

These tests revealed that Transit provided synchronization to UTC(NBS) to within 25 µs the majority of the time given that proper support was present. This support included eliminating data from consideration when advised by USNO bulletins that there were problems with any particular satellites. There is also the requirement to maintain a clock as a "flywheel" to keep time within tolerances when no suitable satellites were available for data collection.

The receiving equipment costs run between $12,000 and $21,000 depending upon features. The antenna is small and lightweight and requires no pointing. General consensus for the future of Transit is that it may be discontinued once GPS is fully operational making Transit's existence unlikely after 1990. There is some possibility that private industry may continue the service.

K. GOES

The Geostationary Operational Environmental Satellites (GOES) are operated by the Nat'ional Environmental Satellite Data Information Service (NESDIS) of the National Oceanic and Atmospheric Administration (NOAA). The GOES satellites are primarily for meteorological purposes including the production of images of cloud systems for improving the accuracy of short term weather forecasts. GOES is not a navigation system and has no need for high accuracy position information. Additionally, a data collection system on the spacecraft, illustrated in Figure K1, receives and relays environmental data sensed by widely dispersed surface data collection platforms (DCP's) such as rain and river gauges, seismometers, tide gauges, buoys, ships, and automatic weather stations. The DCP's transmit data to the satellite at regular intervals, upon interrogation by the satellite, or in an emergency alarm mode.

A time code is sent continuously through the satellite so the DCP's may label the environmental data with the date and time as it is collected, thereby enhancing its usefulness. The time code and its associated generation and monitoring systems are provided by the National Bureau of Standards. The time code is referenced to the NBS time scale UTC(NBS).

The interrogation and time code messages comprise a continuous data stream sent through two GOES satellites. These messages originate at Wallops Island, Virginia, where two 18.3m (60 foot) diameter parabolic antennas maintain the continuous data link with the satellites. The signals are

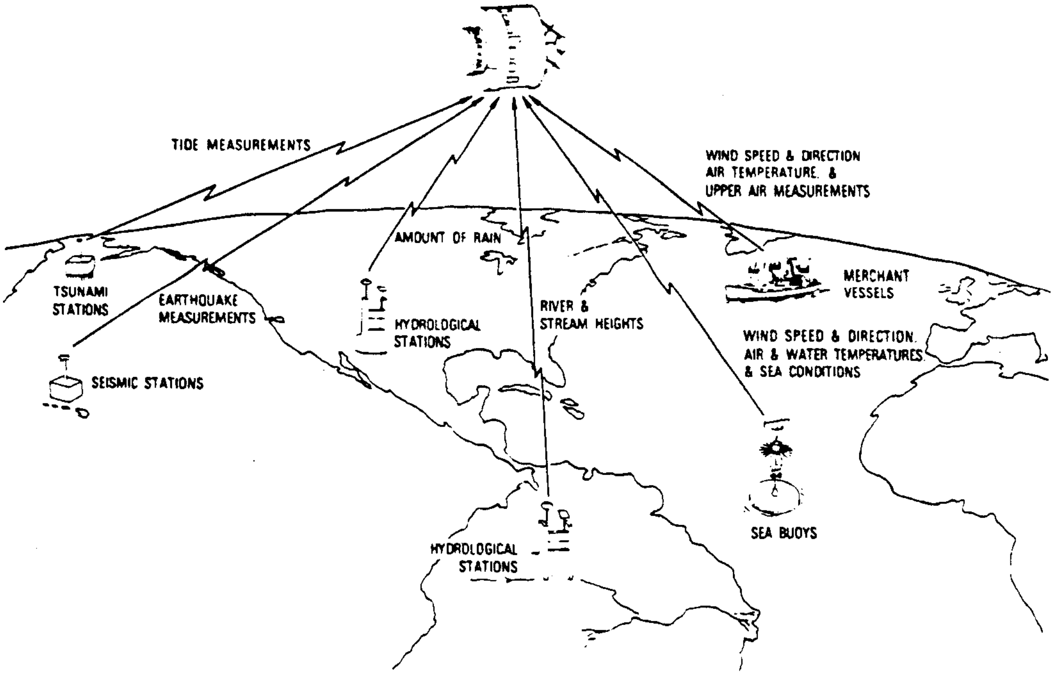


FIGURE K1. Collection of environmental data from data collection platforms.

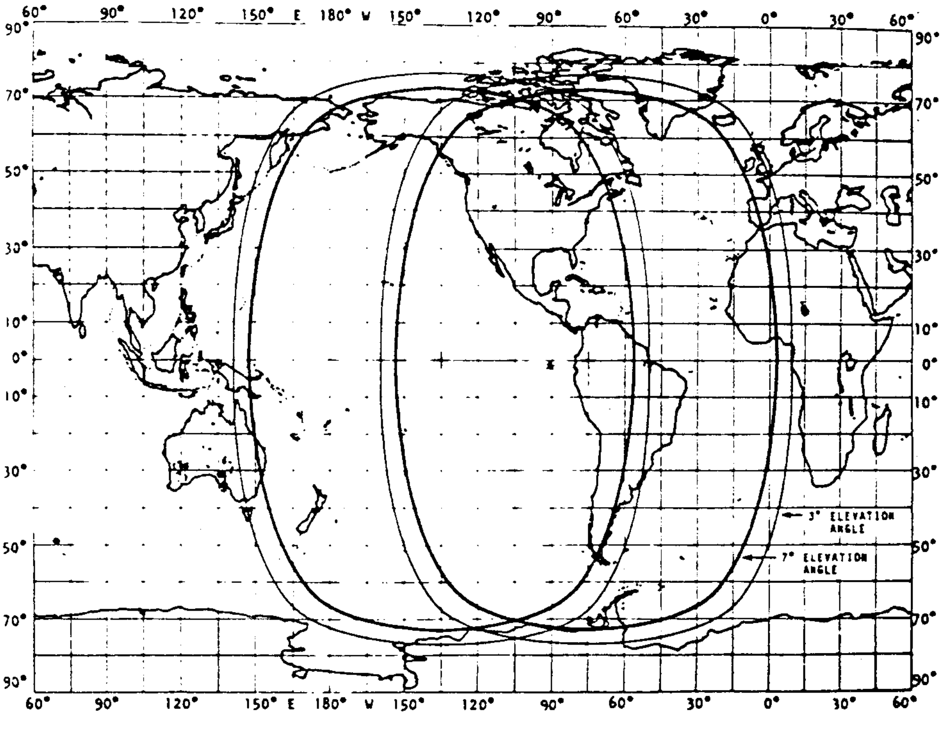


FIGURE K2. Coverage of GOES Satellites

sent to the satellites on a carrier of approximately 1.68 GHz. The 1.68 GHz carrier is changed in frequency at the satellite to nominally 469 MHz and is retransmitted to the earth through antennas with global coverage beamwidths. See Figure K2 for approximate coverages for the GOES satellites.

The time code is contained within the interrogation channel of the GOES satellites. The interrogation channel is used to command remote DCP's to send their collected data to the GOES satellites. The satellites relay these data to the Command and Data Acquisition (CDA) facility at Wallops Island, Virginia, for processing and dissemination to users. Interrogation messages are continuously being sent through the GOES satellites. The format of the interrogation messages is shown in Figure K3.

The interrogation message is 0.5 s in length, or 50 bits. The data rate, controlled by atomic frequency standards, is 100 bit/s (bits per second). An interrogation message consists of 4 bits representing a binary coded decimal (BCD) word of time code beginning on the half second of UTC, followed by a maximum length sequence (MLS) 15 bits in length for message synchronization, and ending with 31 bits as an address for a particular remote DCP. Sixty interrogation messages are required to send the 60 BCD time code words constituting a time code frame. The time code frame begins on the half minute of UTC and repeats every 30 s (see Figure K4). The time code frame contains a synchronization word, a time message (UTC), the UT1 correction, indicators for current system accuracy and daylight savings time, and the satellite's position in terms

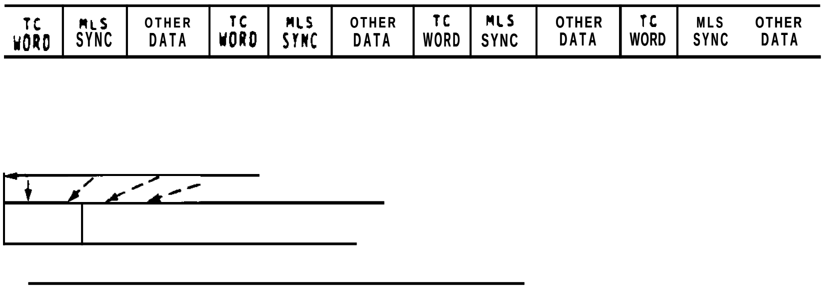


FIGURE K3 **Interrogation channel format.**

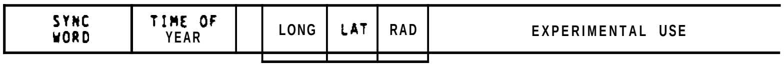


Figure K4. **Time code format**

FREQUENCY	468 8250 MHz	468 8375 MHz
POLARIZATION	RHCP	RHCP
MODULATION	CPSK (± 60°)	CPSK (± 60°)
S STRENGTH (OUTPUT ROY ISOTROPIC ANTENNA)	-139 dBm	139 dBm
COOING	MANCHESTER	MANCHESTER
BANDWIDTH	400 Hz	400 Hz

FIGURE K5. Interrogation channel signal characteristics.

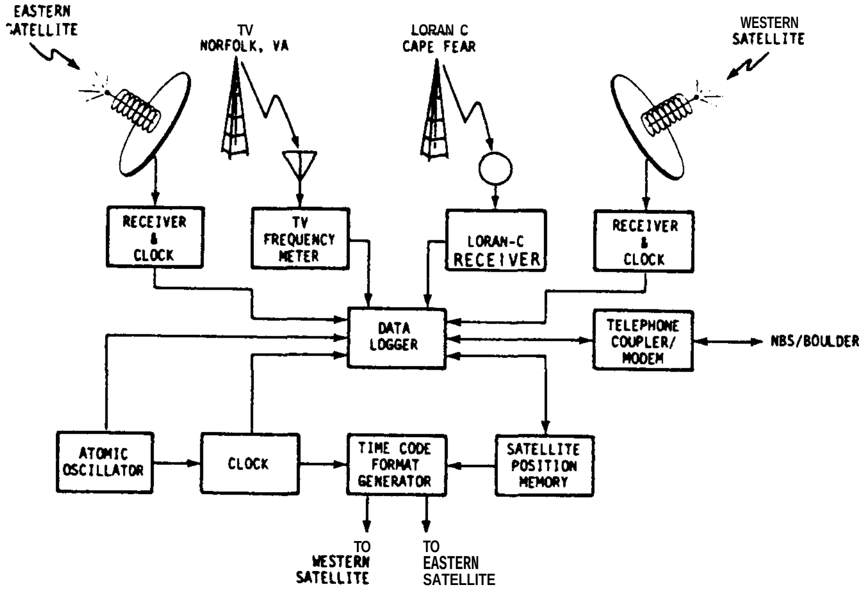


FIGURE K6. Time code generation system

of its longitude, latitude, and height above the surface of the earth minus a bias of 119,300 µs. The position information is updated frequently, presently every 1 min.

The GOES time signals from both satellites are summarized in Figure K5. The signals are right hand circularly polarized (RHCP), coherent phase shift keyed (CPSK), and separated in frequency by 12.5 kHz. The data rate, being 100 b/s, occupies only 400 Hz of bandwidth. The data are Manchester coded and phase modulate the carrier ±60°, thus providing a carrier for conventional phase-locked loop demodulation.

NOAA's CDA ground stations are located at Wallops Island, Virginia, where all interrogation signals sent to the satellite are originated. NBS maintains an ensemble of atomic clocks at that site. These clocks provide the time and frequency reference for the time code. The time code generation system, partly shown in Figure K6, is completely redundant and fully supported by an uninterruptable power supply. There is a communication interface between the equipment and NBS, Boulder, using a telephone line. Over the telephone line, satellite position information is sent to the CDA and stored in memory for eventual incorporation into the time code and interrogation message.

Data are also retrieved from the CDA via the telephone line to Boulder. These data include the frequency of the atomic oscillators and the time of the clocks relative to UTC compared via GPS satellite signals and Loran-C

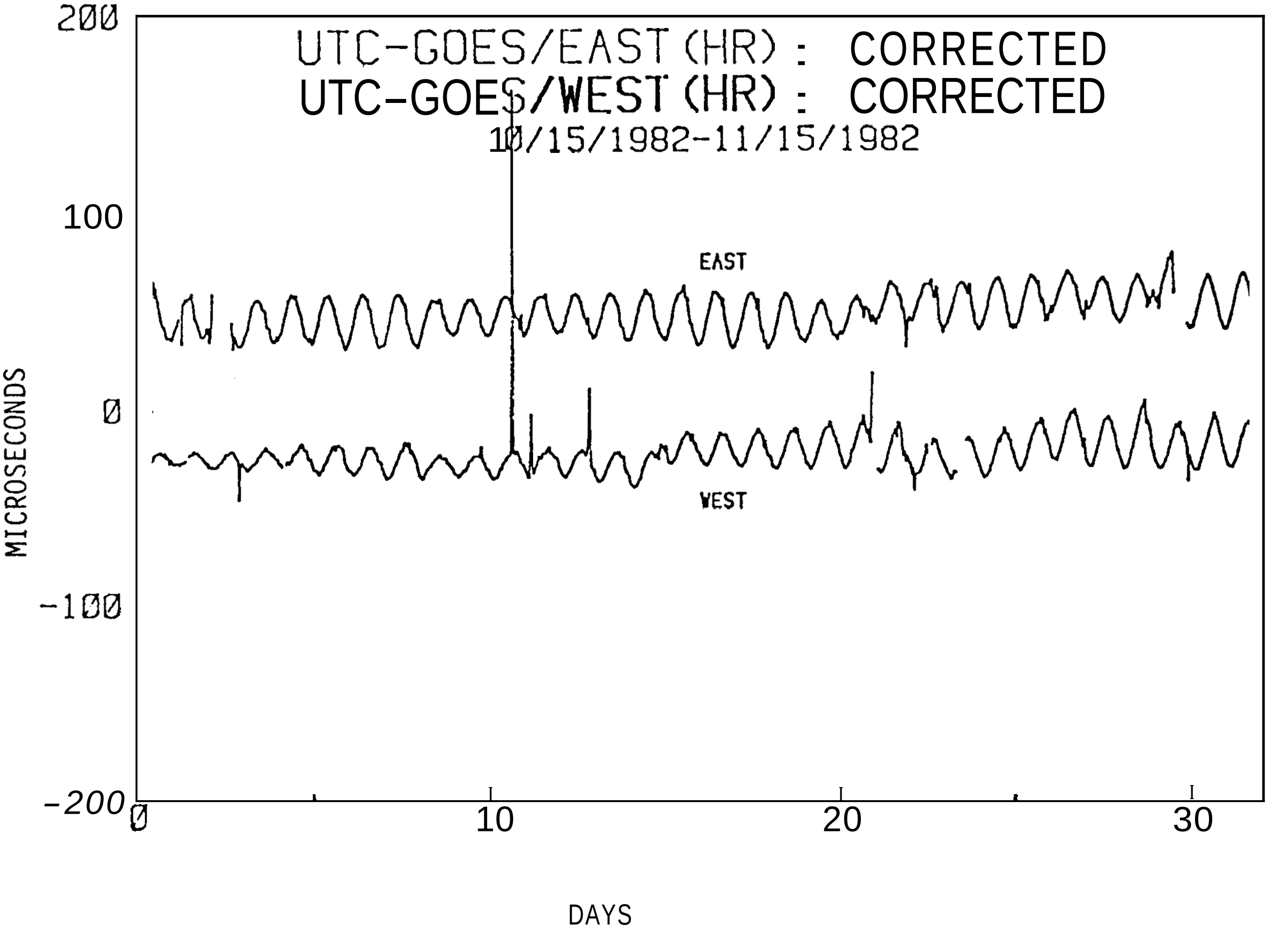


FIGURE K7. Typical corrected timing data from GOES.

transmissions from Cape Fear, North Carolina. Besides the time-and-frequency monitoring functions the NBS equipment at Wallops Island provides the information necessary for NBS staff at Boulder to remotely determine if and where malfunctions exist and to correct them through the switching of redundant system components.

The satellite position information is generated at Boulder by using a large scientific computer and orbital elements furnished by NESDIS. NESDIS generates these orbital elements weekly using data obtained from their tracking facilities at the CDA.

Commercial receiving equipment is available from three manufacturers with costs in the range of $3,000 to $7,500 depending upon features. The antennas are typically of the helix type with overall lengths of about one meter, diameters of approximately 1/4 meter, and weight of 10 kilograms.

The performance for GOES has been typical of that shown in Figure K7. Except for rare occasions when the satellite ephemeris is of poor quality, the GOES signals provide time to within 100 µs of UTC(NBS) throughout the entire coverage areas of both east and west satellites.

Since May 1974 the NBS has operated time code broadcasts from NOAA's GOES satellites. There are three or more satellites in orbit; two are operational, the other serving as the 'in-orbit' 'hot' spare ready to replace either satellite in case of failure. Other satellites are usually ready for launch when needed. The present complement of satellites is expected to insure two satellites in continuous operation. Plans exist to continue the program beyond the year 2000.

Considering the long life of the GOES system, the important mission of the GOES program, and the wide geographical coverage of the satellites the GOES time signals are finding many applications where reliability, automatic signal recovery, and accuracy are desirable. Being geostationary, GOES is a source of continuous synchronization, offering a significant advantage over a non-geostationary satellite which can only provide exposure to the user during brief periods of time. Also, the GOES time signals are not subject to the fading and unpredictable path delays that limit terrestrial systems operating in the low to high frequency ranges.

The time code information is a convenient addition to GOES but not a requirement. The present level of accuracy is 100 µs with no provision for improvement given the low resolution and precision of position information.

L. CONCLUSIONS OF PHASE II

Seven systems have been examined against criteria designed to select the best system or systems that have reasonable potential for satisfying the requirements of the ITS. The BSS has been rejected for further study or development because it did not offer continuous operation time and presents tracking problems that are not supportive of the one microsecond requirement with reasonable costs. LORAN-C was not acceptable because of receiver costs, lack of a time code, and uncertain future.
The Transit system was rejected for basically the same reasons as for LORAN-C with the additional problem of inadequate accuracy. GOES was not acceptable for accuracy reasons.

The FSS, GPS and RDSS will be examined further in the next phase of this study. FSS will be studied because of its excellent potential to meet all requirements and have time and frequency dissemination as its sole mission. An ITS system will be partially developed using the FSS so issues of cost, accuracy and feasibility can be examined in a more realistic environment. GPS is a system that is already working and satisfies or will satisfy all requirements except cost. Long term DoD policy adds some uncertainty which will be explored in the next phase along with some technological forecasting of equipment costs for the near future. The RDSS is a very new system and was a surprise option for this study. If the direction for Geostar continues as planned it may serve as an excellent ITS. We will attempt to establish a dialog with the Geostar organization to provide a clearer picture of their plans. We will assist in developing those plans through a limited cooperative effort if such an effort is found desirable by both parties.

The final phase of the ITS study converges on examining a private sector offering, a DoD navigation system with a mission different from time and frequency dissemination, and the exclusive use of a portion of a telecommunication service (the FSS option). Each option has technical and political advantages and disadvantages. This next phase will attempt to further identify and analyze all pertinent issues needed to make informed decisions for future use of high precision synchronization services.

PHASE 111, PART 1:

THE FIXED SATELLITE SERVICE

A PRELIMINARY DESIGN

CONTENTS

M. PHASE 111, Part 1 INTRODUCTION

The FSS (Fixed Satellite Service) option represents the design of the ITS as a satellite broadcast system using part of a transponder carried by a U.S. domestic communications satellite operating in the Fixed Satellite Service. The FSS is generally intended for point-to-point telecommunications. However, recent footnotes added to the ITU regulations now allows FSS bands to operate on a secondary basis in a broadcast mode. There are several very successful examples of this in use today, most notably that of the Equatorial Communications Corporation who distributes data to small earth stations in a point-to-multipoint or broadcast mode.

The ITS, using a FSS satellite, could be implemented in close approximation to that described in this section. A moderately sized earth station located at the source of time and frequency standards would uplink or transmit the time and frequency signals to a communications satellite. This moderately sized earth station, the diameter of which would be on the order of 6 meters, would guarantee that the total communications link would be downlink limited. In other words the uplink would constitute no liability in the total system noise budget.

The satellite, upon receiving the uplink signals, would change the carrier frequency, amplify, and reradiate them back to the earth's surface. These signals would be received by users equipped with small microwave antennas (likely to be a dish with a diameter of one meter or less) and a receiver which would amplify, down convert and decode the timing signals. The timing signals would provide the information required to set and control a clock to within better than one microsecond of the NBS time scale denoted as UTC(NBS). That information would include the day number, hour, minute, second, and the satellite's current position in longitude, latitude, and earth center distance. The receiver could also generate one or more frequencies such as 1 MHz and 5 MHz disciplined to the NBS frequency standard via this ITS service link.

The tracking of the satellite's position relative to the earth and the generation of its ephemeris would be accomplished using the timing signals. The ephemeris of the satellite is information required by the user's receiver in the computation and correction of signal delay from the NBS earth station through the satellite to the user's receiver. The position of the satellite would be determined by receiving the timing signals relayed by the satellite at three carefully selected points on the earth within the satellite's antenna coverage. One point will be NBS, Boulder. The other two sites will be selected to provide the best geometries for determining the satellite's position as well as for political, economic and other technical reasons. These two sites will communicate their data in real time to NBS, Boulder either through the same satellite or via terrestrial communications facilities. An orbit will be fit to the data. This orbit will then be used to generate the satellite's ephemeris algorithm for deriving ephemeris data.

The timing signal will be encrypted to deny its use by unauthorized or nonsubscribing users. The key for encryption will be provided to the user according to a subscription list. Subscription fees will pay for the operation and maintenance of the ITS. Each user's receiver will have a unique master encryption key built into the receiver. Each key shall be generated, authorized and registered by NBS prior to being installed in the receiver by the manufacturer. A working key could be distributed by NBS or its contractors on a periodic basis and according to subscription fees paid. The key may be delivered either in the form of an electronic apparatus (such as PROMs) which is inserted into the receiver or, more preferably, sent via the satellite to each paid-up user's receiver. Delinquent user's receivers could be made inoperative, as well, by sending an invalid working key. The intent of the encryption procedure is to render cheating a poor use of time and effort when compared to paying a relatively small annual subscription fee for the service delivery of time and frequency information.

The cost of user's equipment must be reasonable enough to guarantee a sufficient population of users to cover the service's cost of operation and maintenance. In the last few years the costs of small microwave antennas, low noise amplifiers and down converters designed for satellite receive-only application have decreased significantly. This cost reduction has been particularly true due to the emerging Direct Broadcast Satellite (DBS) industry in the U.S., Europe, and Japan. The ITS, being broadcast in nature, can enjoy the economies of scale to be realized from the DBS industry. Since tens of millions of units are to be produced, this should particularly benefit the ITS user. The user's antenna must be physically small but not necessarily classified as mobile. Typically, DBS antennas are being designed and manufactured with diameters as small as 0.6 meters. Complete DBS receiving systems not including the TV set are expected to be in $400-500 range.

