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Technical Memorandum

GLOBAL TIMING SYSTEMS OF NANOSECOND ACCURACY USING SATELLITE REFERENCES

by E.F. OSBORNE

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THE JOHNS HOPKINS UNIVERSITY ▪ APPLIED PHYSICS LABORATORY

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ABSTRACT

The application of artificial satellites in providing radio reference signals for the synchronization and calibration of local clock and timing systems has been studied. Space technologies in the specific areas of geodesy and navigation are applied with digital signaling techniques and atomic time and frequency standards. The result of the study predicts that a useful operational service can be provided on a global basis with a low-altitude polar satellite having an on-board atomic clock to most effectively satisfy user requirements at various levels of system accuracy. For fixed site users, system accuracies as good as 100 nanoseconds (rms) are realistic with sophisticated equipment and data processing.

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SUMMARY

Applications are emerging for a reliable service to be operational within about five years that will provide precise radio timing references by which users anywhere on the earth can synchronize and calibrate their clock subsystems with microsecond or better (three sigma) system accuracies relative to the common System Standard. It is postulated that such an operational service can most effectively be supplied at minimum expense by an active satellite system. The satellite(s) will contain an orbiting clock and radio transmitters, while users will operate passively in a receive-only mode. The timing service will be a secondary mission of the composite satellite system, which will have primary missions such as navigation or geodesy.

An engineering study has been performed to establish technical feasibility and probable performance in one-way timing when accurate geodetic models and doppler navigation principles are combined with digital signaling techniques, atomic clocks, modern circuitry, and data management techniques. The purpose of this report is to present in depth the results of the study including:

(1) A comparison of satellite timing methods,

(2) An identification and analysis of errors in timing using the low-altitude orbiting clock satellite concept,

(3) Considerations of appropriate modulation techniques, and

(4) Examples of integrated satellite subsystem designs incorporating atomic references.

A bibliography is provided for the reader who needs greater detail and analytical rigor.

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In the comparative evaluation of satellite systems, one-way low-altitude and near-synchronous orbiting clocks and two-way near-synchronous radio relay methods were considered. If the timing service is to be provided to a large number of users distributed worldwide, then, in the aggregate, the one-way low-altitude system offers the greatest potential. The advantages of worldwide coverage by a single satellite to an unlimited number of passive users, favorable geometry for line-of-sight transmissions, minimum ground support networks and management require-ments, low cost in satellite launch and replacement, and growth from an existing system overcome the disadvantages of intermittent signal availability and the range (delay) compensations inherent with all one-way systems. The low-altitude orbiting clock system is versatile and flexible in its application and use. It is compatible with a wide range of the user's functional and performance require-ments.

In the estimate of performance of the low-altitude satellite systems, error sources are identified and values are tabulated as random (with zero mean) or as indetermi-nate bias uncertainties. The probable system error in timing (one sigma value) is the root of the sums of mean square random values plus the squared magnitude of bias uncertainties. By using data processing techniques, sta-tistical smoothing over a large number of "timing epochs" is used to minimize the probable error in measurement. On a per pass basis the probable error estimates are 100 and 125 nanoseconds (rms) for relative synchronization and normalized time calibrations, respectively. The major assumptions include:

(1) The use of a rubidium atomic standard (or equivalent) in the satellite clock,

(2) Calibration of the satellite by a master station every 12 hours,

(3) Compensation for refraction effects in radio wave propagation,

(4) The use of coherent digital signaling techniques,

(5) The acquisition of local equipment delay calibrations over the satellite observation interval,

(6) At least 50 valid data points (timing epochs and delay calibrations) during each satellite observation, and

(7) A communications link giving an effective +40 dB signal-to-noise ratio (SNR) at the receiver decision logic after filtering and coherent detection, relative to a 100 kHz "clocking" modulation waveform.

This implies a system with navigation capability to compensate for one-way slant range and a satellite with nominal circular orbit and 0.5 to 5 watts RF power, with the exact power level being a compromise depending on antenna gains and system noise temperatures.

In the review of modulation concepts for timing there are many methods, both analog and digital, that are appropriate. However, when incorporated in a satellite system having other primary missions such as geodesy or navigation, the requirements of the primary mission are supervening and controlling, and timing modulation must be chosen for compatibility. Fortunately, the mission requirements of the low-altitude geodetic and doppler navigation satellite systems are mutually complementary with the concepts of precision timing. Digital signaling techniques are preferred and are currently used in these space systems to achieve minimum error rates with coherent (phase) demodulation at poor SNR. For high accuracy timing in an improved system, an auxiliary information channel at 972 or 1600 MHz would be useful in avoiding large ionospheric refraction error with a single channel receiver. As an alternative, the auxiliary information channel can be in the form of a "subcarrier" channel on the 324 MHz geodesy or 400 MHz navigation channels. The subcarrier channel would consist of a clocking square wave (typically at 100 kbps) with coherently related timing and data modulation

according to an organized, discretely coded format. It is
considered that special modulation techniques to achieve
security and antijamming discrimination are inconsistent
with the concepts of dissemination and utilization of the tim-
ing references on a worldwide basis by the international
community.