The use of the FSS can be extremely reliable. One need only notice that the major TV networks are now routing programming to local distributors via satellite and that many major sporting events from around the world are watched live with little interruption. Due to the numerous sources for satellite bandwidth and time, especially in the U.S., one can be assured of a very competitive environment and thus realize the lowest costs possible for satellite bandwidth and time.

The discussion above was a brief statement of one model for the ITS using the Fixed Satellite Service and is intended as an introduction to the discussions of the main issues relevant to the ITS. They are more fully developed and described below.

N. ELEMENTS OF THE ITS

N1. THE SPACE SEGMENT

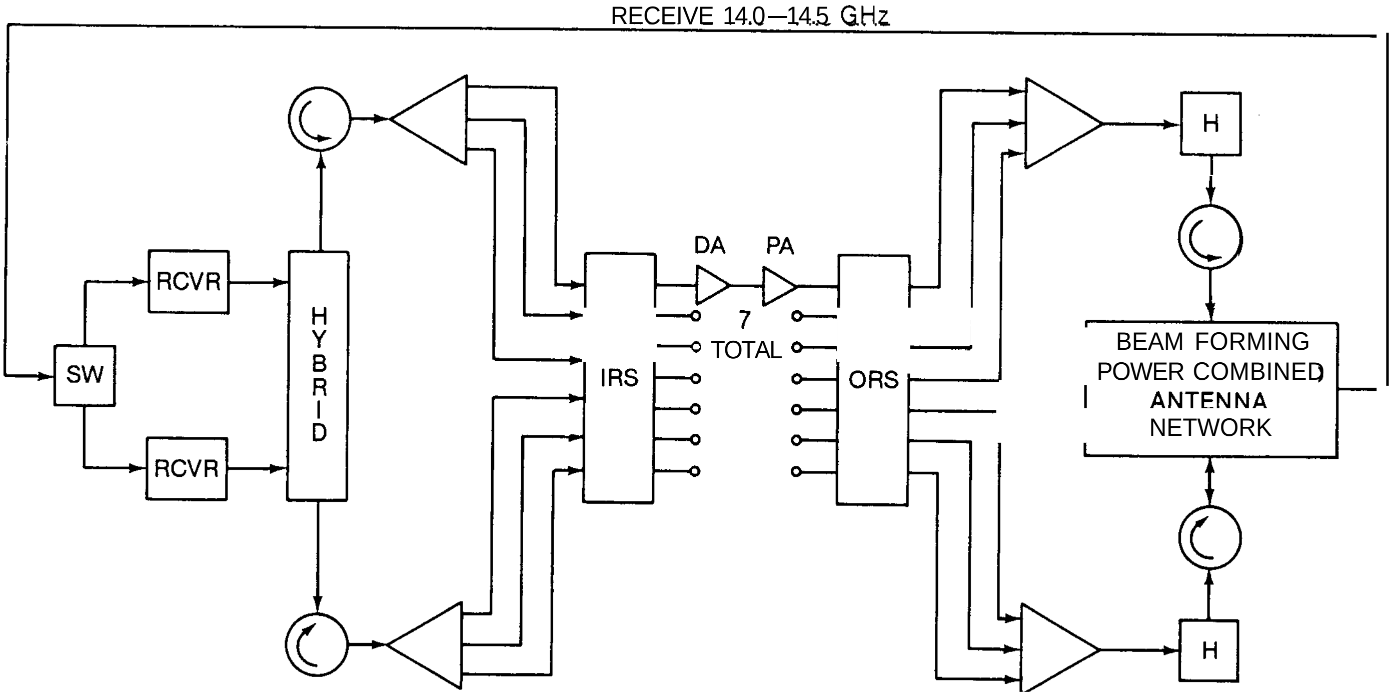
The space segment is that part of the ITS that will be located in space. In this case, it is that part of a satellite that is directly involved with the ITS.

The FSS as operated in the United States is a nonmonopoly satellite service and is priced on an open market basis. It is driven by costs and profit incentive. The costs per channel have been steadily dropping relative to inflation since its inception. This has resulted in a steady growth. Growth has stimulated the design of larger and more cost effective satellites, further reducing costs through economies of scale.

This situation is expected to continue for some years to come, at least until the growth of fiber optics communications begins to assume a major role in the point-to-point telecommunications markets.

The FSS within the United States can be partially understood by looking at the numbers of transponders in space today and the numbers expected in the near term. A transponder is simply a satellite repeater. The transponders have mainly been 36 MHz in bandwidth but other bandwidths are becoming common, especially in the KU band. It has become standard to discuss satellite capacity in terms of numbers of 36 MHz transponders. Recent studies have placed the number of transponders in space at 732 for 1985, 1212 for 1986, and 1336 for 1987. The capacity for 1985 in terms of bandwidth is therefore 732 x 36 MHz, or 26,352 MHz, available to support various telecommunication customers. A typical KU band transponder and frequency plan are shown in Figures N1 and N2.

Satellite services may be acquired at a number of levels. Satellite owners will lease or sell transponders (36 MHz units). Full time holders (owners or leasors) of transponders may lease out the transponder on a part time basis. This may be scheduled, for example, on a "same-time-every-day" or "only-on-Mondays" basis or on an occasional basis for a special event. Fractional transponder users, like the ITS, could obtain their necessary bandwidths from transponder owners or lease holders. An example of a fractional transponder use is a business needing only a narrowband data service or one that does not need a full transponder.



IRS: 6 to 7 Input Redundancy Switch.
ORS: 7 to 6 Output Redundancy Switch.
DA: Driver Amplifier
PA: Power Amplifier

Fig. N1. Typical KU-BAND Transponder Configuration

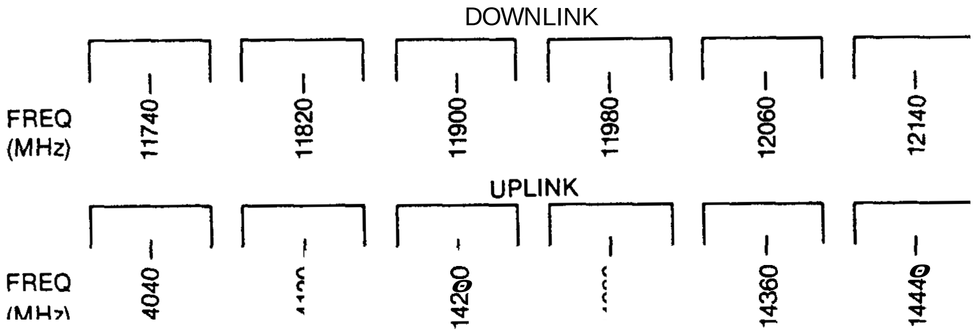


Fig. N2. Typical **KU** Band **Frequency** Plan

The FSS for US domestic use operates in the 5.925 to 6.425 GHz uplink and 3.7 to 4.2 GHz downlink band and is commonly referred to as the C-band. The other FSS domestic assignment is at KU-band with the 14.0 to 14.5 GHz band for the uplink and 11.7 to 12.2 GHz band for the downlink. Additional frequency bands were allocated at the 1979 World Administrative Radio Conference (WARC-1979). These additional bands will not become a factor for the ITS for several years because of technical and economic reasons.

The U.S. domestic satellites operating in the FSS are assigned positions by the FCC in the geostationary arc between 62 degrees West longitude and 146 degrees west longitude (except for the arc between 105 and 120 degrees which is assigned to Canadian satellites). These satellites have antenna patterns that cover the CONUS with some satellites also providing spot beams to Hawaii, Alaska, and Puerto Rico and Virgin Islands. The recent assignments of the geostationary arc are shown in Table 8. These satellites, due to antenna size, provide reduced, but usable, signal levels far into adjacent areas of Canada, Mexico, the Pacific and Atlantic Oceans. A typical foot print is shown in Figure N3 where contours of equal ERIP are shown.

Recent efforts to increase the capacity of the geostationary orbit have led the FCC to require that satellites be spaced at two and three degrees apart rather than the old standard of four degrees. This new spacing means that ground antennas will experience more interference from adjacent satellites through their side lobes. These ground antennas, when transmitting, will interfere with the reception by adjacent satellites

TABLE 8. SATELLITE ORBITAL POSITION ASSIGNMENTS

POSITIONS	SATELLITE	KU BAND	C BAND
146	AURORA 2		X
144	WESTAR 7		X
142	AURORA 1		X
140	GALAXY 4		X
138	SATCOM 1R		X
136	SPACENET 4	X	X
136	GSTAR 3	X	X
134	UNASSIGNED		
134	COMSAT GEN B	X	
132	GALAXY 1		X
132	WESTAR B	X	
130	SATCOM 3-R		X
130	GALAXY B	X	
128	ASC-1	X	X
126	TELSTAR		X
126	MARTIN MARIETTA B	X	
124	WESTAR 5		X
124	FEDERAL EXPRESS B	X	
122	UNASSIGNED		
122	SBS 5	X	
120	SPACENET 1	X	X

POSITION BETWEEN 120 AND 105 DEGREES ARE
ASSIGNED TO CANADIAN SATELLITES

105	GSTAR	X	
103	GSTAR	X	
101	FORD 1		X
99	WESTAR 4		X
99	SBS 1	X	
97	TELESTAR		X
97	SBS 2	X	
95	SBS 3	X	
95	GALAXY 3		X
93	FORD 2	X	X
91	WESTAR 3		X
91	SBS 4		X
89	UNASSIGNED		X
89	UNASSIGNED	X	
87	SPACENET 3	X	
85	TELESTAR		X
85	RCA A	X	
83	ASC 2	X	X
81	SATCOM 4		X
81	RCA B	X	
79	MARTIN MARIETTA A	X	
79	WESTAR 2		X

77	FEDERAL EXPRESS A	X	
76	COMSTAR D4		X
75	COMSAT GENERAL A	X	
74	GALAXY 2		X
73	WESTAR A	X	
72	SATCOM 2-R		X
71	GALAXY A	X	
69	SPACENET 2	X	X
67	SATCOM 6		X
67	RCA C	X	
64	ASC 4	X	X
62	SATCOM 7		X
62	SBS 6	X	

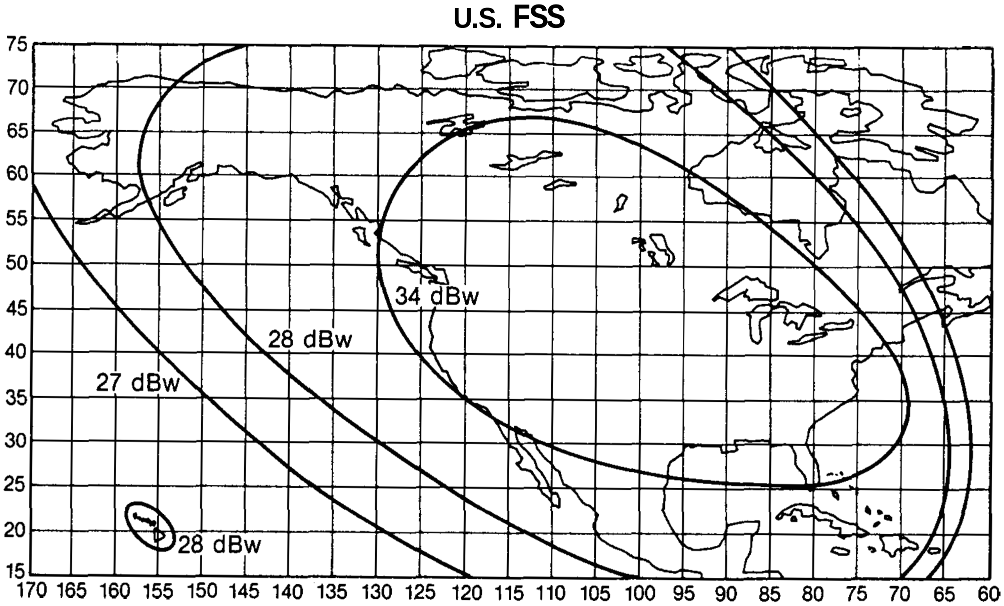


Fig. N3. **Typical** EIRP **Contours** for U.S. FSS Satellites as well. The interference geometry for adjacent satellite systems is illustrated in Figure N4. New sidelobe standards have been imposed by the FCC for the earth station. The effect has been the use of larger and more expensive antennas on the ground. These sidelobe standards are mandatory for all transmit antennas and for all receiver antennas wanting the protection afforded by a FCC license but must accept whatever interference adjacent satellites and terrestrial microwave may inflict. The interference will be particularly severe for the very small earth station whose side lobes are high within two or four degrees from its main lobe axis. Techniques such as the use of spread spectrum are available to reduce the effect this interference and are discussed elsewhere.

The costs of transponders or their long term leases can only be estimated. The reasons are the nearly complete deregulation of satellite tariffs. The current procompetitive policies of the Federal Communications Commission (FCC) have resulted in a number of actions that directly affect domestic satellite firm's charges for their transponder services.

In the FCC's Competitive Carrier decision (CC Docket 79-252) two regulatory tiers for nondominant common carriers were established and include satellite firms providing domestic interstate services, specialized common carriers, and resellers. Nondominant carriers are those not possessing sufficient market power or unable to raise prices significantly above costs for an appreciable period of time or to discriminate against any class of customers.

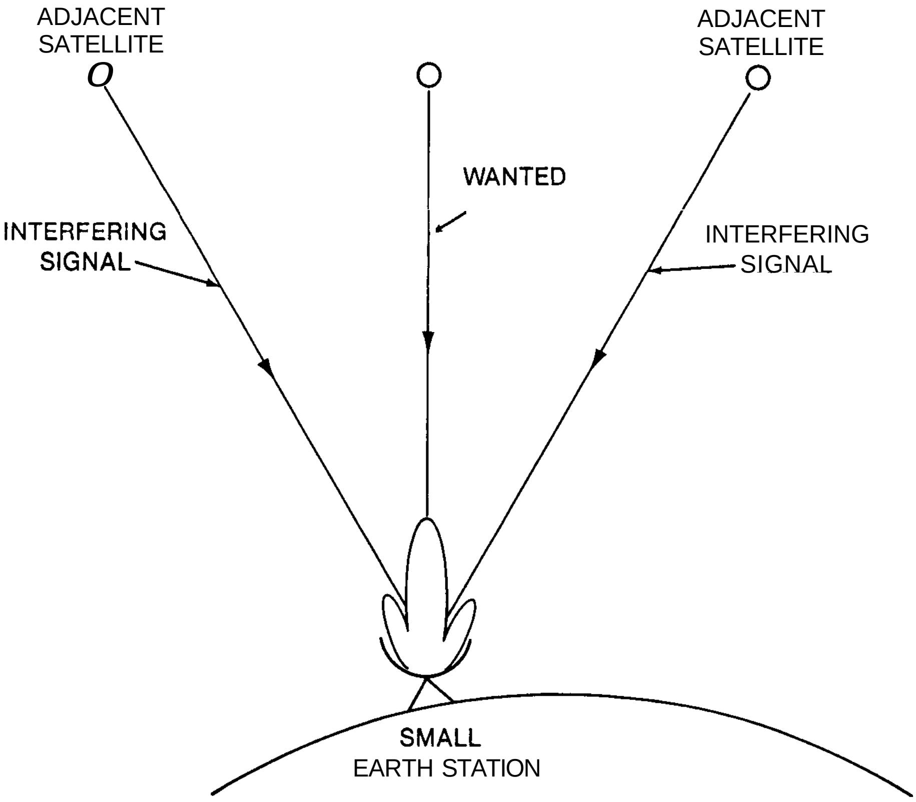


Fig. N4. Interference Geometry for Adjacent Satellites

Under the streamlined regulation order (adopted October 1983) tariff requirements were substantially reduced for these non-dominant carriers. Tariffs could be filed on 14 days notice rather than 90. Carriers were permitted to expand services subject to nominal reporting requirements and to discontinue services subject to a relatively short approval period and customer notice obligation. This order has made for a more dynamic environment where services can more easily meet market demands.

Under the "forbearance" doctrine adopted in August 1984, these carriers were now able to change prices or rate structures, or to expand or discontinue a service without any waiting period requirement or reporting to the FCC. In an action taken in November 1984 the FCC directed common carriers subject to the regulatory forbearance to cancel their tariffs on file and not to file other tariffs in the future. All tariffs are now cancelled. All carriers have an obligation, however, to keep material on file at their offices that can be produced readily upon inquiry from the FCC, in order to substantiate reasonableness of rates, terms and conditions.

This competitive environment has been credited with an increased array of services and choices. In addition to communication services, satellite common carriers, transponder resellers and brokers offer a variety of operational and ownership alternatives. The customer can select from end-to-end services provided by one entity, or customers may contract with a satellite or transponder owner for space segment only and build and own the ground segment.

In this deregulated environment it is difficult to predict the space segment costs accurately without a formal bidding process or direct negotiation with the carriers. A recent example can be informative however. The ITS, in this study, requires a small part of one transponder, approximately 200 kHz of the transponder's 36 MHz or roughly one percent. For a fixed term, protected* service (two years or more), the costs have recently been in the $130,000 to $170,000 per month range. Assuming a partial transponder use of one percent and a mark up of 100% by a broker due to reduced transponder efficiency and brokerage fees, these costs for the ITS would be $2600 to $3400 per month. These costs are for satellite transmission time only.

N2. THE GROUND SEGMENT

The ground segment will consist of three major components including (1) the master earth station with the time and frequency reference, system tracking control, and the information generation system, (2) the remote tracking earth stations consisting of two or more smaller antennas, and (3) the user receiving system each consisting of a small antenna and receiver.

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*Two forms of protected transponder services are common. There is the "Protected-dedicated," in which a company will reserve a specific replacement transponder, consisting of an unassigned transponder or a transponder subject to interruption in a separate satellite or in the same satellite, for use in the event of transponder failure. With "Protected-designated," typically, no specific replacement transponder is identified.

N2a. THE MASTER EARTH STATION

The master earth station will transmit the signals to the satellite for relay to the users. The earth station will be co-located with the time and frequency standards which generate UTC(NBS) at the NBS facility in Boulder, Colorado. A master earth station already exists at Boulder and can serve as the ITS master earth station. It is a 6.1 meter KU band antenna roof mounted using a kingpost mount. A photo of the antenna is shown in Figure N5. The antenna is within 300 feet of the time and frequency standards, i.e., the NBS time scale and the U.S. frequency standard.

The required ITS earth station is represented by a block diagram in Figure N6. The NBS time and frequency standards provide the reference for the time code generator, to the time interval counters (TIC) which output the range measurements data between the satellite and the NBS master and two other smaller earth stations. The computer receives these range measurements from the TIC's and computes an orbit for the satellite. Using this computed orbit, the computer outputs the satellite's current predicted position for inclusion into the next message frame to be sent to the satellite. The computer also looks at the data relayed by the satellite for the purposes of checking operations.

The time code and satellite position are encrypted. The encrypted output is joined with the initiation vector used in the encryption and decryption process, and both are encoded for forward error correction

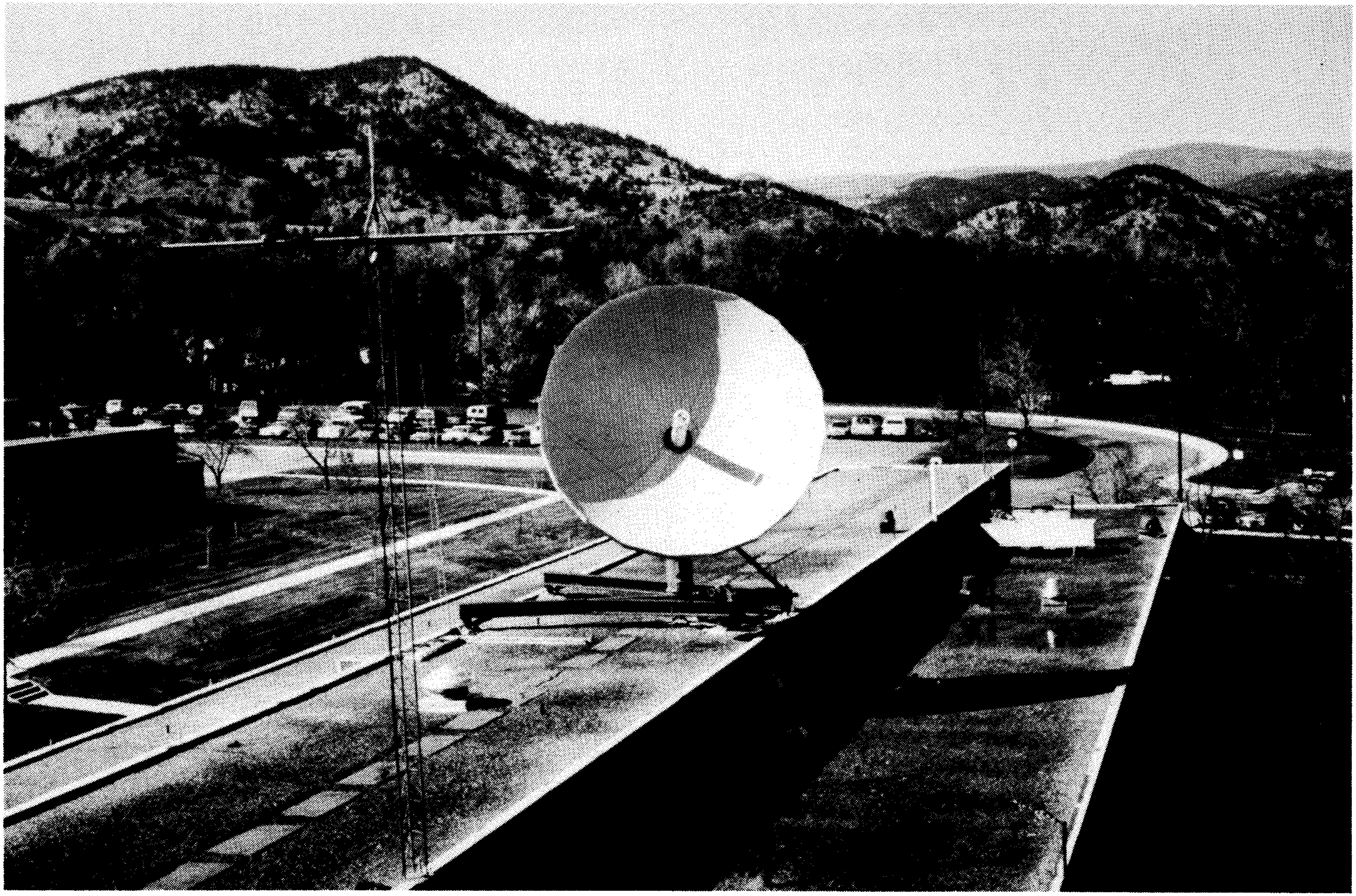


Fig. N5. NBS Earth Station

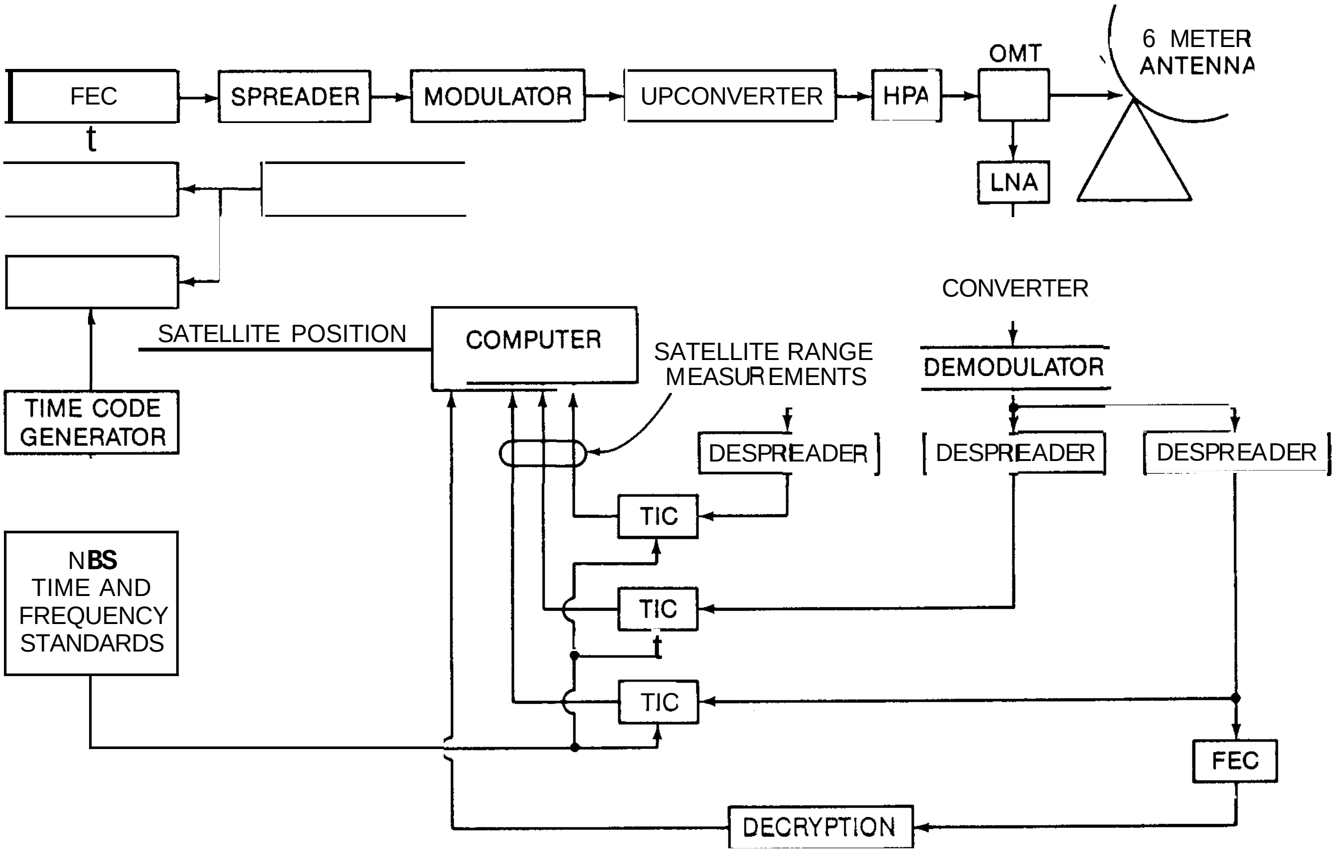


Fig. N6. NBS Master Earth Station

using a rate 1/2 code. The data are then joined with a frame sync word and applied to a spreader where each bit is expanded by approximately one thousand times to give a processing gain of at least 30 dB.

The spread data are then passed through a modulator, upconverted to KU band, amplified and input to the antenna through the ortho-mode transducer (OMT).

The received signals at the master station consist of the signal transponded through the satellite and two others that were transponded by remote earth stations and relayed back to NBS via the satellite. The signals are despread at the remote sites and respread with orthogonal spreading codes for separation at the Boulder earth station.

Upon reception at Boulder, the signals are amplified by a low noise amplifier (LNA), down converted and demodulated. The three signals are despread in their respective channels, the result of which is applied to the TIC's for the range measurements.

N2b. THE TRACKING SYSTEM

An accurate estimate of the satellite position at all times is a requirement for the ITS. This position information is required by each user's receiver to compensate for the time delay of the signal between its source (NBS) and the user's receiver. This time delay is constantly changing since the satellite never maintains a perfect "geostationary" orbit. All geostationary satellites have an orbit with a small eccentricity and a small degree of inclination. Figure N7 illustrates the orbit geometry with respect to the earth.

Communication satellites are maneuvered every week or two to keep their positions, relative to the earth's surface, reasonably constant. Typical requirements for communications satellites are to keep them within a box in space of ± 0.05 degrees north and south of the equatorial plane and ± 0.05 degrees east and west of an assigned position in longitude. Assignments in longitude for U.S. satellites are now made at every two degrees by the FCC. Keeping the satellites at these positions requires tracking procedures by the satellite's operators that are not sufficient to meet the ITS requirements. The operators need only track the satellites at infrequent intervals rather than on a continuous basis as required by the ITS to produce orbital elements accurate enough to produce long term, accurate predictions of satellite position.

The use of communication satellites for the ITS, therefore, necessitates the ITS system to include its own tracking system. A tracking system for the ITS can be generally specified with reasonable confidence.

The ITS tracking system would ideally include three earth stations, each performing ranging measurements to the satellite on a continuous basis. The earth stations would include the same master earth station as NBS used to uplink the time and frequency signals to the satellite. Two

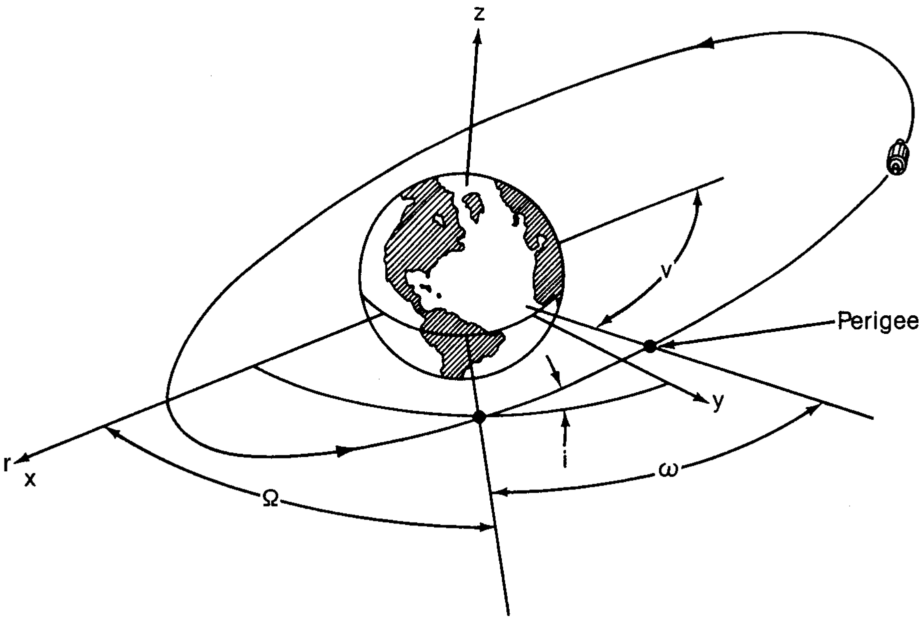


Fig. N7 Satellite Orbit Geometry

other smaller earth stations would be located on the earth's surface at locations to produce the best tracking results. Generally, the coordinates of the three earth stations should define a triangle of the greatest areas possible within the beam of the satellite. If the beam covers CONUS then the triangle would be constrained to lie within CONUS with one vertex located at NBS, Boulder. These three earth stations providing range measurements to the satellite constitute a process called trilateration of the satellite.

Ranging signals will originate at NBS, Boulder, and be sent to the satellite. The satellite will receive these signals, change their frequency, and send them back to earth. Reception of the signals at Boulder will allow a measurement of the range from Boulder to the satellite. Range measurements made through the other two earth stations will produce the combined ranges between Boulder and these sites via the satellite.

The three range measurements from known positions on the earth's surface define the satellite's position. These data taken over a sufficient period of time will be used to fit an orbit in a least squares manner. The computed orbit is then used to predict future positions of the satellite using Kepler's laws alone. The data gathering, processing, and orbit prediction will be at the NBS, Boulder, site. The current satellite's position will be part of the data sent to the user's receiver. This process will be handled using a small computer at the Boulder site and constitutes part of the tracking system. The tracking system is illustrated in Figures N8 and N9.

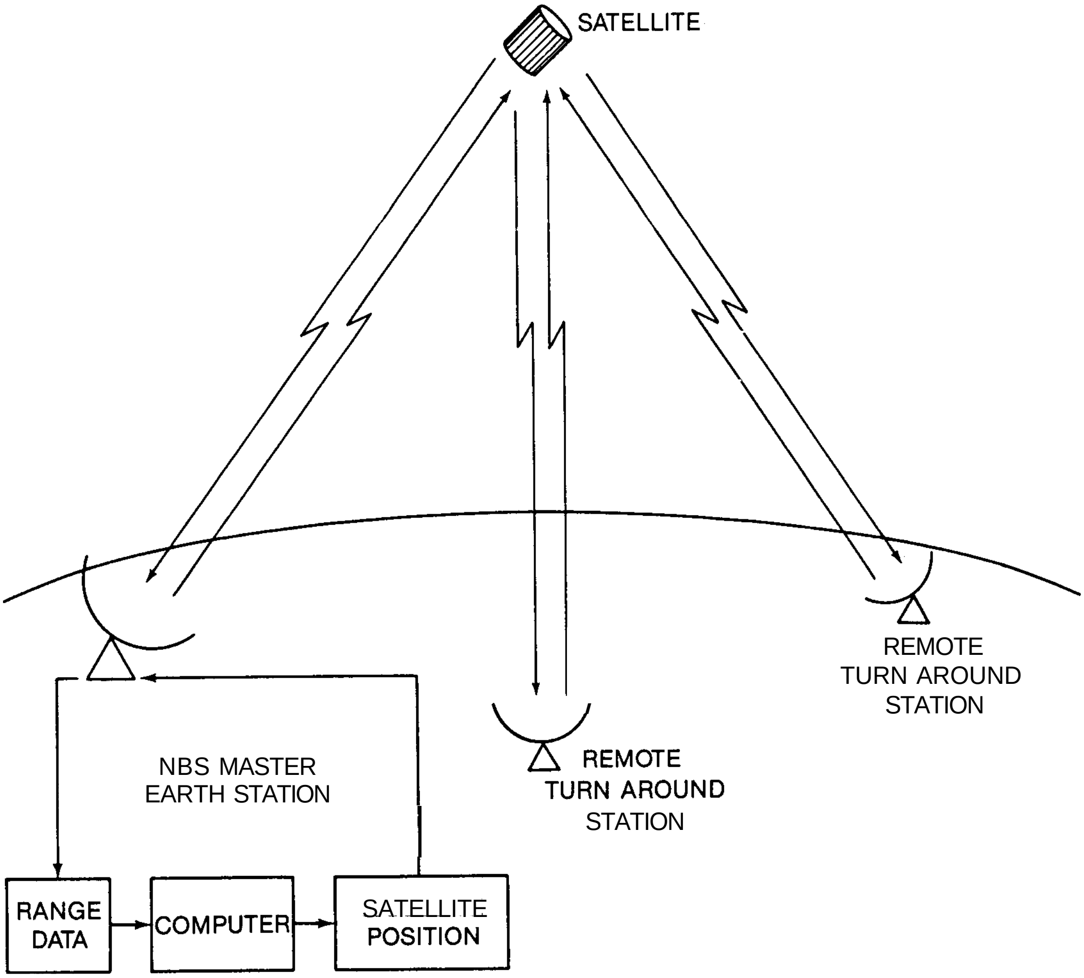


Fig. N8. ITS Tracking System

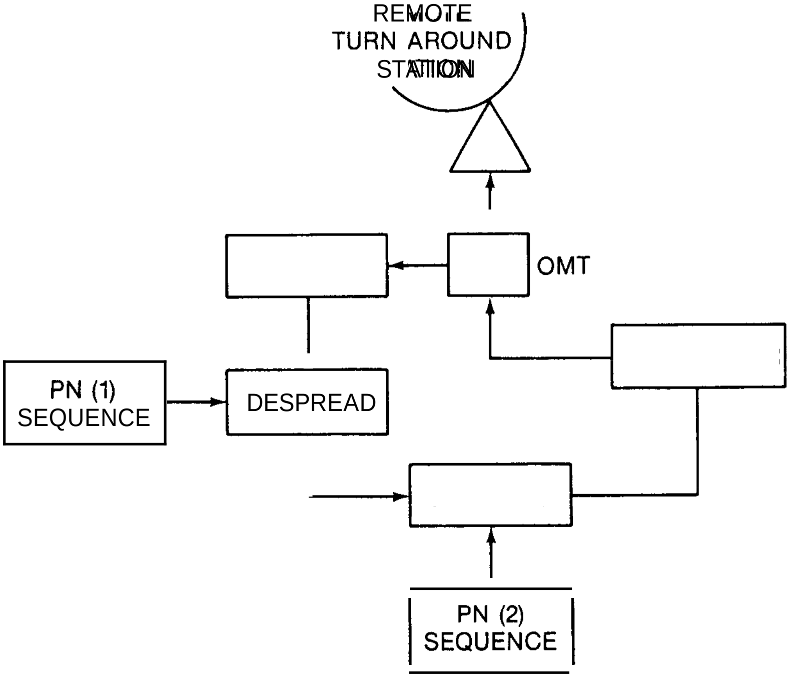


Fig. N9. Remote Turnaround Station

N2c. THE USER'S EQUIPMENT

The equipment will consist of (1) an antenna system, (2) the receiver performing the downconversion, demodulation, timing, and decoding functions, and (3) the processing system for computation of path delays, Doppler shift, control of outputs, and the generation of standard time codes and corrected outputs including displays and 1 pps.

The antenna will consist of the physical antenna and supporting structures and a suitable low noise amplifier (LNA) or low noise block downconverter (LNBC). Making use of economies of scale, a significant cost benefit is expected through the use of the same antenna being manufactured for the direct broadcast satellite (DBS) industry. These antennas are designed to work at the same frequency band, KU band, as is assigned to the FSS and have many new features built in. Included are offset feeds for lower antenna noise temperatures and near vertical mounting (for locations within CONUS) which reduces its snow and ice loading potential. DBS antennas are now being produced with 2 to 4 foot diameters.

Located at the antenna feed is a low noise amplifier or a low noise block downconverter. The LNA amplifies the 11.7 to 12.2 GHz band by approximately 50 dB with a noise figure of approximately 2.5 dB or about 260 K noise temperature. The low noise block downconverter has similar gain and noise figures but has an output typically at 950 to 1450 MHz. A commercial LNBC for the DBS is illustrated in Figure N10. The costs for

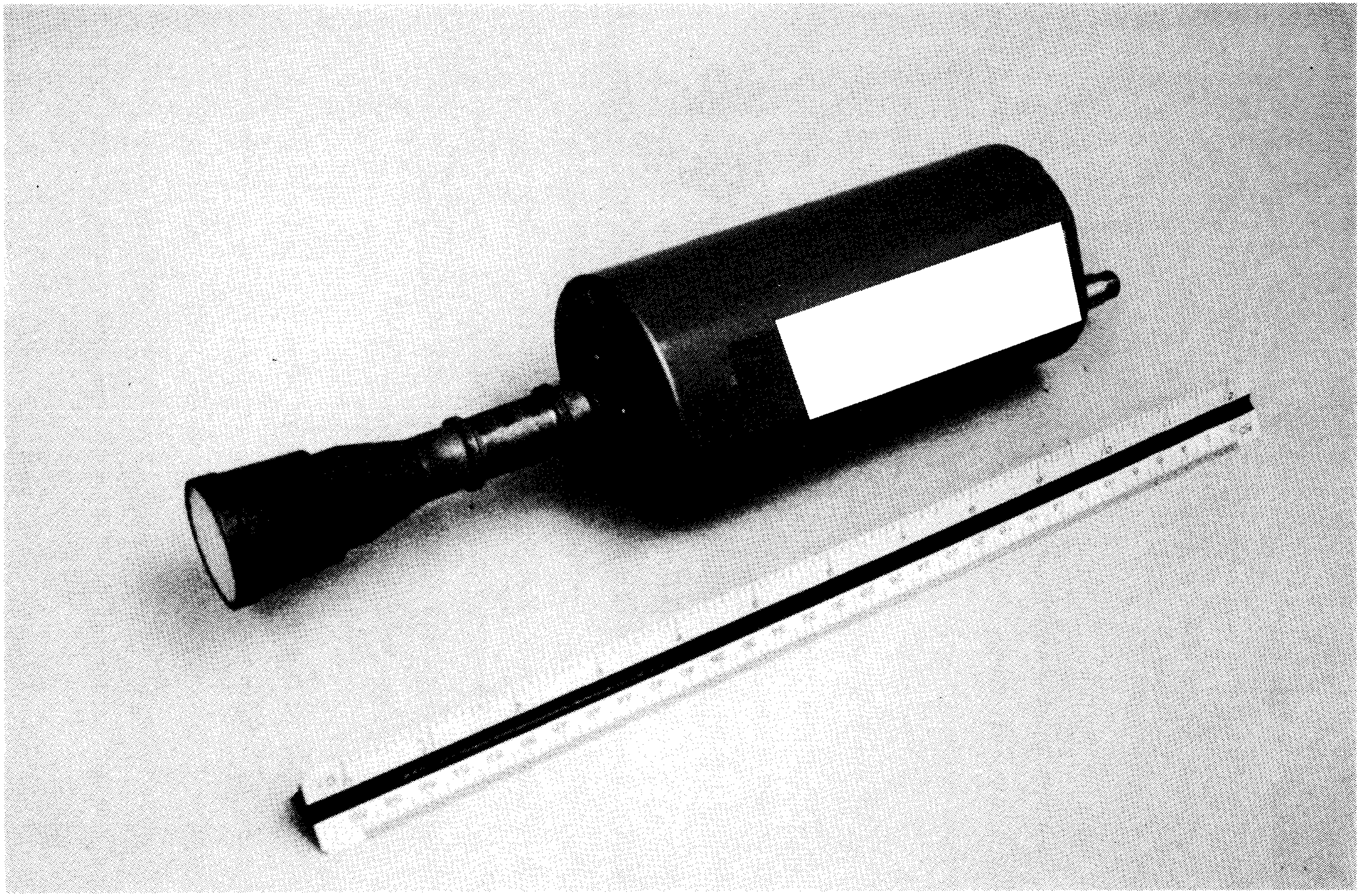


Fig. N10. Low-Noise Block Converter for Direct Broadcast Satellite Application the antenna and LNBC (or LNA) are expected to be less than $500 since tens of millions will be manufactured for a worldwide market. Direct application of these antenna systems to the ITS should make a $2500 ITS receiver system possible.

The receiving system block diagram is shown in Figure N11. The antenna, LNA, and downconverter including its local oscillators will be the same as used in the Direct Broadcast Satellite (DBS) industry for home roof top use. The cost for this system is expected to be less than $500. The output of the downconverter will be the input to a phase lock loop demodulator. Phase lock detection will be possible since the spectrum will be constructed to leave a residual carrier for this purpose. The signal will be phase shift keyed approximately ± 70 degrees to guarantee the residual carrier thus eliminating the need for a Costas or squaring loop demodulator. The output of the PLL is fed to a delay lock loop (DLL) to remove the spreading code from the data. A locally generated PN sequence is used in the DLL to correlate against the received sequence. The DLL shifts its phase until it phase matches that of the received sequence and then locks to it. The phase of the locally generated PNB sequence then is used as a precision timing marker.

The collapsed spectrum is now the data which are run through the FEC circuitry to correct for errors and then through the DES machine for decryption. The decrypted data containing the time code, satellite position, and related data are input to a microprocessor for computation of path delays and correction of an output one pps to be in synchronism with UTC(NBS).

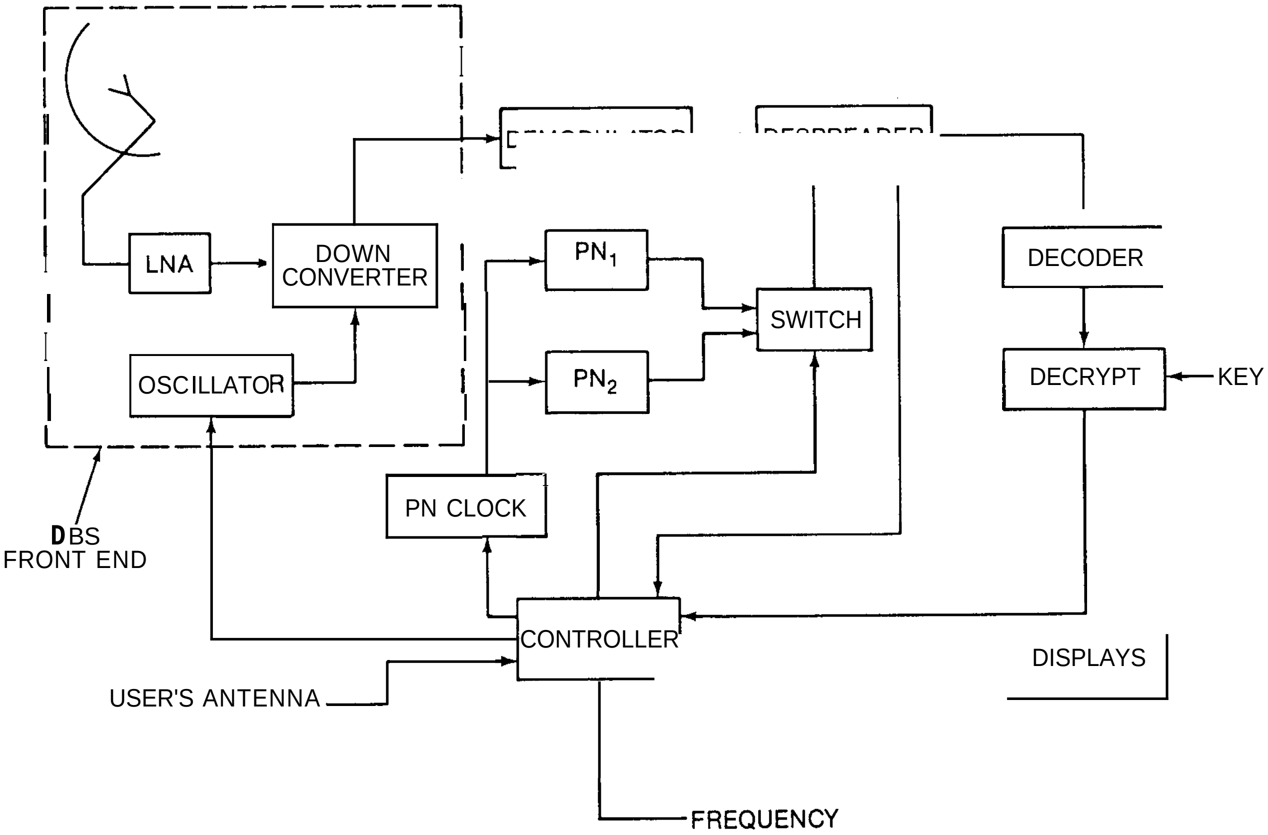


Fig. N11. ITS User Receiving System

Figure N11 shows the technique which generates the PN sequence and provides the key for decryption. This may be a virtual chip in that the PN sequence and decryption key will be sent to the receiver via the satellite rather than chips mailed to the user for insertion into the receiver.

N3. SIGNAL STRUCTURE

The ITS signal structure discussed here is based on careful consideration of all the ITS system requirements as discussed in phase one of this study. Selection of a good signal structure is important since it has been decided that it must serve for both timing and tracking purposes as well as having a major impact for receiver design and reduced costs. This section describes a favorable signal structure and provides a brief discussion of its merits relative to various ITS requirements.

OBJECTIVES FOR THE SIGNAL STRUCTURE

The primary objectives are listed below.