In the area of satellite subsystems' mechanization,
it is shown that it is possible to combine the synthesis re-
quirements of the atomic reference standard with those of
the satellite coherent doppler channels and thereby minimize
hardware and prime power consumption while maximizing
reliability and signal stability. In lock-up to the atomic
reference the designer has options to use feedback direct
from the slaved crystal oscillator, from an IF level prior
to the system phase modulator(s), or from an IF or RF
level following the system modulator. (The latter option is
available only if, after multiplication to microwave fre-
quencies, substantial modulated energy is within the con-
trol characteristic of the atomic reference.) In the satellite
subsystem a programmed incremented phase controller
operating at the crystal oscillator output frequency is
recommended as a method of normalization. Normalization
is necessary if the system requires a chain of time markers
uniformly distributed and coincident with a standard time
scale. Normalization resolves the inconsistency between the
standard time scale and the system channel allocation, for
the aging rate of the reference, and for any compromise in
achieving a practical satellite synthesizer of the microwave
atomic reference frequency; the normalizer may also serve
to time-shift by radio command the time modulating wave-
form for coincidence calibration to UT.

At the present time the rubidium absorption cell and
the cesium beam resonator are the chief candidates for the
satellite atomic reference. Their performance is compati-
ble with the timing accuracy objective and the nominal 12-
hour interval between calibrations. Several block diagrams
are included to illustrate the use of rubidium and cesium
references in geodetic and navigation satellites.

The report concludes with a positive recommendation that, in view of past progress and the present state of the supporting technologies, the development of specific subsystems for the satellite and for user equipments can and should proceed to provide, through a series of demonstrations and experiments, proven reliable operational service within five years.

I. INTRODUCTION

A.   STATEMENT OF OBJECTIVES

Advances are required in the near future that will increase efficiency and accuracy in several areas of general benefit to mankind including, for example, high speed digital communications, command and control, aircraft collision avoidance, transfers of digital information to and from computing centers, navigation, identification, and detection systems (see typical Refs. 8, 12, and 44). The practical feasibility and performance of these systems will be dependent upon the availability of a uniform worldwide reference of time that has a high accuracy and to which users may synchronize or calibrate their local clock and timing subsystems. It is hypothesized that such a uniform reference can be provided by line-of-sight microwave transmissions from earth-orbiting satellites (see Ref. 46) with performance and features not readily achievable in other radio systems. At the present time synchronizations are made by VLF and HF radio, including OMEGA and LORAN-C, and by flying portable clocks from point to point (see Refs. 6, 12, 35, and 39).

A general survey and feasibility study of timing by means of satellites is reported herein, the objectives being:

(1) To make a comparative analysis of competitive systems for the communication of time from satellite to ground,

(2) To perform a design study to establish satellite signal characteristics for two levels of performance: (a) better than 1 microsecond absolute system accuracy with sophisticated equipment, and (b) coarser accuracy with simple equipment (at the user's station), and

(3) To perform a design study of typical spacecraft subsystems to establish efficient RF synthesizer and clock divider proposals using atomic reference oscillators as the precision satellite source.

B.   INTERPRETATION AND GENERAL ASSUMPTIONS

The conduct of studies during this program has been guided by certain interpretations of the stated objectives and by some broad assumptions of which the following deserve mention:

(1) The timing service to be provided is to be used by a receiving station primarily as a high accuracy calibration reference. Its use as an operating standard by which the receiving station might derive a direct timing control of the functional operation of equipment is not intended.

(2) The user of "high accuracy" satellite time is therefore assumed to possess a local reference and clock that have adequate stability to sustain, over the interval between calibrations, the normal operation and timing functions of his station.

(3) Since the user is assumed to have a local clock of respectable performance, it is presumed that the satellite subsystem is not required to transmit a unique modulation format for each marker epoch of the signal. In this study the total resolution of ambiguities during a calibration in terms of the year, day, hour, or minute is not considered to be of first-order concern, since such information can be provided within regular satellite data channels.

(4) In the development of a system design concept
it is desirable to build upon current technology
to achieve a significant level of improvement,
as, for example, the three-sigma tolerance of
0.5 microsecond that is stated as a requirement
for airborne Collision Avoidance Systems (CAS)
(see Ref. 1). For CAS the worldwide accumula-
tion of total system error in timing between in-
tervals of calibration (see Ref. 41) must not ex-
ceed 167 nanoseconds (rms). For the studies
and error analysis to be performed herein it is
useful to accept this requirement as a goal.
(For other references to the CAS problem see
also Refs. 27 and 47.)