- provide a time code and ephemeris message and other related data to the user on a reliable basis.
- provide an accurate tracking capability.
- provide a high precision timing capability.
- tolerate substantial interference from adjacent satellite and other terrestrial sources.

- allow user equipment to operate in a completely passive (one way) mode.
- support the capability to deny access to data by unauthorized users.

Spread spectrum techniques have been chosen as the basic signal concept for the ITS. This is because a spread spectrum signal will provide good timing resolution with arbitrary ambiguity and at the same time serve as an excellent tracking signal. Spread spectrum also will provide the necessary adjacent satellite interference rejection that will be experienced with the use of small user antennas and can provide an additional protection against unauthorized (unpaid) users. These features are "bought" in exchange for using more bandwidth than is generally necessary to accomplish the same tasks. Spread spectrum also has advantages of requiring relatively low signal-to-noise ratios at the receiver. Additionally, since the signal has a noise-like spectrum it is less likely to interfere with other terrestrial and satellite based systems.

Some of the advantages of spread spectrum transmission may be seen from Shannon's theorem, which relates the capacity of a channel (C) to the bandwidth it occupies, B, and the signal-to-noise ratio. The theorem is as follows:

$$C = B\ln(1 + \frac{S}{N}) .$$

For S/N ratio small the expression can be approximated as

$$C = B(\frac{S}{N})$$

which shows that if the capacity is maintained constant, the bandwidth can be increased while decreasing the S/N.

Spread spectrum essentially stretches in time each bit of information. This is done by transforming each bit into a series of many elements or chips called a pseudo-noise (PN) sequence. These elements make up two distinct patterns that are defined as a one or a zero. While the receiving system may make mistakes in receiving all the elements, due to interference or noise, it will see enough of the pattern to understand whether the element represented a one or a zero. An example of a good series of elements, a "one" may be represented as 100010011010111 and a "zero" as its inverse or 011101100101000. In this case the chip rate is fifteen times that of the bit rate, thereby requiring a corresponding increase in bandwidth to transmit.

The generation of the signal is as follows. As shown in Figure N12, a data stream is input to a modulo-two adder where each bit of data is expanded into a PN sequence that is N bits long occupying a duration T, which is the duration of one of the data bits. The modulo-two adder inverts the sequence unchanged when a zero is present. The data in the case for the ITS will be made up of a synch word, an injection vector and encrypted data via the DES. This data structure is explained in more detail in Section 5. The output of the modulo-two adder is passed to a phase modulator where the phase of the carrier is shifted according to the input. The amount of phase shift is adjusted to leave a residual carrier

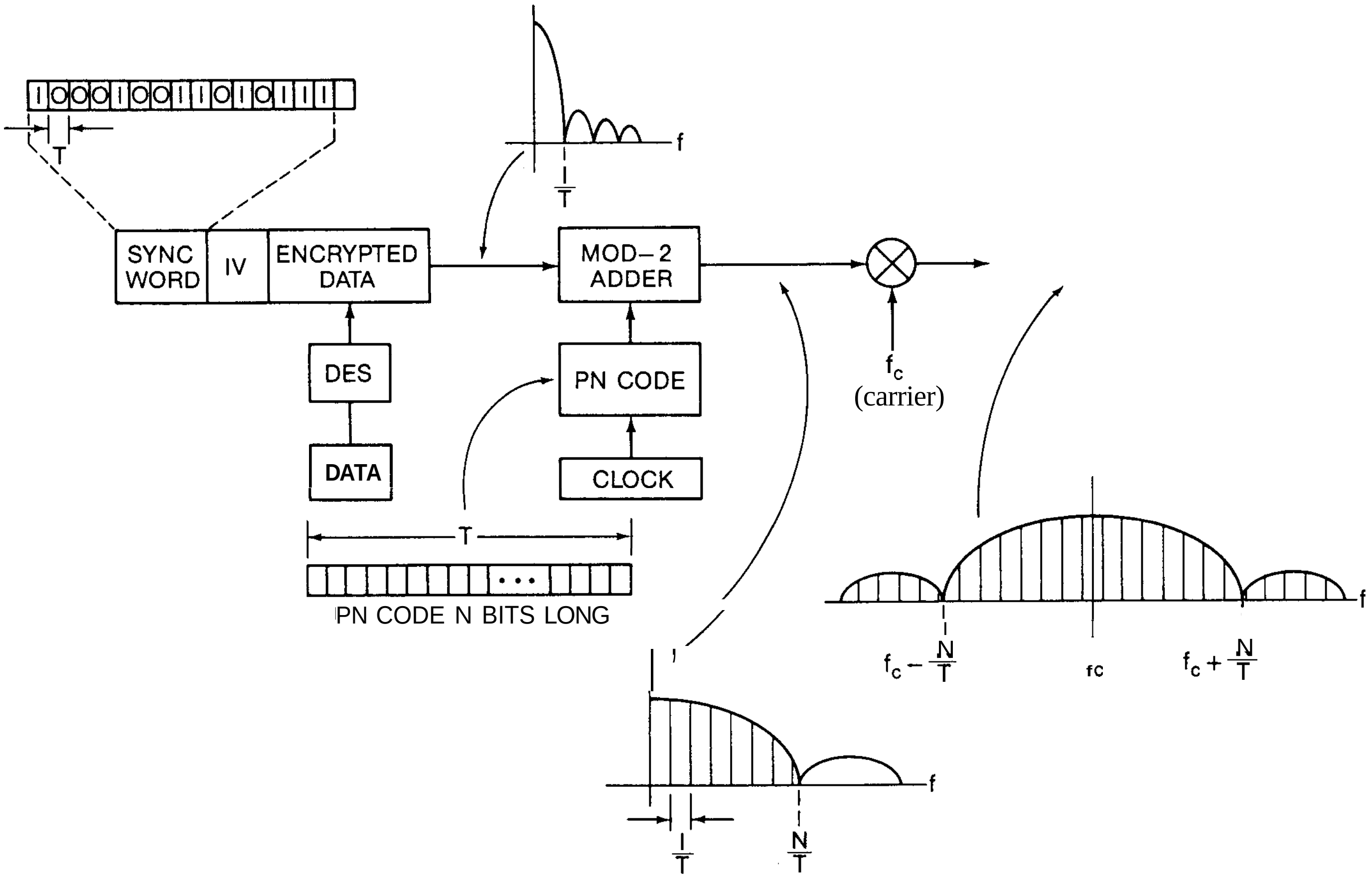


Fig. N12. **ITS Signal Generation**

for simple phase lock loop recovery in the receiver. The spectrum is expanded by N as shown due to the multiplication in the modulo-two adder and shifted up in frequency in the mixing process.

Detection of this signal is by correlation where the received signal is modulo-two added, bit by bit, with an identical replica of this signal and integrated over the entire signal element duration as is illustrated in Figure N13. Not shown are the demodulation and downconversion processes. Here the received signal, when modulo-two added to the in-phase reference signal, is reduced in spectrum width and the spreading code is removed from the data. The reference signal must be in phase with the received signal in order to collapse the spectrum and is accomplished with the aid of a delay lock loop which seeks out this correct phase relationship and locks to it. Figure N14 shows the same process but also illustrates the correlator's processing of a CW and wide band interference signal which is spread by the reference code and then narrow band filtered. The benefit of this process is called processing gain and can be expressed as follows:

$$\begin{aligned}\text{Processing Gain (dB)} &= 10 \log [\text{number of chips per bit}] \\ &= 10 \log [\text{chip rate/data rate}] \\ &= 10 \log [B_s/B_n]\end{aligned}$$

where B_s is the spread spectrum bandwidth and B_n is the bandwidth of the narrowband filter following the correlator.

The interference is reduced by the amount of the processing gain. The ability to reduce interference is useful since the user of small diameter antennas will receive more adjacent satellite interference than conventional signal will allow. New FCC rules place satellites at two

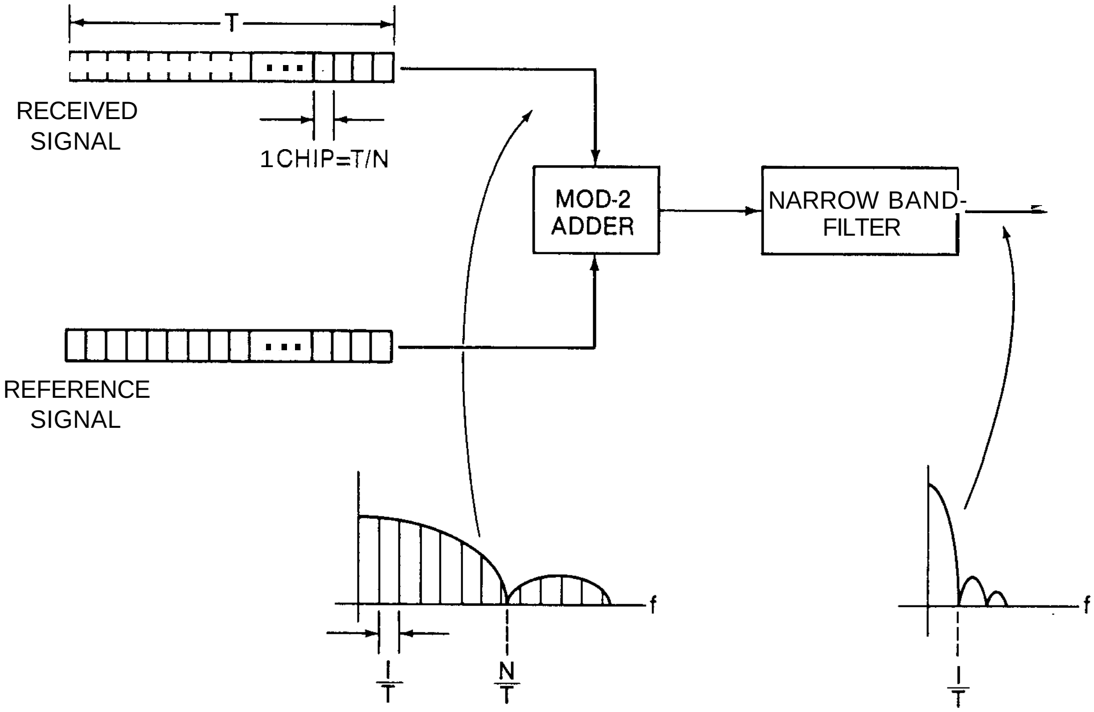


Fig. N13. ITS Signal **Detection**

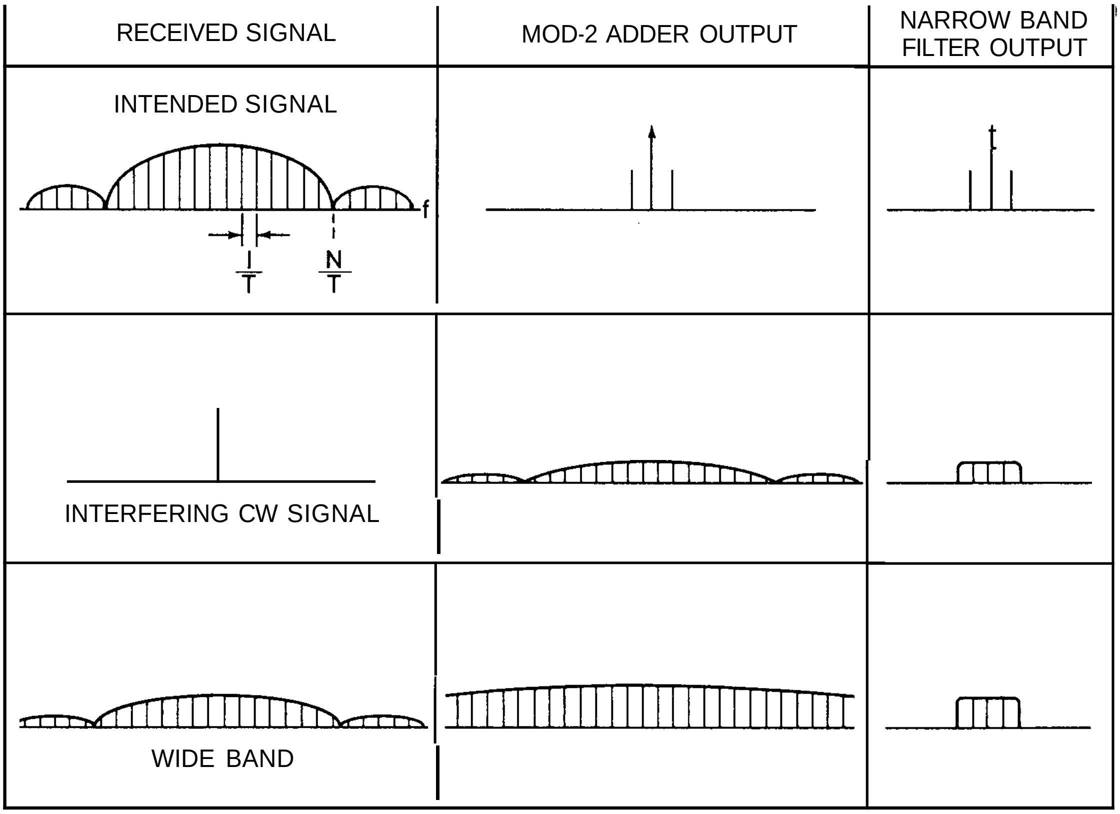


Fig. N14. Interfering Signal Rejection

degree spacings. At KU band a 0.6 m antenna has its first sidelobe at five degrees and the half power beamwidth is 2.8 degrees. Figure N15 shows 0.6 m dish antennas operating at C band and eliminating adjacent satellite interference through the use of spread spectrum techniques.

The use of the PN code also lends itself well to the ranging process. The transmission of a binary sequence of digits (ranging code) as a signal whose period can be designated to be arbitrarily long can reduce the range ambiguity problem to any level desired. Range resolution is a problem of how precise the returned code can be matched to a delayed reference code. In practice this amounts to a few percent of one code chip. The measurement of range is, in reality, the same problem as the measurement of time delay or the time synchronization of clocks. The same PN sequence serves both measurements.

The chip rate must accommodate the data to be sent at the repetition rate found necessary and yield a reasonable processing gain. It must also support the tracking and synchronization precision requirements. The basic data include the time code, the satellite position, synchronization words and other related information. The entire code should repeat at least every minute.

The PN sequence has been selected to run at a 102.3 kHz rate, the chip rate, with a period of 1023 bits or every 10 milliseconds. The processing gain will be approximately 33 dB for this case. The modulation will be phase shift keying at ± 70 degrees to allow for a residual carrier. This will allow direct carrier recovery of the signal and a

Fig. N15. C-BAND Earth Station Using Spread Spectrum Signals coherent delay-lock loop for the PN code tracking. Direct carrier recovery and coherent code tracking will be simpler and more cost effective to implement in the user's receiver but probably introduce more offset errors than non-coherent tracking. We think, however, that these errors will not produce a noticeable impact on the ITS requirements.

N4. ORBIT DETERMINATION AND EPHEMERIS PREDICTION

The requirement to provide the user of the ITS with an accurate value of position of the satellite has been mentioned a number of times in this report. This section discusses NBS's experiences in attempting to obtain this kind of information, the quality of the information obtained, and why the ITS system must provide the information itself rather than relying on outside sources. Arguments are also made that a simple trilateration network can support better than a one microsecond delivery by the ITS. These arguments are based upon results with the ATS-5 satellite, applied to a hypothetical tracking network for the ITS [1].

In the process of generating a set of orbital elements, some or all of the measured quantities, including range, range rate, and angle information, are gathered from one, two, three, and sometimes more widely dispersed sites on the earth's surface. After some minimum amount of data is taken, an orbit is calculated from these data. This orbit is described by six parameters or state vectors. Two of the parameters describe the orbit's size and shape (semimajor axis and eccentricity) since the orbit is theoretically an ellipse for two body point sources. Three of the four remaining parameters describe the orbit's orientation with respect to the earth. They are the inclination, the argument of perigee, and the right ascension of the ascending node. The final parameter describes the satellite's position in the orbit at the epoch of the elements (the mean anomoly).

These elements are then used as input to a prediction program to determine the satellite's position at any time before or after the elements epoch. The sophistication of the prediction program needed depends upon how accurately prediction is required. Also,the greater the time difference between epoch and prediction time the greater the sophistication of the prediction program that will be required.

NBS first experienced and dealt with the position determination problem in 1969 using DoD experimental satellites. DoD-supplied satellite position predictions were sufficiently inaccurate for NBS purposes that NBS chose to determine satellites position using an NBS-operated trilateration network. Results of 1-10 microseconds, without prediction, throughout North and South America were obtained.

During the period of 1970 to 1973 while working with NASA's ATS series of satellites, NBS depended upon NASA-generated predictions using NASA's Goddard Trajectory Determination System (GTDS) program and NASA-run computers. GTDS is a large and sophisticated program that accounts for the earth's geopotential expressed in a 15x15 matrix, the gravitational attraction of the planets, solar radiation pressure on the satellite, and the effects of the moon. This procedure generally provided 1 to 10 microsecond predictions over a one week period. These results were obtained from a tracking network far too complex for consideration with the ITS concept.

Using GOES satellites between 1975 and 1983, NBS has generated its own ephemeris using NOAA orbital elements derived from NOAA's trilateration network and NBS's version of NASA's GTDS. The NBS version of the program requires 40,000 Fortran statements, 250 subroutines, and 19 overlays on a large mainframe computer. It has proved effective but is expensive to run and maintain. Results of 1-10 microseconds for prediction over a one week period were usual.

Recent cost-cutting efforts have forced NOAA to drop the trilateration network associated with the GOES satellite and to make position estimates based upon the earth's image which is transmitted by the satellite every twenty minutes. The resulting orbital elements have generally been of a poorer quality; this resulted, at times, in 100 microsecond prediction errors of the GOES time code service.

Discussions with communication satellite operators in the FSS have revealed that they also do not produce orbital elements of a quality or frequency that can satisfy the needs of the ITS. The conclusions drawn from these experiences are that the ITS service must determine the satellite's position using information gathered from its own ranging system.

The tracking and prediction process for the ITS must be cost effective and simple as well as accurate enough to support the delivery of better than one microsecond to the user. Because of the unique functions inherent with the **ITS,** such as continuous tracking by using the timing signals, these goals will be argued to be possible with surprising simplicity as compared to the efforts and facilities normally expended in the orbit determination and prediction process.

The work done in Ref. 1 using a trilateration tracking network provided the experimental results on which we base our expectations for a trilateration tracking network for the ITS. The geographical positioning of the ITS trilateration network will be limited by the satellite footprint to the northern hemisphere and probably to CONUS, Hawaii, and Puerto Rico. Other locations are either of little benefit or would be on foreign soil (Canada, Mexico, or islands of the Caribbean) and may represent logistical and political problems requiring formal agreements that probably would not justify any technical benefits derived. The NBS does, however, enjoy the advantages of having facilities at Gaithersburg, Maryland and Kauii, Hawaii that may host tracking earth stations of the ITS.

Whatever the trilateration configuration becomes, it will be considerably smaller than that used by Ref. 1 i.e. Schenectady, NY, Hawaii, and Buenos Aires. The results obtained and verified by NASA's sophisticated tracking network has been a valuable tool to support the analysis of a ITS tracking system. The issue is whether the reduced geometry of the ITS trilateration system will affect the precision of the ITS trilateration system. The NASA results provide some indication and an extended analysis was performed to answer the question posed above.

TRILATERATION STUDY:

The trilateration work of Ref. 1 was supported by NASA and accomplished in 1974-75. The purposes of the NASA-supported work were stated among others to be..." to provide a trilateration network capable of location of the ATS-5 satellite including the following tasks:

1. To investigate and report on:
    a) A system of predicting satellite position using measurements made at short intervals spaced an hour apart and prediction for the next hour.
    b) A method of verifying prediction capability (both precision and accuracy).
    f) The design of computer software required to determine near real time satellite position in latitude, longitude, and earth center distance and to predict satellite position.

2...3...4...

5. Develop computer software to determine the nearly real time satellite position in latitude, longitude, and earth center distance. The software will also compute the orbital elements of the satellite, range measurement standard deviation, and short term predictions of satellite position.

6. Conduct cooperative experiments with NASA using ATS-5. These tests will accomplish the following:
   a) An exercise of real-time satellite trilateration ranging, position and predicted position computation, and data transmission to NASA and MARAD (Maritime Administration).
   b) Establish basis for predicting satellite positions up to several hours. The prediction will be an extrapolation based on Kepler's laws from a sequence of trilateration positions.
   c) Verify the accuracy of trilateration position measurements and predicted position. .."

Only the objectives of importance to the ITS were quoted here. These objectives were met and carefully documented in a number of reports and papers including (1-2). The following is a description and summary of the work that had direct impact on the ITS. It is indeed fortunate that this body of work was successfully accomplished, verified, and documented in the detail that directly benefits the ITS. Without it, much of that work would have to be repeated before definitive statements on the feasibility of an ITS trilateration system could be made to the degree afforded at this time. It will be argued by direct analogy to this trilateration work and by further supporting analysis by NBS that a trilateration network can be established that will support 0.1-microsecond-precision time dissemination simply and inexpensively using domestic communication satellites while, at a minimum, serving CONUS and probably most of North America.

PROGRAM DESCRIPTION:

Using signals consisting of short sequences at audio frequency, 9.8 kHz, followed by a digital address in which the audio cycles are inhibited for zeros and transmitted for ones, range measurements were made between the ATS-5 satellite and three locations on the earth's surface. These ranging signals were sent (originated) at Schenectady, NY and transmitted to the ATS-5 satellite at L band (1651 MHz). The audio signal was frequency modulated onto the carrier and occupied a total RF bandwidth of 60 kHz. The trilateration network consisted of the master ground station near Schenectady, NY and remote, unmanned transponders in Buenos Aires, Argentina and a location near Wahiawa, Hawaii. In the operation, NY master sequentially sent ranging signals to the satellite which translated them in frequency and retransmitted them back to earth. Each of the three ground stations had a unique address and responded only to that address. The two remote, unmanned transponders responded by retransmitting the ranging signal to the satellite, after a fixed delay, for eventual reception by the master. In this way the slant ranges r_1, r_2, and r_3 were measured. In actuality $2r_1$, $2(r_1+r_2)$ and $2(r_1+r_3)$ were measured from which r_1, r_2, and r_3 were obtained.

The accuracy of the trilateration network was determined by comparison with NASA's C-band range and range rate measurements to ATS-5 from the NASA Rosman, NC and Mojave, CA tracking stations. A 24 hour test was run where both NASA's C band range and range rate tracking network and L band trilateration tracking network were operated simultaneously. The position for ATS-5 computed agreed very well with the NASA derived positions. The accuracy of the trilateration positions were checked further by computing slant ranges from the ATS-5 satellite to NASA's Rosman and Mojave sites and comparing these with the NASA measured slant ranges.

Additionally, the study determined the positions of ATS-5 on 17 separate days. A comparison of these positions with NASA predictions generated from biweekly range and range rate measurements showed excellent agreement within the bounds of the gradual degradation of the NASA predictions as a function of time from the epoch date of the orbital elements.

The experiment also used three 10 minute ranging periods separated by an hour to define the orbit of the ATS-5 satellite. The position of the satellite was then predicted for the next two hours. The predictions were verified by the NASA network as well as against trilateration measurements.

The conclusion and findings of the trilateration program, particularly during the 24 hour tests directly relevant to the ITS are:

1. L band trilateration positions of ATS-5 agreed with NASA's computed positions based upon their C band range and range rate measurements to within 0.00050 degrees in longitude, 0.00025 degrees in latitude, and 50 meters in earth center distance.
2. Precision of single observatory-satellite slant range measurements were on the order of 12 meters; for single remote transponder-satellite slant range measurements, 23 meters.