II. SURVEY AND COMPARISONS OF SATELLITE TIMING SYSTEMS

A.   CLASSIFICATION OF SATELLITE TIME SYSTEMS

The principles and candidate design concepts for achieving high accuracy in timing for widely separated users through the use of artificial satellites are manifold. It is unlikely, in a survey of this type, that an all-inclusive listing can be made. However, in Table I an attempt is made to set forth general descriptive classifications which are representative of methods, modes of operation and use, and instrumentation.

In weighing the comparative merits of various conceptual proposals for timing, the equipment complexity and total system cost are important factors. In the consideration of total system cost it is suggested that an autonomous satellite system maintained solely for the purpose of timing may never be cost effective. It is therefore desirable and certainly recommended that timing be incorporated within a multifunction satellite, preferably in a system having mutually compatible and complementary missions, as, for example, in a navigation-timing, geodesy-timing, communications-timing, or possibly a surveillance (data acquisition)-timing application.

For the very general classifications listed in Table I the following explanations are offered:

Relative Synchronization Timing — In this concept the clock or time mark generator is derived directly from the reference frequency standard so that the marker modulation is coherent with the transmitted RF carrier signal. No attempt is made to regularly calibrate, synchronize, or normalize the modulation transmitted by the satellite to UT or any other standard of time although coarse adjustments may be scheduled at announced times. In its use each ground station receives satellite signals, recovers the timing modulation, and measures the time of reception

Table I

Satellite Time Systems

General Classifications

1. Type of High Accuracy Timing

   (a) Relative synchronization of remote clocks to a system reference

   (b) Normalized time dissemination for direct calibration to a UT standard

2. Source of Timing

   (a) Active orbiting clock

   (b) Radio relay from ground based clock

3. User Operational Mode

   (a) Independently passive

   (b) Cooperatively passive

   (c) Active, reciprocal paths

4. Satellite Orbital Characteristics

   (a) Low altitude polar

   (b) Synchronous

5. User Clock Error Measurement

   (a) Real time, concurrent to pass

   (b) Delayed time, post pass

of each modulation epoch relative to time kept by its own
local clock. Now, if the clock at a master ground station
receiving the satellite signal is known relative to UT, then
the station's computing center can determine by compari-
son the clock error at each remote slave station relative to
UT or to the arbitrary scale of a particular station.

In orbiting clock instrumentations and with a proba-
ble distribution of ground stations, in general, the slave
stations will not receive the identical series of time modu-
lation epochs as the master station. It is therefore essen-
tial that the satellite reference oscillator have high inherent
stability and low drift rate so that its performance is pre-
dictable over at least a 12-hour period, which is typically
the maximum interval between successive observations of
a polar satellite (orbiting at about 900 nmi or lower altitude),
by any ground station.

The relative synchronization system requires a sup-
porting communications network for data handling to and
from the ground stations and the computing facility.

Normalized Time Dissemination — In this concept
the satellite clock is derived from the reference frequency
standard, but the marker modulation may or may not be
coherent with the transmitted RF carrier signal. A normal-
ization subsystem is required in the satellite by which an
observing ground tracking network can insert commands
via a "housekeeping" radio channel to (a) calibrate, (b) syn-
chronize, and (c) properly scale the (satellite) modulation
to correspond to marker epochs in UT or another agreed-
upon time scale. In use, each ground station can independ-
dently receive satellite signals, recover timing references
and satellite orbital data, measure indicated local clock
error, compute compensations and instrumentation adjust-
ments, and then immediately recalibrate its local clock.
Each ground station can be completely independent by using
its own instrumentation and computation facilities, or,
lacking a local computer, the ground station can still obtain
accurate timing by means of centralized computing services
as described in the preceding paragraph for relative synchro-
nization.

<u>Orbiting Clock Sources of Timing</u> — This classifica-
tion implies a satellite having an on-board reference oscil-
lator and time mark generator, the quality and stability of
which are commensurate with system operational and accu-
racy objectives. The signal originates and is transmitted
directly from the satellite.

<u>Radio Relay and Ground-Based Clock Sources</u> — The
precision reference oscillator and clock are located at a
ground station that must actively transmit to the satellite
and receive back the relayed timing modulation. The satel-
lite is an active radio relay, but need not have on board a
reference oscillator of high precision. Master and slave
ground stations must have concurrent radio visibility to the
satellite.

<u>Independently Passive User Mode</u> — The ground sta-
tion or user is completely passive and has facilities for
independent determination of error of his local clock by us-
ing only the received satellite reference signals. This mode
implies a normalized time dissemination from an active
orbiting clock satellite and navigating capability at the
ground station for range compensation.

<u>Cooperatively Passive User Mode</u> — The ground sta-
tion or user is passive in that timing is not achieved by
direct communication (transmitting) of reference signals
from the station to the satellite. Information links (via
radio, land lines, or mail) between cooperative users are
required, however. This mode implies relative synchro-
nization with the local error being determined by a remote
centralized computing center.

<u>Active, Reciprocal Path User Modes</u> — By simultane-
ously receiving and transmitting timing references via the
satellite, range compensation is unnecessary, and errors
attributable to anomalies of propagation over reciprocal
paths are self-cancelling. The ground station is compli-
cated by the necessity for a high power transmitter as well
as a sensitive receiver. Generally this mode implies co-
operative relative synchronization between two or more
ground stations with the satellite operating as a radio relay.

<u>Low-Altitude Polar Satellite Orbits</u> — The altitude of the satellite is probably determined by primary missions of the system. The low-altitude polar classification includes satellite systems giving global coverage at least daily and typically within 12 hours for each satellite. Highly dynamic geometry between satellite and ground stations is implied.

<u>Synchronous Satellite Orbits</u> — This classification would include near-synchronous altitudes where the distinguishing characteristic is continuous regional coverage rather than periodic global coverage. The geometry between stations and satellite is slowly varying.

<u>User Concurrent Error Measurement</u> — In this classification facilities are provided at the ground station for real-time measurement and computation of local clock error or at least for immediate determination of error on cessation of data acquisition.

<u>User Post-Pass Error Determination</u> — In this classification the using ground station has minimal facilities for data acquisition only. Actual error determination of the local clock is computed at a remote facility subsequent (hours to days) to data acquisition from reception of satellite timing references.

B.   A RELATIVE EVALUATION OF SATELLITE TIME SYSTEMS

From the general classifications of satellite time systems listed in Table I, three design concepts are selected for more detailed comparative evaluation.

The first concept is a navigation-time system incorporating high accuracy improvements in dissemination of normalized timing in the polar-orbiting low-altitude Navy navigation satellites. Users may operate in the independent passive mode. The necessary improvements would be phased into new (replenishment) satellites of the already existing program, which includes operational ground tracking (OPNET) and satellite constellation maintenance (INJFAC)

facilities. Preliminary experiments can be performed with a geodetic-time combination using TRANET and proposed GEOS satellites.

The second concept for comparison uses an orbiting clock in a near-synchronous satellite. Normalized timing is disseminated to independent passive users.

The third concept selected for comparison uses the radio relay method with a multiple channel transceiver in a near-synchronous satellite, with users having both transmitting and receiving capability. The system's precision reference clock is maintained at a master ground station.

Commercial and military communications satellite systems are now operational and might be considered for future high-accuracy timing service with satellites at the near-synchronous altitude.

In the following paragraphs the advantages and disadvantages of these three system concepts are set forth with consideration of timing aspects only. The reader is cautioned that, in the event of a multifunction satellite system, certain advantages or disadvantages may become moot when viewed within the framework of the full system.

1. Merits of Low-Altitude Orbiting Clock Satellite Systems

    a. Principal Advantages

        (1) Worldwide coverage is obtained even with a single satellite (in polar orbit).

        (2) Service is provided to an unlimited number of passive users or ground stations.

        (3) The satellite is available to each user two to four times per day for each satellite.

        (4) Additional satellites reduce the waiting interval and increase worldwide confidence in the system.

(5) All stations (worldwide) can receive satellite signals line-of-sight at high elevation angles with minimum propagation path distortions.

(6) All clocks worldwide can be calibrated to one primary standard of time.

(7) The total satellite system can be launched and maintained in orbit from U.S. territories. Total support by a single ground station is theoretically possible.

(8) The existing OPNET satellite support systems are compatible with high accuracy timing objectives.

(9) Accurate timing and the primary navigation functions are mutually complementary.

(10) Satellites can be launched at relatively low comparative cost with "small" rockets and boosters.

(11) The line-of-sight range is short compared to synchronous and some terrestrial systems. This gives a satellite power or receiver SNR advantage.

(12) Experience with an existing operational system provides a solid foundation for higher accuracy improvements.

b. Principal Disadvantages

(1) The user station must compensate for the dynamic change in propagation delay incurred with the variation in slant range during the satellite pass — a characteristic of all one-way systems. The error budget for timing accuracy must include an allowance for satellite and station position uncertainties.