3. Computed slant ranges based on trilateration and NASA measured slant ranges to the NASA Mojave tracking station agree to within 1.6 ± 9.6 meters and to the NASA Rosman tracking station to within 15.7 ± 8.7 meters.

4. ..5...

6. Satellite position predictions degraded by less than 0.00075 degrees in longitude and latitude and 200 meters in earth center distance in one hour from the last range measurement.

The findings can be condensed into the following facts pertinent to the ITS tracking problem. Position data of an accuracy and precision stated above when used to establish a single Keplerian orbit can be used for short periods of time (up to one hour) to predict the satellite's position to better than 0.00075 degrees in longitude and latitude and better than 200 meters in earth center distance. The issue for the ITS is: What will the performance be for a trilateration system that must be contained, by virtue of its footprint, to CONUS and possibly Hawaii and Puerto Rico? The trilateration network included Schenectady, NY, Hawaii, and Buenos Aires, Argentina. To attempt to answer that question an analysis was made of the geometrical effect on position determination for a general trilateration network.

Using the analysis tool developed in Appendix 111, the geometric dilution of position **(GDOP)** for various satellite and tracking sites were calculated. The GDOP's show that the effects of moving a tracking site from the southern hemisphere to the northern hemisphere greatly magnifies the GDOP's in the Z direction. Likewise, allowing the satellite's longitude to be outside of the tracking site's meridian rather than between them will result in greatly increased GDOP's in the X and Y directions. By careful design of the network it is shown that the ITS can be tracked with sufficient precision that satellite position fixing results of a domestic satellites similar to the trilateration study can be expected. For instance, referring to Table 9, a CO-HA-FL tracking configuration produces a GDOP of 32.6 or just a little more than three times the GDOP computed for the tracking configuration of HA-NY-Argentina. The position error variances for the two tracking configurations can be made equal by improving the range error variances by this same factor. The study had quoted their range error variances as between 80 and 120 nanoseconds. This means the CO-HA-FL tracking configuration should work equally as well for prediction purposes if the range error variances are reduced to approximately 30 nanoseconds. In Section B6, the range resolution is calculated to be less than 27 nanoseconds with less than one second averaging times. This will be possible because of greater C/N_0's expected to be available to the ITS and therefore higher resolution for the slant range measurements. Additionally, benefits should be realized by:

1) Simultaneous slant range measurements. (the study used sequential measurements).
2) More averaging of data.
3) Reduced uncertainties in tracking sites locations.
4) Consideration of the effects of the moon and sun in determination of a set of orbital elements and in the prediction process. (This was not used by the study).

Table 9. Calculated **GDOP's**

TRACKING SITE LOCATIONS	SATELLITE AND LOCATION	σ_x / σ_ℓ	σ_y / σ_ℓ	σ_z / σ_ℓ	(GDOP) $\sqrt{\sigma_x^2 + \sigma_y^2 + \sigma_z^2} / \sigma_\ell$
HA-NY-Argentina	ATS-5 105°W	6.3	2.0	7.3	9.8
NY-HA-FL		8.6	2.3	37.7	38.7
NY-CA-Argentina		13.2	4.4	8.2	16.2
NY-CA-FL		10.0	5.7	46.4	47.8
CO-MD-PR	89°W	23.8	3.56	38.5	45.5
CO-HA-FL	119°W	7.39	3.61	31.5	32.6
CO-MD-FL		27.8	18.8	48.5	56.8

5) Continuous tracking of the satellite.

6) Reduced prediction times from one hour to 10 or 20 minutes.

7) Use of Kalman filter techniques to make better use of our understanding of the mechanics involved.

Based upon the work with the trilateration of the ATS-5 spacecraft, it has been concluded that the ITS tracking of domestic satellites at either C or KU band can be accomplished as well as or better than in the GE case. This is especially true since by providing continuous timing signals there is a continuous source for trilateration. As with GE, the three measurements of satellite range once each hour is satisfied. The results of prediction can be monitored and a new orbit fit to the data as needed. In effect, a sliding set of data can be envisioned, i.e., three sets of positions one hour (or any other interval) apart at any time may be used to generate orbital elements from which predictions are made based upon a Keplerian orbit. As that prediction degrades and falls below some threshhold, a new set (three position values) of data is picked and processed. Other algorithms with other sets of input data may provide better results and should be investigated. However, we can be confident that, provided the ranging resolution and accuracy are available, a better-than-one-microsecond prediction system can be maintained. The problem of orbit maneuvers is still present but its effect can be greatly reduced in magnitude and duration due to the continuous real time tracking of the satellite. Simple techniques such as the "adjustment" of the output ephemeris to keep each tracking station "on time" could be used until a valid new orbit could be calculated. "Adjustment" could be the use of satellite position just determined. Typically the satellite might be moving by 20 ns/s. Measurement of the range rate could be used to aid the prediction process.

N5. DENIAL OF SIGNALS TO UNAUTHORIZED USERS

The NBS has for many years offered time and frequency information free by way of their radio broadcasts from WWV, WWVB, WWVH, and the GOES satellites. Government policy essentially mandates or strongly encourages that new services such as the ITS operate on a "full cost recovery through user charges" basis. Responding to this policy means that the usefulness of the ITS signals must be denied to unauthorized users or at least made unreliable or difficult to use by them. Unauthorized users are those users who have not paid for the use of the signals. A user becomes authorized through subscription after which his receiver becomes useful through some periodic upgrading.

For this part of the study, we consider the use of the Data Encryption Standard (DES) in denying signals to unauthorized users. The DES is a complex ciphering algorithm based upon both substitution and transposition techniques. The DES was first published by NBS in 1975 and it became a Federal Information Processing Standard in 1977 for the protection of non-national security information.

The DES defines a set of operations to be performed on a 64 bit block of information, the plain text, to encrypt it into a 64 bit block of scrambled information or encrypted text, This is done under the control of a 56 bit key block chosen by the sender and known by the receiver.

Data protected by the DES, the experts say, may be recovered by unauthorized individuals or organizations through the use of the large computers expected to be available in about ten years. Even then the cost of using these new supercomputers would make such tasks quite expensive and impractical when as in the case for the ITS, the key may be purchased for perhaps only a few hundred dollars. The DES is presently a very secure encryption device, and its use in the ITS may seem to be a large overkill. The logic in using the DES, however, lies with its low cost. Today the DES may be purchased in the form of a single chip in single quantities for as little as $20 each. Also certain modes of operation of the DES make technical sense for its use in the ITS.

The use of the DES in the ITS would be as follows: The user's receiver would have an access chip which is provided on a subscription basis by the ITS operator. The chip is a complex LSI device and contains the cryptographic key and PN sequence code. Unless it is installed in the receiver, the receiver will not decode the satellite data correctly nor lock to the incoming PN sequence. Each access chip could be unique or customized to a particular receiver with its own unique serial number or encryption key. In other words, each receiver would have a unique master key requiring a unique working key. The unique access code, which changes every year, must be installed in the user's receiver. This access code could be mailed as a chip and installed by the user. Alternatively, the access code could be sent as part of the data from the satellite and loaded automatically into the receiver.

The annual renewal process would be very much like that for a magazine subscription. A month or two before the subscription expires, a renewel notice is sent. The user must send his annual fee to the operator who in turn sends the access code as a chip by mail or by satellite transmission.

An LSI device is an excellent media for the access code. Its production costs can be very low but its cost to copy would be far too difficult and costly to be any significant threat to the ITS support base. Development of the access chip and billing procedure can be subcontracted to a manufacturer. Transmission by satellite is possible but would require a modified data format over that presented in this study.

The subscription fees must cover the costs of operation and maintenance of the ITS. About 2000 timing receivers for the GOES system have been sold, each costing between $3000 and $5000. We estimate that the ITS will have as many as 3000 customers. If each paid $200 per year, there would be $600,000 per year income, easily covering operational and maintenance costs.

The DES has a number of modes of operation. An analysis, not covered here, has determined that the Output Feedback Mode (OFB) will work best with the ITS. Generally there are three functions the receiver must perform to operate properly and to synchronize to encrypted data. These functions are:

1. The receiver must use the same key for decryption as was used for encryption.
2. The receiver must use the same initialization vector (IV) as was used in transmitting.
3. The receiver must find the start of the cipher text in the received data.

In the case of the ITS there will be a continuous transmission of data. The data must, therefore, be constructed to have a beginning and an end. This process must be repeated continuously. The determination of which bit in the received data starts the first cipher text is mandatory. Once the receiver correctly finds the first bit of the cipher text, decryption synchronization is reduced to counting received data bits. The most common solution to the problem is to precede the cipher text with a synchronizing data pattern. This is a pattern which has an autocorrelation function which peaks at the in-phase position and is low elsewhere. Once the pattern is detected, it is used to point to the start of the cipher text. The beginning of an encrypted transmission in the OFB mode is also preceded by a fixed length initialization vector (IV). The position of the IV is also determined from the sync pattern.

In the OFB mode, the DES is used to generate a pseudorandom binary stream which is modulo-two added to plain text to produce cipher text. This DES output is fed back to form all or part of the next input to the DES. The number of bits fed back may be as few as one and as many as 64. Encryption begins by loading an IV as an input block to the DES. The IV is processed through the DES device operating in the encrypt mode and the process yields a block of pseudorandom data. This block of pseudorandom data is added on a bit-for-bit basis to the plain text to produce cipher text. This block of pseudorandom data from the DES is fed back to form a new input to the DES and the block is again encrypted, yielding another block of pseudorandom data. This new pseudorandom block is added to the next block of plain text to form cipher text. This process is illustrated in Figure N16. This process is repeated for each block of plain text to be encrypted.

The decryption process is identical to the process of encryption. The pseudorandom stream is generated in exactly the same manner as that used for encryption. The keystream is modulo-two added to the received cipher text to create the plain text. In order to decrypt correctly, the decryption keystream generation process must be synchronized with the encryption process. That is, the same bit of the keystream used to encrypt a particular bit of plain text must be used to decrypt the corresponding cipher text bit.

The OFB mode had one major advantage over the other modes. Since the two keystreams are generated independently and do not depend upon the

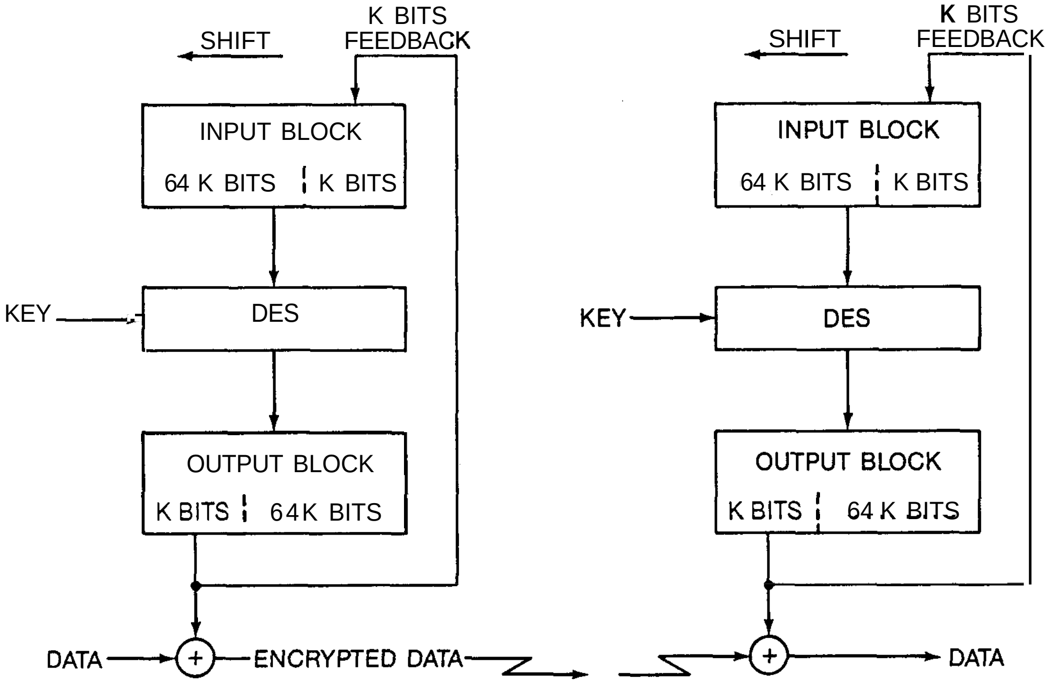


Fig. N16. K-bit Output Feedback Mode (OFB) integrity of the received data, OFB mode does not cause error extension. A single bit error in the received cipher text results in a single bit error in the plain text. This property is appropriate for the ITS application.

The DES operated in OFB modes can be thought of as a pseudorandom sequence generator. The IV in OFB mode determines a starting point in the particular output sequence. Each time the transmission is started, the encryption process should begin with a new randomly derived IV. This will minimize the possibility of multiple use of the same portion of the pseudorandom output sequence. If the receiver started each time with the same IV, the identical sequence would be generated and used to encrypt plain text. Synchronization between the transmitter and receiver requires that both start at the same point in the pseudo random sequence. In addition both must generate the sequence in step with 'one another. In other words, the same bit of keystream used to encrypt a bit of plain text at the transmitter must be used to decrypt the corresponding cipher text bit at the receiver. The receiver must generate the same sequence as the transmitter but delayed by any propagation delays between them. If the receiver does not generate keystream in synchronism with the transmitter, approximately 50% of the decrypted plain text bits will be in error.

Starting at the same point in the sequence requires that both transmitter and receiver begin with the same IV. In OFB mode, this requirement is much more important than in other modes. Other modes will eventually synchronize even if both the transmitter and receiver start

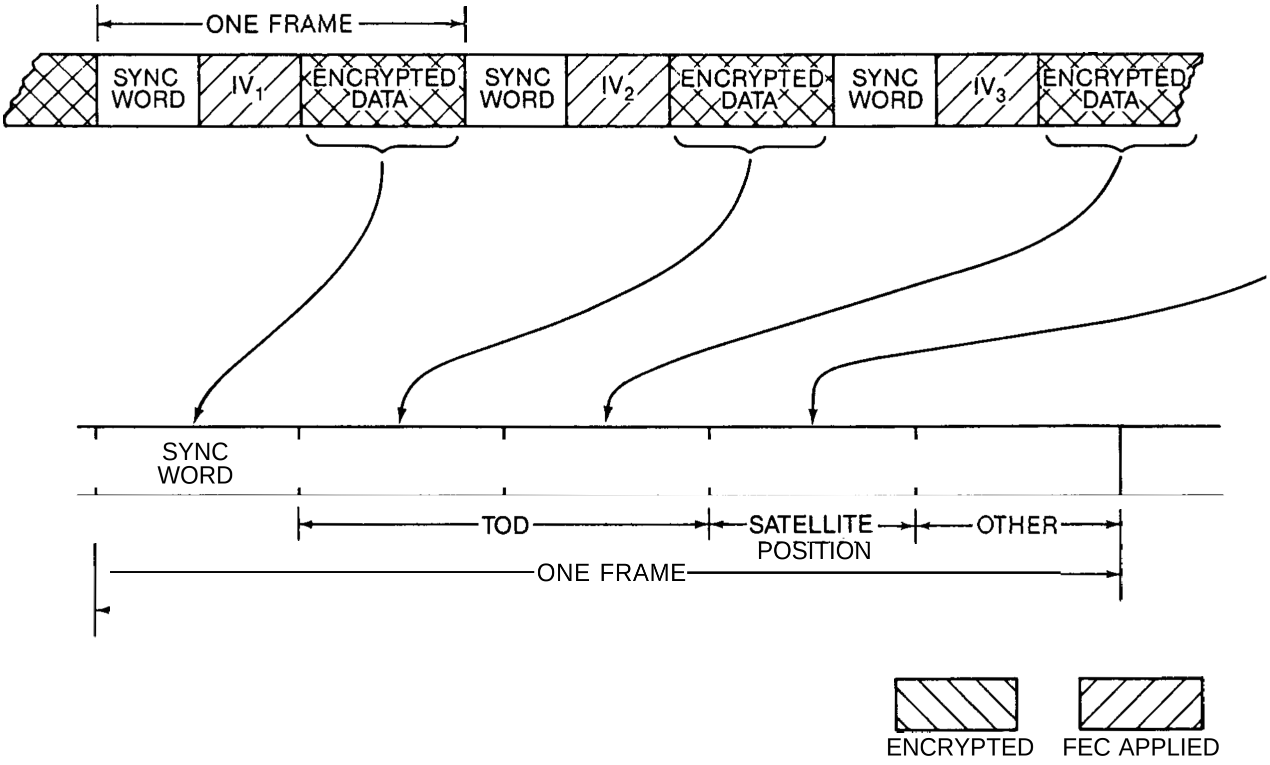


Fig. N17. ITS Data Format

with different IV's, given that the block boundaries are correctly established. However, if the transmitter and receiver in OFB mode are started with different IV's and are clocked at the same rate, they will never synchronize.

The data stream for the ITS is shown in Figure 17. One section of the encrypted message contains the sync word, and IV and the encrypted data. This structure will allow any receiver that has either just been turned on or has lost sync to properly sync or resync to the data stream, load the IV, and decrypt the data. The sync word is a fixed word that is repeated frequently, possibly every second. The frequency of the occurences of the sync word is a fixed word that is repeated frequently, possibly every second. The frequency of the occurrences of the sync word would be a function of the error rates that can be tolerated for the IV and data. The IV and encrypted data may be protected from errors by adding Forward Error Correction (FEC) if needed such as a rate 1/2 code. Having the sync word in the clear and repeated at a fixed rate provides its own error correction or error forgiveness. If the receiver is in sync it should see the same sync word repeated at a given rate. If the sync pattern shows up in the IV data field it is highly unlikely it would appear again at the proper interval. Sync to the message frame is assured then when three or four sync words are detected at the fixed intervals of the data stream. If this test fails, sync is assumed to have been lost and the receiver reverts to the mode of resyncing to it.

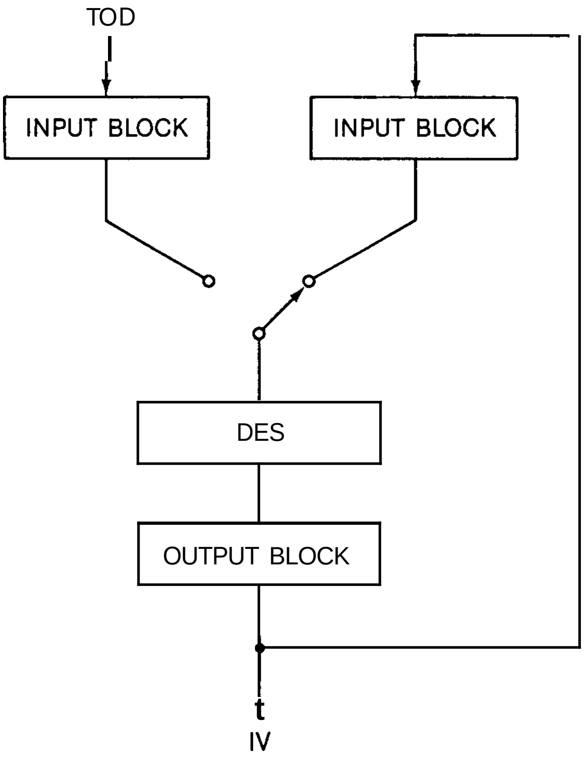


Fig. N18. Generation of Initialization Vector (IV)

At the transmitter, the IV's might be generated in the following manner. The time of day is the input or seed to the DES machine operated as shown in Figure N18. The TOD is also the key to the DES initially. After one cycle of the DES machine, a switch is thrown so the output of the DES becomes the input and the key. Each cycle of the DES produces a random 64 bit output which may be used for an IV in the ITS transmission.

N6. LINK CALCULATIONS

The objective for the ITS is to deliver to the user a signal which is synchronized to the NBS(UTC) time scale at a level of one microsecond or better accuracy. The two main factors are accurate satellite position and a signal strength to yield sufficient precision. The issue on satellite predictions has been discussed in Section N4. The results of those investigations were favorable and it has been concluded in this report that a simple trilateration network will support the one microsecond accuracy for the ITS. In this section link calculations are made to determine the synchronization precision that will be available using a transponder in a typical communications satellite operating in the FSS at KU band.

The uplink from the master earth station to the satellite requires 89 dBW EIRP at the earth's surface to fully saturate this typical KU band transponder on a geostationary satellite operating in the Fixed Satellite Service. The transponder is assumed to be supporting 100 separate users in a single channel per carrier (SCPC) basis. The required input backoff in the transponder necessary for SCPC operation and for reduction of intermodulation products, is assumed to be 10 dB. The maximum EIRP per channel is then 53.4 dBW.

Using a 1.6 dB/K spacecraft quality factor for G/T and including reasonable allowances for the path loss, tracking loss etc., a C/N_o for the uplink is calculated to be 74.9 dB-Hz. The downlink, satellite to the user, is calculated to have an EIRP of 13.4 dBW. The user's receiving system noise temperature is taken to be 250K or 50K for the antenna and 200K for the LNA. The C/N_o for the downlink is then 53.3 dB-Hz. The link is therefore downlink limited as expected when uplinking with a large antenna and placing the burden on a small receiving antenna on the other end. The combined C/N_o is 53.3 dB-Hz. A tracking bandwidth of 3 Hz was used to compute the timing-error variance in the delay-lock loop. The result was 27 nanoseconds, nearly a factor of 40 better than the required accuracy of one microsecond. The complete link calculation is shown in Table 10.

O. SUMMARY OF PRELIMINARY DESIGN

A preliminary design for the ITS using a small portion of a typical FSS transponder has been presented. All technical and cost requirements for the ITS appear to be achievable through this design. The tracking of the satellite by means of a simple trilateration network should produce orbit fits of sufficient accuracy to predict satellite position at the accuracy levels necessary to support the ITS goals of one microsecond or

Table 10.

PARAMETER		
UPLINK, 14.25 GHz		
Uplink EIRP for Transponder Saturation	89.0	dBW
Total Number of Carriers	-25.6	dB
Required Input Backoff	-10.0	dB
Required EIRP per Channel	53.4	dBW
Total Path Loss	-207.5	dB
Tracking Loss	- 1.2	dB
Spacecraft G/T	+ 1.6	dB/K
Boltzmann's Constant	-228.6	dBW/K-Hz
(C/N_o) up	74.9	dB-Hz
DOWNLINK, 11.95 GHz		
Spacecraft EIRP	44.0	dBW
Total Number of Carriers	-25.6	dB
Required Output backoff	- 5	dB
EIRP per Channel	13.4	dBW
Total Path Loss	-205.9	dB
Receive Antenna Gain	42.0	dB
Tracking Loss	- 0.8	dB
Receive Carrier Power	-151.3	dBW
Boltzmann's Constant	-228.6	dBW/K-Hz
System Noise Temperature	24.0	dB-K
Spectral Noise Density	-204.6	dBW/Hz
(C/N_o) down	53.3	dB-Hz
Combined (C/N_o)	53.3	dB-Hz
Timing Error Variance..(T_c = 10 µs, B_L = 20 Hz/3 Hz)	70ns/27ns	

better synchronization to UTC(NBS). These conclusions on the tracking system were arrived at through direct comparisons with extensive experimental work done in Ref. 1 and NASA during the mid 1970's.