(2) The availability of reference signals, while dependent on constellation size and design and also the user's latitude, is limited to 10-15 minute intervals per pass, which eliminates applications in <u>direct</u> continuous timing.

(3) The ultimate accuracy in time epoch recovery in the user's equipment requires a correction for doppler shift of both the RF carrier and the marker modulation.

(4) High-altitude nuclear weapons testing is a potential threat to satellite life.

2. <u>Merits of Synchronous Orbiting Clock Satellite Systems</u>

a. Principal Advantages

(1) The satellite has continuous availability to users in a regional coverage area.

(2) Service is provided to an unlimited number of passive users.

(3) The satellite clock is available continuously to a ground support station for calibration.

(4) Continuous availability permits relaxation of drift rate requirements on the satellite reference oscillator.

b. Principal Disadvantages

(1) The system requires several satellites for total worldwide coverage of users.

(2) Compensation is required for radio path delay and propagation anomalies. Consequently the system's error budget must include allowances for satellite and station position uncertainties.

(3) A fringe zone of ground station locations will have continually poor reception because of low antenna elevation angles (to a particular satellite).

(4) Clocks in a worldwide system cannot all be calibrated directly to a single common reference. Multiple transfers are required to close the system.

(5) A global system cannot be sustained by ground support stations located only within U.S. territories. In the typical near-synchronous system global coverage requires distribution around the world of four master plus several remote secondary control stations.

(6) Accurate satellite position determination is comparatively difficult.

(7) Satellites are launched at relatively high cost with large rockets and boosters.

(8) Long radio path suggests either high satellite prime power subsystems or the use of high gain directional antennas.

(9) The exoatmospheric radiation environment is more severe than at lower altitudes.

3. Merits of Synchronous Orbiting Radio Relay Satellite Systems

   a. Principal Advantages

      (1) The satellite has continuous availability in a regional coverage area.

      (2) Simultaneous radio transmissions over reciprocal paths eliminate propagation and range compensation measurements or computations.

    (3) The high accuracy system reference standard and clock are accessible, since they are located at a master earth station.

    (4) High system accuracies in time transfer have been experimentally demonstrated.

b.   Principal Disadvantages

    (1) The system requires several satellites for total worldwide user coverage.

    (2) Simultaneous service to more than one user is limited by radio relay channel availability.

    (3) A fringe zone of ground station locations will have continually poor reception because of low antenna elevation angles (to a particular satellite).

    (4) Clocks in a worldwide system cannot all be calibrated directly to a single common reference.

    (5) A global system cannot be sustained by ground support stations located only within U.S. territories. In the typical near synchronous system global coverage requires distribution around the world of four master plus several remote secondary control stations.

    (6) Satellites are launched at relatively high cost with large rockets and boosters.

    (7) Long radio path suggests either high satellite prime power subsystems or the use of high gain directional antennas.

    (8) The exoatmospheric radiation environment is more severe than at lower altitudes.

(9) The satellite receiving system is suscepti-
ble to degradation, jamming, or capture by
multiple (earth-generated) sources of noise and
interference. The effective system noise tem-
perature will have contributions from station-
to-satellite as well as satellite-to-station links.

(10) Reliable and accurate system performance
requires that each ground station have a high
power radio transmitter facility.

(11) In a military environment there is a high
probability of detection and location of the user's
position because of transmitting radio signals.

From the advantages and disadvantages cited above
for the three primary candidates it is possible to conclude,
assuming adequate performance in terms of accuracy and
assuming no supervening multifunction system requirement,
that the most favorable design concept for worldwide timing
to a large number of users is the low-altitude orbiting clock
system. The principal determining factors include passive
user systems, global coverage with a single satellite,
superior geometry between the satellite and user, total
system support from within the national borders, low cost
to implement and maintain the system, and universal appli-
cation to either civilian or military users.

C.   USE OF THE LOW-ALTITUDE ORBITING CLOCK
       SYSTEM

1.   Impact of High Accuracy Timing on Navigation

The impact on the scientific, commercial, and mili-
tary fields of a regular operational timing service that is
dependable and is capable of system accuracies at or near a
100-nanosecond level anywhere on the earth can be enor-
mous. In the specific area of navigation (by satellite dopp-
ler aids) the high accuracy of time may:

a.   Aid in the (signal) search and acquisition modes of ground station operation.

b.   Improve the accuracy of doppler data acquisitions, and, hence, navigation accuracy, particularly in those types of navigator's systems that rely   on timing received from the satellite, to set the doppler counting interval.

c.   Improve the navigation accuracy (to a lesser extent) of those types of navigator's systems using preset fixed events or fixed interval counting by providing a means for frequent calibration of the local clock to a national standard of time, UT, or other standard time reference.