The partial transponder typical of the FSS was shown to be capable of supporting the one microsecond objective while working into small user antennas. Through use of antennas, amplifiers, and downconverters being manufactured for the Direct Broadcast Satellite industry on a very large scale, acceptable cost user equipment appears to be feasible. The use of the Data Encryption Standard (DES) for denying the signals to unauthorized users will guarantee that only fully subscribed users will benefit from the ITS signals. The DES will be a cost effective solution to insuring the "full cost recovery through user's fees" policy.

A spread spectrum signal will provide the tracking and timing precision necessary for the proper functioning of the ITS while protecting the data from interference from adjacent satellites and terrestrial sources. The spread spectrum signal will make a small user antenna possible while adding an additional inhibitor to its use by unsubscribed receivers.

The preliminary design requires additional study efforts in order to optimize all parameters and to insure proper interaction of all system components. Final verification of the ITS operation can be accomplished through limited experimental use of a partial satellite transponder and full tracking system deployment accompanied by the testing of a prototype user receiver.

PHASE 111, Part 2:

THE GLOBAL POSITIONING SYSTEM OPTION

CONTENTS

P. PHASE 111, Part 2 INTRODUCTION

The NAVSTAR Global Positioning System (GPS) is a worldwide navigation system developed by the U.S. Department of Defense for use by the Armed Forces and our Allies. Completion of the system is targetted for between 1988 and 1990. Time information is transmitted in the system in two forms, one for DoD use only (the P-code) and one for DoD and civilian use (the C/A code). The P-code is a high precision mode and is not available to civilian users. However, the C/A code used for receiver coarse acquisition will have time transfer accuracy to 250 ns or better. The C/A code would meet the 1 μs criterion needed by BPA.

Seven GPS satellites are currently in orbit and are being used for evaluation purposes. Eighteen satellites make up full implementation of the next phase called BLOCK II (full coverage using nonstationary, low orbit satellites). Atomic standards (rubidium or cesium) are carried on each.

The current DoD policy regarding civilian access to the C/A code is available from the U.S. Naval Observatory automated data service. The latest statement is shown below (12/20/85):

> Revised Comprehensive GPS User Policy (Effective 22 May 85):
>
> "The GPS is a continuous worldwide satellite-based radio navigation system currently in full-scale development by DoD. The system will provide properly equipped users the capability to obtain navigation and geodetic positions in three dimensions, velocity in three dimensions, plus highly accurate time. The

system will simultaneously transmit navigation information that permits positioning accuracy at two levels. The higher level of accuracy can be obtained from the standard positioning service (SPS).

This policy provides that DoD intends that the SPS signal will be broadcast in the clear and will be available for use by any properly equipped user. There will be no annual or other direct fee associated with the use of this signal. The SPS will be made available to civil, commercial, and other users on an international basis at the highest level of accuracy consistent with U.S. national security interests. It should be noted that at the direction of the defense subcommittee of the senate appropriations committee, the GPS has been designed and engineered in a manner to protect the user-fee option should it be appropriate in the future. If Congress does decide to require a user-fee implementation in the future, an appropriate time would be allowed for the transition of user equipment into a user-fee configuration."

Some key issues regarding the CIA code service are in the process of being evaluated as pointed out in the last CCIR concluding report:

1. The first priority of GPS is for military tactical missions, and as such civilian users have no control, of the CIA service.

2. Possible degraded service of the C/A code is 250 ns (two sigma estimate), but the level of degradation could change depending on prevailing military policy.
3. GPS contains an implementation of the service using a user fee, but present policy is to allow free access.

This section of the BPA study will elaborate on the NAVSTAR GPS. In spite of key issues, it is useful to review GPS as a viable solution for BPA's requirements because some of the service is available now. Furthermore, the full military implementation is virtually assured in the coming years.

Q. GPS SYSTEM OVERVIEW

The NAVSTAR GPS concept evolved from a DoD Joint Program Office which was established in 1973. It's purpose was to consolidate separate navigation systems which were in service (or proposed) to form a single military-based, highly survivable system to serve all armed services. The GPS is jointly supported by the Army, Navy, Marine Corps, Air Force, and Defense Mapping Agency. The Air Force is designated as lead agency to develop, test, acquire, and deploy the GPS. Bradford Parkinson and Stephen Gilbert were among the leaders of the GPS planning and development, and much of the material in the section comes from their literature [2].

The CPS is a satellite-based radio navigation system intended to provide highly accurate three dimensional position and precise time on a continuous global basis. When the system becomes fully operational, it will consist of 18 satellites in six orbital planes inclined at 55°. Each plane will contain three satellites spaced 120° apart in 12 hour orbits. The relative phasing of the satellites from one orbital plane to the next is 40°. Each satellite will continually transmit navigation signals at L1 = 1575.42 MHz and L2 = 1227.6 MHz consisting of the P-code ranging signal (10.23 MBPS), the C/A code ranging signal (1.023 MBPS), and 50 BPS data providing satellite ephemeris and clock bias information.

Navigation using GPS is accomplished by passive triangulation. The GPS user equipment measures the pseudorange to four satellites, computes the position of the four satellites using the received ephemeris data; and processes the pseudorange measurements and satellite positions to estimate three dimensional user position and precise time as depicted in Figure Q1.

There are situations where the user only has three satellites available and still wishes to utilize GPS. This can be accomplished by equipping the user with a precise clock synchronized to GPS time.

Q1. THE SPACE SEGMENT

As currently planned, the operational NAVSTAR GPS will consist of 18 primary satellites deployed in six orbital planes. These will be augmented by three on-orbit spares to insure a high degree of system availability. To accomplish this, the Air Force awarded a 1.17 billion dollar multi-year procurement contract, one of the first of its kind, for production of 28 NAVSTAR GPS satellites. The first four of these satellites are to be delivered in 1986; eight more in 1987; nine in 1988; and the remaining seven in 1989. The planned launches aboard the Shuttle closely follow the satellite delivery schedule.

Table 11 gives the reference orbit values for this baseline deployment, including the three on-orbit spares which are located in every other orbit plane to provide quick reaction and recovery in the event of a primary satellite failure. The satellites are all in circular orbits at altitudes of approximately 20183 km (10898 nmi).

This selection of parameters results in a repeating daily ground trace or, in other words, an orbital period that causes each satellite to pass over the same point on the earth every 23 hours 55 minutes and 56.6 seconds, i.e., a sidereal day. This could have been accomplished by placing the satellites at synchronous altitude--the concept embodied in the FSS and GEOSTAR approaches. However, to avoid the need for a global tracking and control station network that could continuously "see" each satellite in the system, the orbital altitude was selected to provide a

TABLE 11.
REFERENCE ORBIT PARAMETERS: BASELINE SATELLITE DEPLOYMENT

Satellite Number	Orbit Plane	Longitude of Ascending Node (deg)	Right Ascension of the Ascending Node (deg)*
1	1	0.180	30
2	1	240.60	30
3	1	300.120	30
4	2	260.80	90
5	2	320.1 40	90
6	2	20.200	90
7	3	340.160	150
8	3	40.220	150
9	3	100.280	150
10	4	60.240	210
11	4	120.300	210
12	4	180.00	210
13	5	140.320	270
14	5	200.20	270
15	5	80.260	270
16	6	220.40	330
17	6	280.100	220
18	6	160.340	330
Spares			
19	1	95.15	30
20	5	215.35	270
21	3	25.105	150

*Referenced to Astronomical Coordinates of 1950.0 as of July 1, 1985 0 h 0 min GMT and regressing at -0.04009°/day.

period exactly one half synchronous-- 11 hours 57 minutes and 58.3 seconds. Another way of looking at this is to imagine that each satellite completes exactly two orbits while the earth turns one complete revolution on its axis thereby causing the satellite to pass directly over the same spot once a day. The difference between this and the solar day of exactly 24 hours causes the satellites to pass over the same spot about 4 minutes earlier each day. The real importance of this feature of the system concept is to allow each satellite to be viewed by a single control station at least once each day, thereby eliminating or at least minimizing dependence on stations outside of the direct control of the United States.

The minimum number of satellites required to provide continuous global coverage with at least four satellites in view at a given location is 18. Thus a satellite failure in any of the six orbital planes could disrupt service (for position determination) over one or more critical areas of the globe. The time required to launch, check out, and place into operation a spare satellite is likely to be unacceptable from an operational standpoint, and this will become even more critical as civil and international users of the system become more plentiful and dependent upon the system. The ability to quickly reposition one of the on-orbit spares, which has already been checked out and placed into full operation will be a major asset to the system reliability and availability. In addition, while the baseline constellation of 18 satellites is fully operational, careful selection of the "storage location" for each of the three on-orbit spares will result in significantly enhanced coverage and accuracy over any specific area--e.g., the continental United States.

The widely dispersed monitor stations employ extremely stable GPS receivers to gather transmitted navigation data from each of the GPS satellites as they pass overhead. The location of each monitor station is precisely surveyed and the navigation measurements are combined with additional data on atmospheric conditions, etc. This information is transmitted back to the Master Control Station where precise predictions of satellite ephemerides and clock offsets are made.

The Master Control Station, to be colocated in Colorado Springs, CO, with the Consolidated Space Operations Center (CSOC), will process the data received from all of the monitor stations to determine the predicted satellite ephemerides and clock bias parameters for each satellite in the system. These data are then used to generate upload messages for each satellite to correct the satellites' navigation messages describing those parameters to the users. The upload messages are then relayed to the appropriate upload station for subsequent transmission to the satellites.

Q2. USER EQUIPMENT SEGMENT

The NAVSTAR GPS User Equipment Segment is a separately operated department which provides development and testing of military receiver hardware. It also provides information regarding nonsecure specifications for civilian users. The information here is derived directly from the GPS literature.

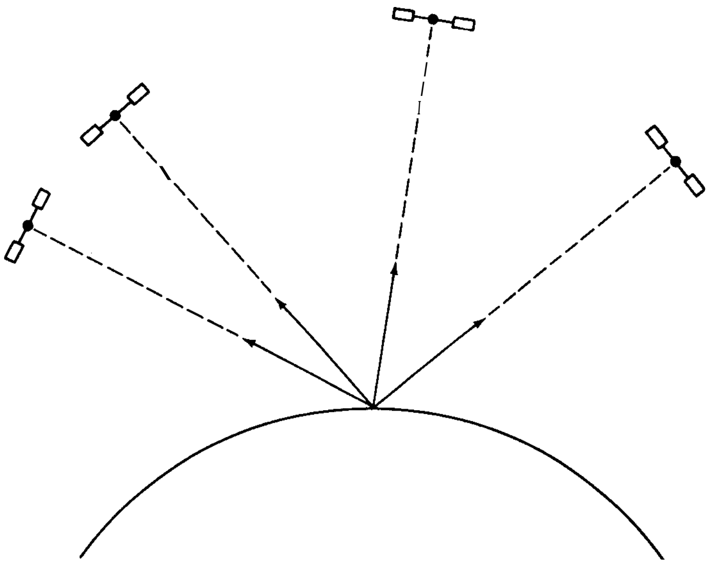


Fig. Q19. GPS Four Satellite Position and Time Recovery

Each satellite continuously transmits a unique navigation message that contains the information that the user equipment requires to perform the measurements and computation to effect the navigation solution. All satellites transmit on the same two frequencies, L1 at 1575.42 MHz and L2 at 1227.6 MHz, coherently derived from the 10.23 MHz atomic frequency standards on-board each satellite. The L1 signal is modulated with two pseudo-random noise codes in phase quadrature, historically called the Precise (P) and the Coarse/Acquisition (C/A) codes. The L2 signal is modulated only by the P-code during normal system operation, but for special applications and testing the P-code modulation on L2 can be switched to the C/A code. Both the L1 and L2 signals are also continuously modulated with a navigation data bit stream at 50 bit/s.

The P-code operates at 10.23 Mbit/s and completes a code generation cycle in 267 days. It is the modulo-2 sum of the output of two pseudo-random code generators, each of which employs an input from the sum of the output of two subsidiary generators. Each satellite uses the same basic code generator, and each is assigned a unique and mutually exclusive 7 day segment of the 267 day cycle. The initial state of the code in each satellite is made to occur every 7 days by resetting the two code generators to their initial state at the end of each week. In this manner, using a code-division, multiple-access scheme up to 36 satellites could transmit synchronized navigation signals simultaneously on the same two frequencies and each satellite can be uniquely identified by the 7 day phase segment of the long code it is transmitting.

The P-code provides the fundamental accuracy of GPS. However, unless the user equipment has been provided with both a precision time reference synchronized to GPS time and an estimate of current position (within 3-6 km), direct acquisition and tracking of the code segment for any specific satellite will be extremely difficult. It is necessary in most instances to resort to initial acquisition on the shorter C/A code. They operate at 1.023 Mbit/s, as compared to the 10.23 Mbit/s rate of the P-code and they repeat each millisecond as opposed to the 267 day cycle of the P-code. Thus the C/A codes are much easier to acquire without prior knowledge of system time and user position. As part of the data stream contained in the modulated C/A code, a Handover Word (HOW) is transmitted every 6 s, indicating the correct phase point in the incoming P-code associated with the transmitting satellite. Based on this information, the user equipment P-code generator is shifted in phase to synchronize with the incoming P-code at the next change of the HOW.

The navigation message transmitted by each satellite includes the following information:

1) Status of the satellite so the user can either accept or reject the data for use in the navigation solution.
2) The HOW used to determine time synchronization for transfer from the C/A to the P-code.
3) Satellite clock correction and ephemeris parameters.

4) Parameters for correcting propagation delays through the ionosphere.
5) Almanac information including ephemerides and status of all other satellites in the system.

R. TIME FROM GPS [3]

Obtaining time from GPS is a three step process. One must first determine the time kept by the satellite being tracked. Next, one applies corrections to the satellite time to derive UTC(GPS). The reference for GPS time is an ensemble of three cesium clocks at the Master Control Station at Vandenberg AFB. Then, one applies corrections to UTC(GPS) to obtain UTC(USNO) which in turn allows calibration to UTC(NBS) through published bulletins. A complete navigation message consists of 1500 bits of information. A subframe of 300 bits is transmitted every 6 s. From Subframe 1 of the navigation message one computes the relationship

$$t = t_{sv} - a_{f0} - a_{f1}(t - t_{oc}) - a_{f2}(t - t_{oc})^2 + (\Delta t_r)$$

where

t	GPS system time
t_{sv}	space vehicle PRN code phase time
a_{f0}, a_{f1}, a_{f2}	polynomial coefficients of Kalman filter determined by MCS
t_{oc}	clock data reference time
Δt_r	relativistic term which user must now calculate $= Fe(A)^{1/2} \sin E_k$
F	constant $= -4.443 \times 10^{-10}$ s/(m)$^{1/2}$

One corrects t for several factors, e.g., ionospheric correction, tropospheric correction, dither (if present), etc.

$t_e = t$ + corrections.

One then gets UTC from

$$UTC = t_e(\text{mod } 86400) - \Delta t_{LS} - A_0 - A_1(t_e - t_{OT}),$$

where

Δt_{LS} leap second correction (Subframe 4),

A_0, A_1 coefficients of polynomial (Subframe 4) provided by USNO,

t_{OT} reference time for A_0, A_1.

Presently, Δt_{LS} is 3 s, i.e., UTC(USNO) = (GPS time) - 3 s. It will increase by 1 s every time a leap second is introduced.

The received-time **marks** (one every 6s) adjusted by these corrections are now within 100 ns of UTC(USNO). Present steering is such that the rms error of this adjusted time reference is 25 ns.

S. RECEIVER SYSTEM COST

GPS receivers intended for time transfer using the C/A code are currently priced from approximately \$15,000 to \$25,000 from commercial manufacturers. Examples of manufacturers at the time of this report are listed below:

Allen Osborne Associates
756 Lakefield Road, Bldg. J
Westlake Village, CA 91361
Tel: 805-495-8420
TWX: 910-494-1710

Austron Inc.
P. O. Box 14766
Austin, TX 78761
Tel: 512-251-2341

Ball/Efratom Division
18851 Bordeen Avenue
Irvine, CA 92715

Frequency and Time Systems, Inc.
343 Tozer Road
Beverly, MA 01914
Tel: 617-927-8220
TWX: 94-0518 FTS BVLY

Stanford Telecommunications Inc.
1195 Bordeaux Dr.
Sunnyvale, CA 94086
Tel: 408-734-5300

Kinemetrics/True Time
3243 Santa Rosa Avenue
Santa Rosa, CA 95407
Tel: 707-528-1230
Telex: 176-687

Interstate Electronics Corp.
1001 E. Ball Road
P. O. Box 3117
Anaheim, CA 92803
Tel: 714-758-0500
TWX 910 591 1197

There are more manufacturers who supply receivers for navigation use only. Prices are coming down as more receivers are built and sold as a result of lower manufacturing costs. Competition is also causing some price reductions. Although a reducing price trend should continue for a number of years, the market for timing receivers is very limited. The navigation market on the other hand is considerably larger (by possibly 1000 times or more) so the predictions by manufacturers for prices to ultimately fall to approximately $1000 are probably valid. Even though the time transfer capability is closely tied to the navigation capability within GPS, the support, added circuitry, reliability aspects, and special timing requirements all suggest that the cost of timing receivers will not be nearly as low.

T. CONCLUSION REGARDING USE OF GPS

The Global Positioning System in its present phase of study has demonstrated its normal time transfer capability to better than 100 ns. The military has stated that the civilian time transfer capability may be degraded to 250 ns (2 sigma estimate) in the final (Block II) implementation which will be operational by 1988-1989. This level of performance will meet BPA's 1 μs accuracy goal.

There are no technical stumbling blocks to using GPS to satisfy BPA's timing requirements. Receiver costs are high at this time ($15,000-$25,000) with a possibility of future reductions, although we do not believe the costs will drop to the same degree the navigation receiver costs are projected to drop.

An important issue still is that there is an unsatisfactory statement of policy regarding a civilian (nonmilitary) time service via GPS. Realizing BPA will invest a great deal of time and money toward an internal timing system, the use of GPS carries a risk if it is to be its source of timing. Although the service is now freely available, there is also no military statement regarding future subscription fees in the actual Block II implementation.

The GPS policy as stated by DoD is a strong indicator of an intent to accommodate civilian users to the fullest extent possible given a peacetime situation. However, any level of military need which is greater than that of the prevailing peacetime situation can change DoD's policy. There is no policy now regarding civilian use of GPS in a national alert situation. Certainly a full scale national emergency situation would put military use as a top priority.

PHASE 111, Part 3:

THE GEOSTAR OPTION

CONTENTS

U. PHASE 111, Part 3, INTRODUCTION

During the course of this contract, NBS has gotten information regarding a new navigation system based on geostationary satellites. This system is called GEOSTAR, and because of the additional potential for precise time dissemination GEOSTAR has the potential for satisfying BPA system requirements. It is important to keep in mind a number of factors:

1) The GEOSTAR system is not an operational service. It is a system which is projected to have the qualities which will be described in this section.

2) The system has as its principal feature navigation and message handling capability. An enhanced mode allows GEOSTAR to deliver time to a high precision to a special GEOSTAR receiver.

3) Much of the information regarding GEOSTAR is proprietary. NBS, given access to much of this information, has attempted to draw clear technical conclusions. Information presented here will not be detailed on those proprietary matters.

4) The GEOSTAR system is intended strictly for civilian applications. There are no military sources of funds nor any support funds that we are aware of other than those ultimately derived from end users. In this sense, the GEOSTAR system is a risk venture for those people investing in the system at this early stage.

We have tried to evaluate the GEOSTAR prospect in enough detail to get a clear understanding of the advantages and disadvantages of this future system. Although there are a number of questions still remaining, we still believe that GEOSTAR needs to be explored for satisfying the BPA requirements. We have seen enough documentation and evidence to warrant the time for this phase of the study.

V. GEOSTAR SYSTEM OVERVIEW [4]

GEOSTAR Corporation was founded in February 1983 by Dr. Gerard K. O'Neill. The company was formed to look at the feasibility of a satellite based system to provide position determination, navigation, two way digital message service and emergency location services to transceivers used by the recipients of the service. The original feasibility study stemmed from the airline industry's desire to move in a direction of automated aircraft navigation. Some work was done prior to 1983 but O'Neill at that time gathered enough support that the GEOSTAR system was created for general civilian use. The work done by GEOSTAR has passed much of the preliminary feasibility stage. A key experiment has been completed in the vicinity of the Sierra Mountains (Nevada, U.S.A.). This experiment used a ground station, a user transceiver and satellite emulators located on mountain peaks. From this technical feasibility study, there emerged a number of other studies and directions which further proved the viability of such a system. More recently the FCC has approved the use of the

USRDSS system which will consist of authorization for a number of operational satellites in geostationary orbit to provide information to a large population of mobile subscribers.

The GEOSTAR system will provide the following services:

1. Navigational positioning
2. Radio location
3. Emergency location
4. Terrain warnings to pilots
5. Warnings of potential collisions between GEOSTAR equipped aircraft
6. Precise Time Dissemination
7. Two way digital message service
8. Interconnection to ground data bases

As the system evolved, it found additional markets. The market appears to be very large for items 1, 7 and 8. The system as it has been planned provides for particular needs which are not met by any other existing system, the strongest of which is the two way digital message service in which large volumes of information can be distributed to users and small amounts of information can be sent from a user to a GEOSTAR central dispatch or another user. This system of high level multi-point distribution coupled with information "trickle back" is a desirable feature of the USRDSS service. A powerful aspect of the GEOSTAR system is that subscribers are given both a receiver and a transmitter (transceiver). This ability to transmit data to a satellite on a trickle back basis opens up opportunities not available in most other multi-point distribution services. It is in fact this transceiver aspect which allows for precise navigation, hence precise time distribution.

The transceivers are designed to be low in cost. Each uses the same bandwidth for transmitting as well as receiving. All transceivers are on the same frequency. The single channel can accommodate a large number of subscribers for three reasons.

1. Each transceiver is silent most of the time, transmitting only in short, occasional bursts.
2. Transceivers use spread spectrum transmissions, which permit many messages to occupy the same channel simultaneously without interference.
3. Different satellites of the GEOSTAR system will cover different geographical areas using controlled spot beam techniques. It is proposed that several satellites be used ultimately. This will provide wide area coverage and only three ground stations are seen now as being necessary to provide all services worldwide, excluding only the extreme polar latitudes. Having a multi-satellite system not only allows for space diversity but also provides more redundancy to back up system capabilities if any single satellite should fail. A strong point is that GEOSTAR-like systems could coexist using the same frequency bands because of the noninterference among various spread spectrum modem schemes.

V1. GEOSTAR MARKET

The market for the GEOSTAR system has changed since the original feasibility studies were done. Indeed, the market has changed because of other available services such as the Global Positioning System. The GPS for example has surfaced many users by drawing attention to new navigation and timing performance levels never before seen. In a way, the GEOSTAR system has become considerably more credible because of the GPS system. There was original skepticism since GEOSTAR in its original concept offered even more capability (two way message communication). The market studies to date done by GEOSTAR indicate a very large, worldwide market. In fact the original market (civil aviation) is diminishingly small and nearly 0% compared to over a half dozen other viable markets. The GEOSTAR marketing reports to date indicate favorable response to the system given its low cost per user (around $45 per month). Coupled with the ability to add enhancements, the end user acceptance has particularly grown strong on two fronts: (1) general navigation, and (2) multi-point data distribution and information trickle back.