d.   Lengthen the period between successive calibrations of the orbiting satellite clock via the radio command channel from the injection station.   Since high accuracy in timing is achieved with atomic clock systems at the injection station and also in each orbiting NAVSAT, lower (and more predictable) drift rates of the references will permit navigation by the current programs and procedures of the operational fleet systems for prolonged periods of time, even in the absence of injection.   (This improved capability also depends upon predictability of satellite position and may require an orbit-keeping subsystem in the satellite.)

e.   Enhance the tracking performance of computer-aided navigator's systems by significant reduction of errors in the predictions of doppler shift, doppler velocity, and doppler acceleration functions that are used as primary forcing functions for phase-locked tracking oscillators when in the automatic receiver mode.

f.   Reduce (by virtue of the coherence of timing and RF (carrier) signals and by the control of satellite frequency) the vulnerability of the navigator's

equipment to multiple navigation satellite signal sources and to other casual interfering signals.

g. Improve the accuracy of collocation systems by the scheduled simultaneous reception at each station coincident with specific timing epochs of high precision.

h. Aid in the reduction of exposure or data acquisition time required for a navigation fix in longitude and latitude, or provide for additional navigation outputs such as altitude or velocity.

2. System Facilities Requirements

In a worldwide satellite time distribution system capable of high accuracy and precision, the facilities that are required include:

a. A constellation of polar-orbiting low-altitude satellites. Note that accurate calibration of users' clocks could be supported by a single satellite that would be visible at satisfactory elevation angles on a global basis at least twice a day. More than one satellite improves confidence by providing redundancy and statistical averaging. If all satellites carry precision timing, then convenient schedules can be set for local clock calibration during normal working hours at any geographical location of the user's station.

b. Supporting ground tracking stations and a computing center. At least one tracking station is required.

c. A supporting ground injection station for satellite calibration, control, and memory loading. The tracking and injection stations need not be at the same location.

d.   One authorized primary standard of time, ground-based at the Naval Observatory, for example.

e.   A distribution of using stations or navigators requiring timing.

f.   A central facility for computing satellite-to-station slant range for nonnavigating users.

g.   A network of supporting communications linking the ground support systems and also linking the non-navigating users to the central computer.

3.   General System Operation (with Normalized Time Transmissions)

The major functional requirements for each of the facilities or subsystems of the time system are as follows:

a.   The OPNET ground system tracks and predicts the orbital parameters of each satellite and forwards these data to the injection station (INJFAC) and to the central computer for nonnavigating time users.   (In this context the central computer need not be the computer facility of OPNET.)

b.   The authorized primary standard of time must make periodic transfers of time to a precision local clock system of atomic quality maintained at the INJFAC.

c.   The error in timing of the satellite clock is measured and is recalibrated by INJFAC either by radio command or satellite memory loading.   (As an alternative the error of the satellite clock could be measured by facilities to be provided at or near the national time standard facility.)

d.   Each satellite will generate and transmit modulation sequences defining timing epochs from which ground users recover time to either high or coarse accuracy.   Each satellite also transmits its orbital parameters.

e.   The user (or navigator) must calibrate with an internal test signal the time delay of his ground station equipment.

f.   The user will receive the satellite signal(s) and decode the timing data and orbital data with options to:

(1)   Compute on-site (if a moving navigator) for each data point the magnitude of the propagation delay or slant range compensation,

(2)   Transfer data, if a nonnavigator, to a central computer for post-pass delay compensation, or

(3)   Program pre-pass predictions, if a nonnavigator, of a central computer for delay compensation concurrent with a scheduled pass.

g.   The user combines his equipment time delay with the propagation delay at each data point to establish local clock error relative to the primary standard of time.   The user's local clock is then adjusted to remove the error either on a single pass or an aggregate of several satellite passes.

4.   User Options

As in most complex electronic equipments, the time user's station may be fabricated according to one of several optional design concepts.   The traditional design objectives and tradeoffs apply, including, for example (1) accuracy vs cost, (2) the degree of station autonomy, and (3) convenience in functional operation with automated data acquisitions and processing.

The low-altitude orbiting clock system is compatible and can service a wide variety of ground station user equipments.   The full range of design concepts is beyond the scope of this report; however, it is desirable to emphasize options that can have a major impact on the user's station.

The passive recovery of accurate time references from any radio dissemination system requires that a compensation be made for the propagation time of the signals during their transit from the transmitting source antenna until their effective recovery by the user's demodulating circuits. This compensation must be done with great accuracy if nominal system objectives of 100 nanoseconds (rms) are to be obtained. The delay time in a satellite-to-ground station link is a function of:

a. Effective Propagation Range

(1) Geometric line-of-sight

(2) Bending because of refraction of the radio wave as a function of the ionospheric electron density (profile)

(3) Bending because of refraction of the radio wave in the lower atmosphere due to climatic factors (temperature, pressure, and humidity)

b. Receiver Time Delay

Note that the nominal delay of the satellite transmitter between its clock and transmitting antenna is common to all ground stations and is therefore calibrated out as a source of error.

(1) User Options in Delay Compensation

Option A - Fully Independent Passive User

This user has an integral receiving instrumentation plus computation facilities for performing navigation as well as time recovery. The system provides measurement (or calibration) of the user's clock timing error. Measurement of doppler shift, refraction error (both ionospheric and tropospheric), and receiver time delay are used to determine accurately the compensation required.

This option applies to both fixed-site and highly mobile users.

Option B - Dependent Passive Time Recovery Only User

With the knowledge of satellite and geodetic parameters plus the position of the user, a central computing facility predicts and publishes in advance compensation data for specific satellite passes. The compensation is probably limited to geometric line-of-sight values. The user measures refraction parameters and receiver time delays to make the final fine adjustments to the indicated error of his clock.

This option is not generally recommended for highly mobile users.

Option C - Dependent Active Time Recovery Only User

In this mechanization the user acquires from specific satellite pass(es) data including timing and doppler, ionospheric refraction, local tropospheric (climatic) parameters, and receiver time delay calibrations. All data are forwarded by some supporting communications channel to a central computer facility for analysis, computation, and determination of timing error, which is then communicated back to the user.

This option is not generally recommended for highly mobile users.

(2) **User Options in Quantity and Use of Time Reference Data Acquisitions**

The orbiting clock satellite will emanate a repetitive sequence of modulation markers representing time epochs. As the satellite passes through the cone of visibility from the ground station, a multiplicity of epochs will be available for ground station calibration. There are options available to the user both as to the quantity of data measured and recorded and also as to the processing method by which local error is determined. The choice would be determined

by cost and accuracy objectives. The options include:

Option D - Full Data Curve Fitting

In this case the maximum number of timing epochs obtainable is recorded for least squares curve fitting analysis relative to a theoretical response for the particular satellite and the station location.

Option E - Qualified Data Curve Fitting

Under this option, data acquisition is truncated to eliminate epochs at very low elevation angles that generally are of low quality. In addition, each data point recorded is analyzed to determine its quality, i. e., its presence within acceptable boundary values. Qualified data remaining are then used in the least squares analysis to establish timing error.

Option F - Limited Data Near Point of Closest Approach

Fixed-site users with minimum cost and modest accuracy objectives (for example, on the order of a few microseconds) may obtain satisfactory service with as little as one recorded datum obtained at or as near as possible to the point of closest approach (PCA). The time of occurrence of PCA and the geometric slant range can be computed in advance of the satellite pass.

This option is recommended for consideration only by fixed sites having competent and well-trained personnel.

D. PERFORMANCE EVALUATIONS OF THE LOW-ALTITUDE ORBITING CLOCK SATELLITE TIME SYSTEMS

In the application of satellites to achieve accurate worldwide timing, one of two general principles is

employed: relative synchronization or normalized time dissemination. These concepts are defined in Section II. A.

In either approach to the achievement of accurate timing there will be an accumulation of errors whose magnitude is bounded by (1) the performance of components chosen for a compatible price, (2) the anomalies of the satellite-to-earth station geometries and the radio propagation paths, (3) the procedures employed in use, and (4) routine maintenance of the system. Considering only the magnitude of (rms) timing error, it may be generally anticipated that the relative synchronization system would be superior since a simpler satellite instrumentation is used. According to the estimates reported herein, the difference in rms error between the relative synchronization and normalized time systems is not, however, very large. According to the estimates a relative synchronization of two stations can reasonably be expected with accuracies of 100 nanoseconds (rms). Comparable assumptions and conditions indicate an accuracy of 125 nanoseconds (rms) for normalized time dissemination to a totally independent user station.

1.   Estimates, Assignment, and Computation of System Errors

A presentation is made in this section of numerical values of errors contributing significantly to system error. In a section to follow further discussion is presented on selected error sources to explain the assumptions, the method of operation, and some justification for the value selected. Values are presented in Table II for the relative synchronization system and in Table III for the normalized time dissemination system.

The sources of error are classified and listed under one of three major headings: the satellite subsystem, the radio path and satellite-to-user geometry, and the user's subsystem.