The possible applications of the GEOSTAR system extend to a variety of areas in today's society. A few of the more notable applications are listed below:

Positioning and Navigation. Any GEOSTAR-equipped aircraft could be located, in three dimensions, to within at most 7 meters. For more accuracy, as in terminal navigation, the presence of a stationary ground-mounted "benchmark" transceiver at or near an airport could improve accuracy to 1 meter--far better than current Cat 3 ILS standards. Guidance can be provided direct from one point to another or along any path stored in the almost limitless memory of the central computer, including curved approaches and/or stepped-down glidepaths. Other diverse uses for the positioning/navigation capability include taxicabs, fire and police services, trucking and freight lines, and emergency, service-oriented professional individuals such as doctors and medical dispatch personnel.

Aircraft collision avoidance. Since the central computer knows the location of every user and can send messages to any of them either individually or simultaneously, it can monitor potential collision hazards and advise the aircraft not just of the hazard, but of its exact location and the required evasive action. By the same token traffic conflicts could be avoided by issuance of enroute holding advisories when necessary.

Terrain avoidance. Among the information in the central computer's database will be a complete terrain map of the United States, which will continually be crosschecked against aircraft position and altitude. Messages such as "pull up--radio tower 3 miles ahead" can be generated and transmitted automatically to aircraft as required, without disturbing other user transceivers.

Communications. Since each transceiver has a unique address code, messages can be addressed to it without being registered by other units. Moreover, the user transceiver can originate messages.

Weather services. The system's communication capability can be used to transmit routine or special weather information.

Emergency help. The press of a single key places a user transceiver in emergency mode. If this signal is transmitted by any unit, the central computer can alert local authorities and respond with immediate nearby help.

V2. GEOSTAR FCC AUTHORIZATION

On March 31, 1983 the GEOSTAR Corporation petitioned the Federal Communications Commission to begin a proceeding to allow spectrum use for developmental purposes for this new type of satellite system. Developmental licensing was requested for GEOSTAR's original radio determination and associated messages transfer services to subscribers throughout the continental United States. At this time no allowable frequency allocations existed for any such services. During the proceedings a substantial amount of support came in the form of comments to the FCC for the GEOSTAR proposal. Sufficient interest was demonstrated by a very broad cross section of potential users to suggest that a nationwide radio determination satellite service would be beneficial and a spectrum should be assigned for this purpose. Only two companies, ONI (Offshore Navigation Inc.) and **MOBILSAT,** objected to the overall proposals in the proceedings.

After one and one half years of deliberation the FCC began a general rule making procedure to allow spectrum for the USRDSS proposal. The procedure which took place at the middle of 1984 was abnormal for the FCC but not without precedent. The FCC typically refuses applications for spectrum which is not allocated within the FCC rules. An exception was made here because of the interest in adopting the USRDSS concept. General rule making was then carried out which created the spectrum for the USRDSS system and that rule making was complete in the summer of 1985. Needless to say the GEOSTAR corporation was in a first hand position to gain licensing and full authorization for the construction of their system. The general rule making proceeding, consolidated with the application process, was unacceptable to Commissioner Dawson of the FCC. However, the other commissioners were generally inclined to move expeditiously on behalf of a new USRDSS service because of the large number of positive comments in the initial phases of the proceedings.

V3. SYSTEM CONFIGURATION

The GEOSTAR system is based on several concepts that were unavailable at the time the Transit and GPS systems were designed. Central to GEOSTAR's system is the idea of keeping the sophisticated hardware on the ground while Transit and especially CPS require advanced computational capability in both the satellites and user equipment. GEOSTAR fundamentally uses transponders and keeps system control located on the ground. Three satellites plus a fourth inactive on-orbit spare are proposed for the GEOSTAR system. The satellites are in geosynchronous equatorial orbit aligned with the Eastern, Central, and Western United States. All three are above the horizon anywhere in North America and appear to be stationary. User equipment is a digital transceiver with a function of exchanging messages with the satellites. They in turn are relay stations that exchange data with the user's transceivers and retransmit it to the central computer on the ground.

The central computer transmits an interrogation signal analogous to that used by today's transponders; one hundred times per second. Relayed by tight microwave beams to the three satellites the signal from the central computer is rebroadcast by them on a single frequency of 2492 MHz in a pattern which covers CONUS.

The user transceivers each have a unique digital signature code which identifies it. These codes are built in at the factory. When a transceiver receives the interrogation signal from the satellite, it answers with its identifier on a frequency of 1618 MHz. A small antenna system on the user equipment is all that is required for the relatively low power needs of its transmitter. The satellite antenna system and modulation technique carries the necessary sophistication to properly receive any and all identifier signals.

The transceiver's answer back identifier is received by all of the satellites and relayed by microwave to the ground station. There the computer compares its time of arrival at each of the satellites and computes using a triangulation technique the location of the user transceiver. This information is encoded and addressed to the transceiver and relayed back to the satellites. The total time for the entire transaction is about 1/2 second.

An important aspect of GEOSTAR's probable success lies in the tremendous computational capability which will be available on the ground. Tests of software on a **CRAY-1** supercomputer similar to those planned for the system indicate that a single such computer could handle the entire projected maximum system load of 100,000,000 users with relative ease. By addressing each user individually, the system can handle all of them using the two frequencies, one frequency used for interrogations and data transmitted from the satellite and one for identifications and data transmitted by the user transceivers. The limit on the number of users is statistically derived, based on a 90% chance of deciphering signal collisions from the user transceivers. Because of the nature of the signals, many transceiver messages can occur simultaneously and the system will properly decipher them. The system has a reasonable upper limit of 350,000 users per satellite. This number of users allows for channel contention and still meets the 90% success within a one second interrogation time. Keep in mind that messages are polled during the uplink and confirmed during the downlink so that all messages conceivably will be deciphered, but not all may be deciphered within one second. Because the system software identifies which users are associated with aircraft and which, for example, are associated with light users such as pedestrians, it can budget its time and update aircraft position twice per second while pedestrians may only require updating once every few minutes. As the need changes the system can adjust its response rate for aircraft to meet en route or terminal requirements.

GEOSTAR has the potential to provide its stated accuracies with inexpensive equipment because it is a two way, interactive system. Most of the errors in other satellite locations systems cancel out in GEOSTAR because positions are measured relative to fixed-site "benchmark" transceivers. GEOSTAR is a strictly differential, closed-loop system rather than open-loop system. The basic transceiver has a projected cost of $450 and the size is projected to be smaller than checkbook size, having a space for keypad and LCD display and about an inch of thickness including a built-in antenna. The system will consume low power much like a present day calculator, and only two wrist watch batteries are required to power the unit for about a year. The projected monthly lease of the basic transceiver unit is expected to be about $45 per month for the basic services. In all probability, the bulk of the system would serve users such as fire and police services, taxicabs, freight lines, and individual pedestrians. Virtually all of these users would subscribe to the basic service consisting of the navigation and message-handling capability.

V4. EXPERIMENTAL TESTS

The first test satellite equipment is scheduled to be orbited at the end of 1985. The GEOSTAR equipment is an add-on package using a proprietary central encoding and decoding technique of burst spread spectrum. This add-on package properly implements the multi-point distribution and trickle back transceiver capability aboard the satellite. The add-on package is called the LINK 1 system. Testing of the LINK 1 system will be carried out through most of 1986. GEOSTAR has been performing a series of tests near Lake Tahoe on the California-Nevada border. This site was chosen because it combines good logistic support including an all weather airport with surrounding mountains on the summits of which satellite emulators can be placed. These units are called EME's (electromagnetic equivalents). Each EME is solar powered and simulates the actual operation of the satellites and their representatively low signal levels. In 1983 a complete test for the GEOSTAR system was put in place consisting of a computer control ground station, some user transceivers, and the EME's. Since the EME's were located on the peaks in the Sierra Mountains the conditions simulated operation in extreme northern latitudes near the limits of the proposed satellite coverage. The system demonstrations included guiding a pedestrian to a hidden marker in a field, guiding a vehicle to a precise street address, and guiding an aircraft to a precision landing. In good conditions, positions were repeatable to approximately one meter. This test was the first full scale test, and some technical adjustments were made to the system to enhance overall capability.

In 1984 the transmissions were done with high elevation angles similar to those of a real satellite system. With the EME's located on two light aircraft to altitudes of about 3,000 meters the system more closely approximated projected kinds of satellite angles. The ground station had additional computing power and calculated the changing positions of the emulators as they were not in fixed positions. This configuration allowed more realistic testing, although with precision degraded from that of the actual satellite system because of the motion of the emulators in turbulent air. In spite of these effects, the 1984 tests confirmed the positive result of having a higher elevation angle for the EMEs. The improvement in position was of the order of 1 meter under a larger variety of conditions. This is because the prevailing limit of the 1983 tests was multipath due to terrain clutter around the low lying EMEs.

Throughout the tests the hand-held display was able to transmit its messages back and forth to the central computer system. The hand-held display was transferred to the top of an instrument panel on board a light aircraft. In the approach mode it indicated distance and bearing to a waypoint, ground track, ground speed, and time to waypoint. During the final approach of the aircraft, the display changed to include left and right deviation and glide slope. Accuracy and stability of the position and steering indications were above the capabilities of any other system for an aircraft approach. "Distance to go" zeroed out properly over the threshhold and left and right guidance were accurate to a couple of feet. Holding vertical speed called for by the display units resulted in altitude which corresponded exactly with the normal on board vertical positioning system to within one half meter.

One can derive normal levels of expected timing accuracy given the tests of the differential navigation capability of GEOSTAR. Figure V1 shows raw timing data from the GEOSTAR airborne test system. Standard deviation of the 1984 tests was 15.9 ns. The projected improvement in timing for the full system is expected to be to about 5.9 ns standard deviation. This corresponds to a positioning error of about 1.6 meters for a typical location in view of the three satellites.

V5. GEOSTAR TECHNICAL SPECIFICATIONS

The information here outlines the major operational specifications for Geostar based on its FCC application for licensing in the USRDSS Satellite Service. A developmental license has been authorized; the information here, however, refers to the full system configuration which is targetted for 1987.

1. The Geostar system's space segment is to consist of three geostationary satellites located at 70° west, 100° west and 130° west longitude to provide coverage to the contiguous 48 states. Each of the satellites is to be identical in design. The proposed satellite system would use random access time division multiplex with slotted ALOHA protocol and differential phase shift keying (DPSK). The satellites are to relay information between the system's users and a control center. The control center will contain facilities to communicate with each satellite

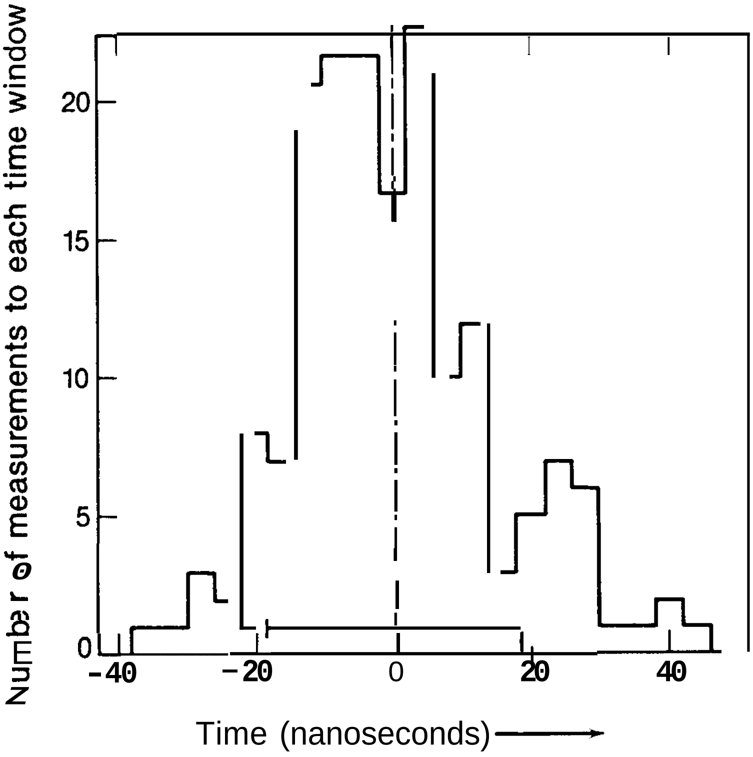


Fig. V1. Raw Timing Data of Geostar Airborne Test System and computers required to perform position determination and other system functions. Geostar has proposed to locate its control center at Princeton, New Jersey.

2. Four communication links are required for the radio-determination system proposed by Geostar: two space-to-earth links and two earth-to-space links. The users' radiodetermination uplink would operate within the 1610-1626.5 MHz band. The users' radiodetermination downlink would operate within the 2483.5-2500 MHz band. The control center would be linked to each satellite using a single data uplink bandwidth of 16.5 MHz located within the 6425-7075 MHz band. For the data downlink, the band 5117-5183 MHz would be used to link each of the satellites to the control center.

3. Operationally, the control center continually transmits via each of the three satellites what Geostar terms an Interrogation Pulse Group (IPG) available to all users throughout the continental U.S. The IPG's are transmitted at a 100 Hz rate and consist of a preset pattern of 64 bits of 80 nanoseconds duration each. The user may respond from what Geostar calls an Automatic Beacon Transfer (ABT) by transmitting a message which will be in one of several possible formats, depending upon the needs of the user. The message always contains timing and identification information and may contain a user message. Based on elapsed time from the emission of an IPG from the control center to the receipt of an ABT's response via each of the 3 different satellites, the user's position is calculated using direct range measurements. The control center then

transmits an addressed message, which may include the user's position, through one of the satellites for relay to the user intended to receive the message.

4. A user may access the system through three basic types of responses to the IPG: a position request, an emergency signal or a message signal, Based on the user's selection for the type of response, a varying length digital message transmission will be relayed to the control center through the satellite system. After responding, the user awaits a system reply. The reply will be either the user position location information or confirmation that the user message has been received by the control center and sent out as instructed. If the user does not receive a reply within 0.6 seconds, either due to coincidence of the user's response with that of another user's at the satellite antenna, or bit errors on the user-to-control-center communication link, the ABT will automatically repeat the response message. Randomization is introduced into the time of repeat to avoid consecutive coincidences on the uplink.

5. Geostar claims its radiodetermination system will provide position information with accuracies in the range from 1 to 7 meters. To accomplish such accuracy, Geostar will employ fixed "benchmark" transceivers at known locations. Accordingly, systematic errors for each mobile user's measured range can be corrected by subtracting range errors to fixed benchmark transceivers in the same geographical area. Such errors include ionospheric delay variations, drifts in the electronic delays through the satellites, variations in the positions of the satellite antennas, and lack of knowledge of details of the earth's

shape. The only equipment error which cannot be subtracted, according to Geostar, is drifting of the electronic delay within an individual user transceiver.

6. At the present time, the 1610-1727.5 MHz band, requested for use to provide the user radiodetermination uplink, is allocated internationally and domestically to aeronautical radionavigation. International Footnote 732 provides for satellite-based facilities associated with aids to air navigation. Within the U.S., no telecommunication use is presently being made of this band. However, the 1610.6-1613.8 MHz band is used by the radio astronomy service for observing the hydroxyl spectral line.

7. The 2483.5-2500 MHz band has been proposed by Geostar to provide for the radiodetermination downlink to users. The band 2483.5-2500 MHz is part of the 2400-2500 MHz industrial, scientific, and medical (ISM) band. Geostar has provided a technical analysis regarding the potential interference that would result from ISM equipment operating in this band to Geostar user equipments. In particular, it carried out a statistical analysis and performed on site field measurements for interference resulting from operation of microwave ovens. From its study, Geostar has concluded that this interference source should not pose a serious operational problem to its proposed system. The sole effect of possible microwave oven interference to Geostar user equipments would be to cause a modest increase in the "retransmit" rate.

8. The next proposed band used by Geostar is 5117-5183 MHz. This band, like the 1610-1626.5 MHz band, is allocated primarily for aeronautical radionavigation. This band would be used by the Geostar system to provide a downlink to the earth station located at Princeton, N.J. and would contain seven channels, condensed into the width of four channels by use of dual polarizations; this accounts for a total bandwidth of 66 MHz (4 x 16.5 MHz).

9. Last, a 16 MHz bandwidth within the 6425-7075 MHz band is proposed to provide for an uplink to transmit commands and message traffic from its proposed computer center and earth station at Princeton, N.J. to each of the three geosynchronous satellites. This band's allocation status is currently being used by licensees in the Domestic Public Fixed, Private Operational Fixed, and Auxiliary Broadcast services.

W. ESTIMATED TIME TRANSFER ACCURACY OF GEOSTAR

Although the primary purpose of the USRDSS service is navigational position determination for a user, a by-product could be the precise transfer of time to end users. There are two modes of time transfer claimed for Geostar users: (1) general time transfer to 150 µs accuracy and (2) high accuracy time transfer to as high as 10 ns accuracy.

For general time dissemination, an operational mode of Geostar includes corrections to a time code which correct for the user position. This is performed by a microprocessor within the user's transceiver. Computed position parameters from the control center will be used, and the estimated accuracy for users in this mode is 150 μs. This is intended to be a minimum cost service and, for this reason, ignores errors due to ionospheric delay, tropospheric delay, and satellite latitude and longitude wander. In contrast to the high accuracy mode, this is a broadcast mode and the computational load on the control station is independent of the number of users accessing the time information.

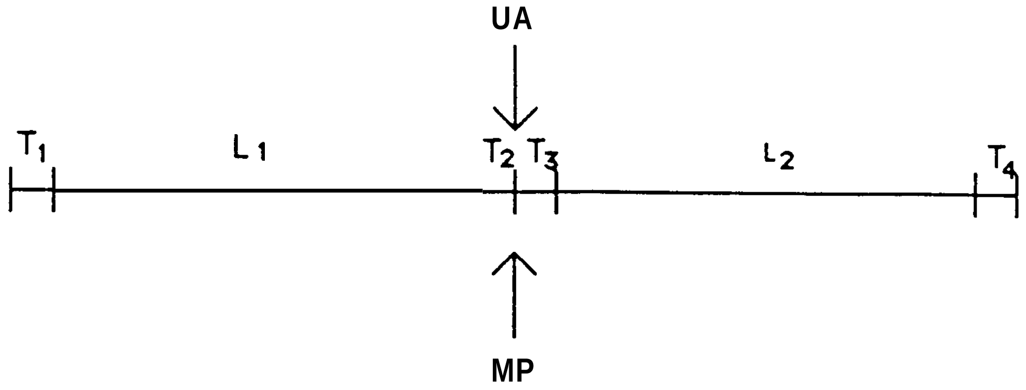
The high-accuracy capability uses a comparison between two users who each receive a specific code transmitted from a common satellite. The comparison is done back through the satellites, and the control center estimates the difference of the outbound signal's time of arrival at the two user sites. A comparison of the actual time code arrivals and the calculated times of arrival of the outbound signals allows the offset between the two users to be determined. Brian Tunstall studied the errors of the high accuracy mode for Geostar in a report of July, 1985 [5]. The following information is derived from that report.

The high accuracy mode is intended to provide time transfer services with accuracies in the nanosecond range. The suggested technique compensates for ionospheric delays and is independent of user and Geostar satellite positions and of tropospheric delays. The mode requires some Geostar control station processing for each time transfer executed. The suggested high accuracy mode is a round trip technique in which time can be transferred from the Geostar control station to User A or between User A and User B via Geostar. Consider first the more general case in which User A wishes to compare his clock with the clock of User B.

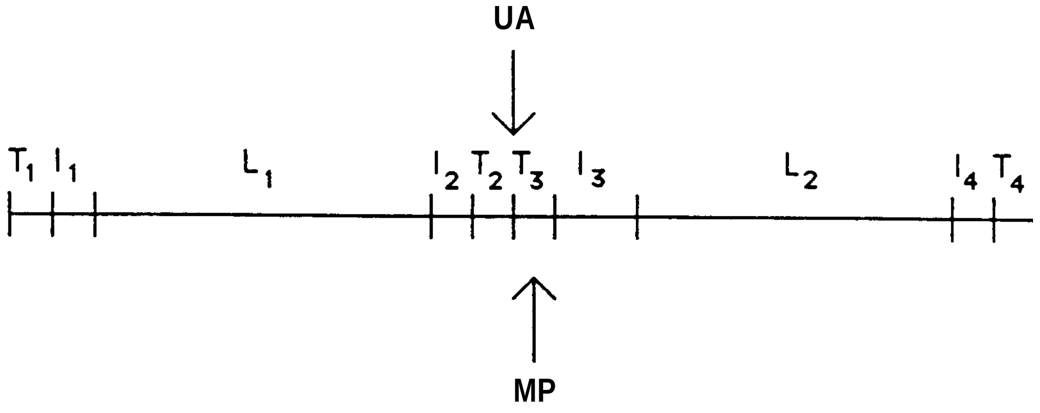
Assume that the Geostar control station broadcasts the outbound signal through the Geostar central satellite. By prearrangement Users A and B read their clocks upon receipt of a particular numbered frame and transmit a response back to the control station via the central satellite. The response is synchronized to the outbound frame just as in the usual navigational mode. The control station then knows the round trip time delay to User A and to User B. To a first approximation, the time at which each user reads his clock is just the midpoint of his round trip time delay. The time difference between the midpoints of the round trip delays, as observed at the control station, should equal the difference in the clock readings observed by the users. If not, the discrepancy equals the relative clock offsets.

Several observations may be made at this point. No position information is required concerning the satellite or either user. Further, the Geostar control station need not maintain an absolute time reference; it need only measure time differences of less than a second.

To refine the technique description somewhat and to develop an accuracy estimate consider the time delay diagram shown in Figure W1. In Figure W1(a) (not drawn to scale) the signal delays encountered in a round trip between the Geostar control station and User A are portrayed, assuming zero ionospheric delay. The delays encountered are labeled as follows:



(a) No ionospheric delay



(b) With ionospheric delay

Fig. W1. Time Delay Diagram

T_1 = tropospheric delay on control station to satellite link

L_1 = geometric path delay from control station to satellite to User A

T_2 = tropospheric delay on satellite to User A link

UA = Point at which the signal is received by User A

T_3 = tropospheric delay on User A to satellite link

L_2 = geometric path delay from User A to satellite control station

= L_1 (assuming quasi-stationary satellite position)

T_4 = tropospheric delay on satellite to control station link

Tropospheric delay is dependent on temperature, pressure, water vapor, elevation angle, and user altitude but not on RF frequency. Therefore $T_1 = T_4$ and $T_2 = T_3$. As a result of this symmetry, the signal reception at User A, point UA, is coincident with the round trip midpoint, point MP. Also Figure W1 does not illustrate delay lock loop jitter. This is treated in subsequent paragraphs.

Figure W1(b) adds the effect of ionospheric delay to the delays shown in Figure W1(a). Because of the $1/f^2$ frequency dependence of ionospheric delay the delays on each of the four links involved will, in general, differ. The symmetry of Figure W1(a) is no longer present and the point UA will be shifted to the left of the midpoint, point MP. The suggested technique attempts to minimize and to compensate for this offset.

Ionospheric delay follows a 24 hour daily cycle reaching a minimum shortly before dawn. In order to maximize accuracy the predawn hour will be utilized for time transfers. Within CONUS, for a zenith trajectory (90° elevation) and a frequency of 1.6 GHz, the maximum pre-dawn delay has been measured and shown to be less than 10 ns. Nonzenith trajectories show increased delays with a maximum of 35 ns at 0° elevation.

Assuming the worst case elevation and the $1/f^2$ frequency dependence, the ionospheric delays in Figure W1(b) have the following values:

I_1 = ionospheric delay on the control-station-to-satellite link
= 2.1 ns at 6533 MHz
I_2 = ionospheric delay on the satellite-to-User A link
= 14.8 ns at 2492 MHz
I_3 = ionospheric delay on the User A to satellite link
= 35 ns at 1618 MHz
I_4 = ionospheric delay on the satellite-to-control station link
= 3.5 ns at 5150 MHz

The resulting offset between points MP and UA is calculated as follows:

$$MP - UA = 0.5\,[T_1 + I_1 + L_1 + I_2 + T_2 + T_3 + I_3 + L_2 + I_4 + T_4] - [T_1 + I_1 + L_1 + I_2 + T_2]$$

$$= 0.5\ [I_1 + I_2 + I_3 + I_4] - [I_1 + I_2]$$

$$= 10.8 \text{ ns.}$$

Figures W1(a) and W1(b) represent the two extremes of measurement error due to ionospheric delay. In order to minimize the average error, the point UA will always be assumed to be 10.8/2 = 5.4 ns prior to point MP. This results in an ionospheric delay error, E_I, of

$$E_I = \pm 5.4 \text{ ns}$$

on the link between the control station and User A.

Assuming that the customer for high accuracy time transfer will use the higher performance transceiver for geophysical survey applications, the round trip timing error due to delay lock loop jitter will be ±2.8 ns. This implies the error, E_j, in locating the midpoint will be

$$E_j = \pm 2.8/2$$

$$= \pm 1.4 \text{ ns.}$$

Root sum squaring of the two error components, the overall error, E_A, in measuring User A's time of reception is

$$E_A = \pm(E_I^2 + E_J^2)^{1/2}$$

$$= k5.6 \text{ ns.}$$

The analysis of the link between the control station and User B is identical to that given above for User A, i.e.

$$E_B = E_A.$$

The overall error in transfering time from User A to User B, i.e., the error, E_{AB}, in measuring the offset between the midpoints of the signal paths to User A and B, is therefore given by

$$E_{AB} = (E_A^2 + E_B^2)^{1/2}$$

$$= \pm 7.9 \text{ ns.}$$

Two extensions of the high accuracy mode described above are (a) release of the predawn operating restriction and (b) maintaining accurate absolute time at the control station which can be transfered to users on an individual basis.

For extension (a), no restriction on time of day of operation, the dominant error component, E_I, increases by a factor of 5 resulting in an overall accuracy of

$$E_{AB} = \pm 38.2 \text{ ns.}$$

For case (b), (maintaining absolute time at the control station) it is assumed that the control station clock is updated by means of a Geostar link to the National Bureau of Standards. Then the control station clock is accurate to the level of E_A,

$$E_A = \pm 5.6 \text{ ns.}$$

When this time is transfered to an individual user, the overall accuracy of the user's update is again $E_{AB} = \pm 7.9$ ns.

X. PROSPECTS FOR HIGH-ACCURACY TIMING

For high accuracy time transfer, no cost estimates have been put forward in any of the Geostar documents to this date. Medium accuracy broadcasts of time transfer to the 150 μs level is suggested as being available at a small or no additional charge. A special user ABT is required for time transfer in the high accuracy mode to the level of 50 ns or better. Geostar at this point is putting all of its emphasis on other concepts and services of the system and the size, scope, and costs of just the preliminary 1986 test (Link One test) has left no resource for any high accuracy time transfer cost analysis or commitment. To add justification for licensing, Geostar has done a preliminary analysis of the high-accuracy potential capabilities (Tunstall, 1985) and has not committed to servicing users at any level of time transfer.

It is assumed that full costs of the Geostar high accuracy mode will be borne by the users of such a service just as in the navigation and telecommunication services. In our opinion, it is unlikely Geostar would themselves invest in deployment of a high accuracy time transfer service. This is because (1) it is not implied or stated in Geostar's prospectus that the ground computer software is easily or directly extendable to high accuracy time transfer, (2) a "special" ABT of unknown size and cost is necessary by the user, and (3) the market for high accuracy time transfer is only a few percent of Geostar's navigation and telecommunications market. Given the current Geostar prospectus and timetable, if funding were available outside of Geostar Corporation and if high accuracy timing capability were targetted for 1988 or later, such a capability could be in place.

Geostar could provide its advertised high accuracy capability with appropriate actions. First, we suggest that Geostar go ahead with installation and maintenance of a suitable cesium clock at its central ground station in Princeton, NJ. Although this eliminates the requirement to do time transfers at "predawn" times to reduce ionospheric delay uncertainties, these uncertainties are not a significant problem for BPA's one microsecond accuracy. The intent hoped for here is to simplify the overall operation by having a master clock at Geostar's Central dispatch. Second, NBS would monitor the accuracy of time transfer using a satellite receiver-decoder at Boulder, Colorado by comparison against UTC. Next, corrections would be applied to the Geostar clock as needed to steer its time to within preset limits relative to UTC. A practical limit would be ±100 ns (one sigma estimate). This is ten times better than BPA's specification, yet coincides with rugged, commercial clock instabilities and reasonable correction updates of say, once per day or less. Along with this, equipment would need to be made which automatically did the UTC comparison and Geostar clock updates. Correction data would need to be sent from Boulder to Princeton via a telephone link or Geostar's own communications system.

To make the system operate in the high accuracy mode, additional computations need to be executed at Geostar's central computer at Princeton, NJ. The cost of the additional software development cannot be estimated now. As mentioned earlier, Geostar Corporation has made no commitment to do this development.

A rough estimate of costs is shown below.

Initial Cost Estimate

Cesium Clock	$ 45k
Automatic Correction Equipment	$200k
Total	$245k

Unknown Initial Costs

High accuracy ABT (at Boulder, CO)

High accuracy Software at Geostar Central

Ongoing Cost Estimate

NBS Ceostar-UTC Comparison	$30k/yr
Maintenance, travel, misc. (1/3 man year)	$33k/yr
Total	$63k/yr

Unknown Ongoing Cost Estimate

Geostar monthly subscription fee (high accuracy timing)

The items listed above are given as a basis only. They do not constitute a proposal. Little can be concluded about actual overall costs until the high accuracy equipment and software is priced and Geostar's ongoing fee for high accuracy time transfer is determined.

Y. CONCLUSION REGARDING USE OF GEOSTAR

We believe GEOSTAR will technically and financially realize its objectives in the radio determination satellite service (RDSS) of navigation and message handling capability. However, it is difficult to say whether GEOSTAR will meet its own timetable of being fully operational by 1988.

More important is the fact that GEOSTAR does not appear to have put in place adequate measures to provide a high accuracy time transfer capability at this time. However, the potential exists and has been evaluated to provide as good as 10 ns accuracy. Development of high accuracy timing capability may occur later, but there is no clear direction or policy regarding this.

Our analysis of the USRDSS concept has focussed on the GEOSTAR proposal since it is now the only one in which detailed information pertinent to this study is readily available. Other companies may arise in the future and should be considered if the USRDSS option is deemed appropriate for accurate time dissemination.

SUMMARY

This report has studied ways in which time transfer could be achieved to meet all requirements of the Bonneville Power Administration and NBS. This work has concentrated on systems which disseminate time in a broadcast mode and are independent of the existing internal communications links of the BPA. The desired level of accuracy throughout the power transmission system was established as one microsecond.

The first phase of study gave policy guidelines for this work. The NBS provides several time-and-frequency broadcast services. Although it was not true in the past, current U.S. administration policy is that any new work or services should contain a method of full cost recovery for NBS. The second phase concentrated on existing and potential services. Pertinent issues such as accuracy, cost to users, reliability, coverage, and other items were discussed. In all, seven time distribution systems were considered and details on them were given. Six of the systems were satellite based, and one (Loran-C) was not. Phase III then presented extensive review of three systems which were likely to serve the needs of BPA based on the phase II study. The three systems determined as viable were:

1. The Fixed Satellite Service (FSS) used as a time broadcast link directly from NBS,

2. the military's Global Positioning System (GPS), and
3. GEOSTAR, a private sector Radio Determination Satellite Service (RDSS) under development

There are advantages and disadvantages associated with each of these systems. Table 12 shows a breakdown of the main features of each of these three systems with regard to system issues outlined at the beginning of Phase 11.

The Phase III portion of the study elaborated on the FSS, GPS, and GEOSTAR options and the conclusions are summarized as follows:

1. FSS option: All technical and cost requirements appear to be achievable using the FSS preliminary design presented in Phase 111. Possibly the most important factor to successful FSS operation is accurate tracking of the satellite which NBS proposes as integrated into the time distribution system. Based on experimental satellite tracking done by NASA during the mid-1970's, time synchronization to less than one microsecond should be achievable. No technical or policy obstacles prevent NBS from developing the FSS as an "Industrial Time Service" which could meet BPA's objectives and could serve a variety of users on a full cost recovery basis.

2. GPS option: Technical requirements can be met using GPS. Receiver costs are high now with an average cost of $20,000 and a range of $15,000-25,000 with a possibility of future reductions, but we

TABLE 12.

ISSUE / SYSTEM	Study Requirements	Fixed Satellite Service (FSS)	NAVSTAR Global Positioning System (GPS)	Radio Determination Satellite Service (RDSS)
ACCURACY	1 μs	100 ns	100 ns	10 ns
UNAMBIGUOUS UTC TIME CODE	Yes	Yes (feasible)	Yes	Yes
COVERAGE	CONUS	CONUS +	Global	CONUS +
STATUS	NA	FSS extensively developed -- many independent operators. T/F undeveloped.	Partially developed Fully operational by 1988.	Satellite system under development. Time and Frequency Service being discussed as option.
OPERATIONAL USE	Continuous	Continuous	14-18 hours per day -- will be continuous when fully operational.	Continuous when operation in 1987 or 1988
RECEIVER SYSTEM COSTS	< $[illegible]00	~ $2500	$20,000 -- cost expected to decline significantly during next 5-10 years.	$1000, unknown for high-accuracy timing
OPERATOR	NA	~[illegible] independent operators	Department of Defense	4 private sector entries expected
ANTENNA PACKAGE SIZE	Maximum dimension 1 meter	dish < 1 meter in diameter	15.2 cm high 9.4 cm diameter	Undetermined
NBS OPERATIONAL MAINTENANCE COSTS FOR THIS SERVICE	Recoverable through user fees if NBS involved.	may be recovered through user fees -- encrypted data data	None - DOD support navigation system	Small costs associated with maintaining time to UTC(NBS)
SUBSCRIBER FEES	Sufficient to cover O&M costs -- $300/yr. thought to be adequate	~ $300/yr	None expected -- has been discussed however.	Undetermined service charge
LONG TERM PROSPECTS	20 year lifetime	Excellent	Questionable -- may be degraded or denied during national emergencies.	RDSS recently approved by FCC

do not believe the costs will drop to the same degree the GPS navigation receiver costs are projected to drop. Of special importance is that the military policy regarding a civilian time service carries some risk which leaves open the possibility for altered, degraded, or discontinued service at the future disposition of the military administration. Furthermore, the service is now considered to be freely available, but the option for future civilian user fees exists in the final Block II implementation.

3. GEOSTAR option: Although technically and financially strong, GEOSTAR Corporation does not appear to have put in place adequate measures for providing a high accuracy time transfer capability. However, the potential exists for accurate time transfer and has been evaluated to provide accuracy as good as 10 ns. Development of high accuracy timing capability may occur later, but there is no clear direction or policy regarding this. In fact, the GEOSTAR system is operated entirely by the private sector, and future operational aspects are difficult, if not impossible, for NBS to predict at this time.

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5. "Time Dissemination Accuracies Using Geostar," B. Turnstall, Systematic General Corporation memorandum to Geostar, July 3, 1985 (Copy submitted to ITU-CCIR Library, October, 1985).

APPENDIX I

PHASE 2: TECHNICAL APPROACH--

OPTIONS FOR SERVICE DELIVERY

Below are some of the options to be studied and considered as the delivery vehicle of a TOD and frequency system. The list includes most of the present thinking at NBS but may be expanded depending upon new information received prior to or during the actual study.

System Configurations:

a. The use of a partial transponder aboard a communications satellite operating in the Fixed Satellite Service with downlinks of 3.7 to 4.2 GHz or 11.7 to 12.2 GHz. This option has the advantages of high reliability and low costs due to the extremely competitive environment existing in this industry. Special techniques will have to be used, however, to compensate for the rather low power flux densities available and the potential interference from adjacent satellites and other terrestrial services.

b. The use of the Direct Broadcast Satellites (DBS) operating in the bands allocated to the Broadcast Satellites Service (BSS) with downlinks at 12.2 to 12.7 GHZ. This option has advantages of high flux densities and inexpensive equipment due to high production quantities. Several tens of millions of small earth stations will be built by the DBS industry in the next five years.

c. The use of the time and frequency service space-to-earth broadcast channel allocation at 400.1 MHz. This allocation is exclusive in that it is a primary allocation and will not be sharing the channel with other services thus assuring interference free operation. It also has the advantage of not being limited in power flux density, it may broadcast to the earth's surface.

d. The service may be integrated into an already existing system. Although dedicated to other purposes or other users, systems such as LORAN-C, OMEGA, TRANSIT, GPS, and the terrestrial distributions of telecommunications services do provide certain useful levels of time and frequency information. These systems suffer the disadvantage of being subject to modification, with notice, in such ways that nullify or reduce its utility as a source of time and frequency information.

These above options shall be examined from the standpoint of how well they might meet technical and operational requirements determined in phase 1 of this study.

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UNITED STATES OF AMERICA

DRAFT REVISION OF REPORT 518-3

Time/Frequency Disseminations and Coordination Via Satellites

(Question 2/71

1. Add new section 4.3.4 as follows:

4.3.4 USRDSS

The USRDSS is a proposed system envisioned in the radiodetermination-satellite service which will consist of a number of operational satellites in geostationary orbits, one or more fixed location control centers, and a large population of mobile users (subscribers) located within the system coverage zone. In the envisioned system, a periodic time reference PN code, originating at a control center, is relayed through one satellite to all user stations within a coverage zone. The user stations are expected to be relatively inexpensive, pre-programmed transceivers designed to respond with uniquely identified signal bursts back to the control center via two of the satellites in the system. Responses may Include messages for other users or requests for other services. The control center will determine the two associated roundtrip propagation path delays and, using a stored terrain map or altitude information from the user station, compute the precise location of the user station using redundant high speed computers. Computed positions along with pending messages are addressed and transmitted back to the appropriate user via the original signal containing the embedded periodic reference PN code. During operation, the system will be continuously calibrated using known, fixed-location "benchmark" transceivers. Outbound links from a satellite to the user stations are planned for the frequency range 2483.5-2500.0 MHz while inbound links from the users to the satellites are planned for the frequency 1610.0-1626.5 MHz.

As a complementary byproduct of its primary service of precision radiodetermination, the USRDSS System is expected to provide both general time dissemination to a large number of users and high-accuracy time transfer. The capability for wide area coverage and the design emphasis on low cost, automated user transceivers enables a large user base for these functions. For general time dissemination the operational mode of the envisioned USRDSS includes corrections for the user position performed by a microprocessor within the user transceiver. Computed position parameters from the control center will be used and the estimated accuracy for users in this mode is 150 microseconds [Tunstall, 1985].

The operational mode for high accuracy time transfer service with the envisioned USRDSS involves a method analogous to the simultaneous exchange of timing signals through a communications satellite link. Two users desiring to correlate their local clocks will respond to a specified epoch on the outbound USRDSS signal. The time of receipt of the epoch at the user station is labeled with the local clock value. The control center can estimate the difference in the outbound signal's time of arrival at the two stations by measuring the time difference in the arrival of their responses and incorporating calibration factors derived fran the "benchmarks". By comparing the clock value labels and the calculated times of arrival of the outbound signals, the offset between the two user clocks can be determined. The estimated accuracy for this service is 10 nanoseconds [Tunstall, 1985].

A special case of the high accuracy time transfer service makes use of an accurate clock at the central control center. The clock is periodicaly recalibrated by transfering time from a reference standard clock such as that available at the United States National Bureau of Standards. The control center can then transfer precise time, upon request, to any user located within the system coverage zone. The estimated accuracy for this special case is also 10 nanoseconds [Tunstall, 1985].

2. Make the additions to Table 1 as attached.

3. Make the additions to Table 2 as attached.

4. Add to the list of references the following:

Tunstall, B. [October, 1985] Time Dissemination Accuracies Using Geostar. Prepared for Geostar Corp. by Systematics General Corporation, March, 1985. (Copy submitted to ITU - CCIR Library, October, 1985).

APPENDIX 111: GEOMETRICAL DILUTION OF PRECISION FOR TRILATERATION

An equation relating the range error variances with position error variances is derived for the simple trilateration model illustrated in Figure Al. Three tracking stations on the earth's surface are shown with coordinates (X_i, Y_i, Z_i) for i = 1, 2, and 3. The satellite is located at (X, Y, Z). The ranges to the satellite are ℓ_1, ℓ_2, and ℓ_3.

The range error variances are shown to be directly proportional to the position error variances by a constant generally known as the geometrical dilution of precision or simply the GDOP.

The equations for the ranges, l_i, to the satellite are:

$$l_1 = \sqrt{(x_s-x_1)^2 + (y_s-y_1)^2 + (z_s-z_1)^2} \tag{1}$$

$$l_2 = \sqrt{(x_s-x_2)^2 + (y_s-y_2)^2 + (z_s-z_2)^2} \tag{2}$$

$$l_3 = \sqrt{(x_s-x_3)^2 + (y_s-y_3)^2 + (z_s-z_3)^2} \tag{3}$$

It is assumed that the satellite coordinates and ranges may be expressed as:

$$x_s = x_{sn} + Ax \tag{4}$$

$$y_s = y_{sn} + \Delta y \tag{5}$$

$$z_s = z_{sn} + \Delta z \tag{6}$$

$$\ell_1 = \ell_{1n} + \Delta\ell_1 \tag{7}$$

$$\ell_2 = \ell + \Delta\ell_2 \tag{8}$$

$$\ell 3 = \ell_{3n} + \Delta\ell_3 \tag{9}$$

where x_{sn}, y_{sn}, z_{sn} ℓ_{1n} ℓ_{2n} and ℓ_{3n} are stochastic variables; Ax, Ay, Az, $\Delta\ell_1$, $\Delta\ell_2$ and $\Delta\ell_3$ are errors and $x_s = E\{x_{sn}\}$, y_s $E\{y_{sn}\}$ etc.

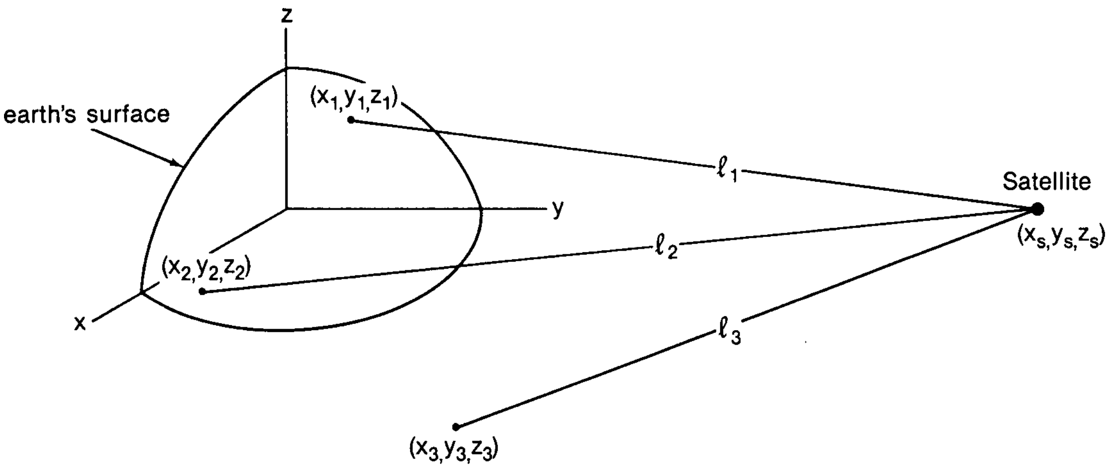

Fig. APP1. Trilateration Geometry

Therefore

$$\ell_{1n} = \sqrt{(x_{sn}-x_1)^2 + (y_{sn}-y_1)^2 + (z_{sn}-z_1)^2} \qquad (10)$$

$$\ell_{2n} = \sqrt{(x_{sn}-x_2)^2 + (y_{sn}-y_2)^2 + (z_{sn}-z_2)^2} \qquad (11)$$

$$\ell_{3n} = \sqrt{(x_{sn}-x_3)^2 + (y_{sn}-y_3)^2 + (z_{sn}-z_3)^2} \qquad (12)$$

Substituting Equations 4-9 into 1 yields

$$\ell_{1n} + \Delta\ell_1 = \sqrt{(x_{sn}+\Delta x-x_1)^2 + (y_{sn}+\Delta y-y_1)^2 + (z_{sn}+\Delta z-z_1)^2}$$

Squaring both sides and ignoring 2nd order terms yields

$$\Delta\ell_1 = \frac{x_{sn}-x_1}{\ell_{1n}} \Delta x + \frac{y_{sn}-y_1}{\ell_{1n}} \Delta y + \frac{z_{sn}-z_1}{\ell_{1n}}$$

Likewise

$$\Delta\ell_2 = \frac{x_{sn}-x_2}{\ell_{2n}} \Delta x + \frac{y_{sn}-y_2}{\ell_{2n}} \Delta y + \frac{z_{sn}-z_2}{\ell_{2n}}$$

and

$$\Delta\ell_3 = \frac{x_{sn}-x_3}{\ell_{3n}} \Delta x + \frac{y_{sn}-y_3}{\ell_{3n}} \Delta y + \frac{z_{sn}-z_3}{\ell_{3n}} \Delta z$$

Defining

$$A \equiv \begin{vmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{vmatrix}, \text{ where } a_{11} = \frac{x_{sn}-x_1}{\ell_{1n}} \text{ and soforth}$$

$$X \equiv [\Delta x \ \Delta y \ \Delta z]^T$$

$$L \equiv [\Delta \ell_1 \ \Delta \ell_2 \ \Delta \ell_3]^T$$

We have

$$L = AX$$

$$X = A^{-1}L$$

Since the above equation is linear, the relationship holds for errors in positions and ranges also.

$$\varepsilon_x = A^{-1}\varepsilon_\ell$$

To obtain the position and range error variances, the covariance matrix is formed as

$$\mathrm{cov}(x) = E\{\varepsilon_x \varepsilon_x^T\}$$

and $$\mathrm{cov}(L) = E\{\varepsilon_\ell \varepsilon_\ell^T\}$$

$$\begin{aligned}\mathrm{cov}(x) &= E\{A^{-1}\varepsilon_\ell (A^{-1}\varepsilon_\ell)^T\} \\ &= E\{A^{-1}\varepsilon_\ell \varepsilon_\ell^T A^{-T}\} \\ &= A^{-1}E\{\varepsilon_\ell \varepsilon_\ell^T\}A^{-T} \\ &= A^{-1}\mathrm{cov}(L)A^{-T}\end{aligned}$$

However $\mathrm{cov}(L) = \sigma_L^2 I$ assuming the range residual errors are uncorrelated and equal for each log or range.

Thus $\mathrm{cov}(x) = \sigma_L^2[A^{-1}A^{-T}]$ or

$$\mathrm{cov}(x) = \sigma_L^2[A^T A]^{-1}$$

The geometrical dilution of precision, GDOP, is defined as

$$\mathrm{GDOP} \triangleq \sqrt{\mathrm{TRACE}[A^T A]^{-1}}$$

Thus

$$\mathrm{GDOP} = \sqrt{\frac{\sigma_X^2 + \sigma_Y^2 + \sigma_Z^2}{\sigma_\ell}}$$

GDOP is then the amplification factor of range error variances to the position error variances.