Table II

Estimates of Error, Relative Synchronization System
(Values in Nanoseconds)

	Nonrandom and Bias (B)	Random (Zero Mean) (R)
1. Satellite Subsystem		
(a) Epoch Marker Generator		
(1) Rb Reference (Drift in 12 hr)	5	
(Offset in 12 hr)		20
(2) Logic and Modulator Circuit Jitter		20
(b) Transmitter Time Delay Stability	6	
2. Radio Path and Satellite-User Geometry		
(a) Navigation Computation and Geodesy		
(1) Satellite Position vs Time	30	
(2) User Antenna Position	20	
(b) Radio Wave Propagation Errors		
(1) Ionospheric Refraction (Compensated or at 972 MHz Carrier)	20	
(2) Tropospheric Refraction (Compensated)	25	
3. User's Subsystem		
(a) Receiving and Detection		
(1) SNR (Phase) Jitter (Using f_m = 100 kHz and SNR = 40 dB)		10
(2) Uncertainty in Receiver Time Delay (Calibrations Distributed Over Pass)		50
(3) Resolution of Epoch Decision Logic		50
(4) Dynamic Signal Tracking and Phase Bias	50	
(b) Data Processing and Recording		
(1) Pulse Shaping, Gating, and Clock Comparator		20
(2) Data Chopping Error (100 MHz Digital Counter)		10
(3) Local Rb Reference and Clock Drift (Over 15-min Period of Pass)		1

NOTE: System Error in Timing: $\epsilon_t \simeq$ 100 nanoseconds (rms)

Table III

Estimates of Error, Normalized Time Dissemination System
(Values in Nanoseconds)

	Nonrandom and Bias (B)	Random (Zero Mean) (R)
1. Satellite Subsystem		
(a) Calibration of Control Station to UT (Injection Station Clock)	100	
(b) Satellite Epoch Marker Generator		
(1) Epoch Calibration via Radio Link	25	
(2) Normalizer Resolution		10
(3) Rb Reference (Offset Error in 2 hr)		4
(4) Logic and Modulator Jitter		20
(c) Satellite Transmitter Time Delay Stability	6	
2. Radio Path and Satellite-User Geometry		
(a) Navigation Computation and Geodesy		
(1) Satellite Position vs Time	30	
(2) User Antenna Position	20	
(b) Radio Wave Propagation Errors		
(1) Ionospheric Refraction (Compensated or at 972 MHz Carrier)	20	
(2) Tropospheric Refraction (Compensated)	25	
3. User's Subsystem		
(a) Receiving and Detection		
(1) SNR (Phase) Jitter (Using f_m = 100 kHz and SNR = 40 dB)		10
(2) Uncertainty in Receiver Time Delay (Calibrations Distributed Over Pass)		50
(3) Resolution of Epoch Decision Logic		50
(4) Dynamic Signal Tracking and Phase Bias	50	
(b) Data Processing and Recording		
(1) Pulse Shaping, Gating, and Comparator		20
(2) Data Chopping Error (100 MHz Digital Counter)		10
(3) Local Rb Reference and Clock Drift (Over 15-min Period of Pass)		1

NOTE: System Error in Timing: $\epsilon_t \simeq$ 125 nanoseconds (rms)

In arriving at an estimate of total system error, the contributions of each nonrandom or bias source are combined in a root-sum-square, while short-term random sources with zero mean value are combined in a root-mean-square computation where the number of observations or measurements provides smoothing for the total period of the satellite pass. For the values given in Tables II and III it is assumed that the interval between time markers provides 50 valid data points per pass. For the relative synchronization system, the system error is computed using the equation

$$\epsilon_T(\text{rms}) = \sqrt{\Sigma(B_s^2 + B_1^2 + B_2^2) + \Sigma\left(\frac{R_s^2}{\sqrt{N_1 N_2}} + \frac{R_1^2}{N_1} + \frac{R_2^2}{N_2}\right)} \quad (1)$$

where B values are nonrandom or bias errors, R values are random, N is the number of valid time marker data points, s denotes a single satellite observed by both users, subscript 1 denotes user number 1, and subscript 2 denotes user number 2. In contrast, for normalized time dissemination the system error is computed using

$$\epsilon_T(\text{rms}) = \sqrt{\Sigma\left(B^2 + \frac{R^2}{N}\right)} \quad (2)$$

where it is unnecessary to distinguish the source of bias or random error. As mentioned with the values listed in Tables II and III, the calculations resulted in expected errors of 100 and 125 nanoseconds for the relative synchronization and normalized time dissemination systems, respectively.

2.   Comment and Discussion of Specific Error Sources in Relation to System Operation and Use

In commenting on specific sources of error we begin with a treatment of the relative synchronization system

and conclude with a coverage of the additional sources peculiar to the normalized time system.

In the tables of errors the specific sources are judged and listed depending on their influence on the system, the criteria being whether its predominant effect is a random variation with a statistical zero mean distribution or a bias when considered over an interval of data acquisition by a using ground station. Certain sources listed as biases are, in fact, random, but the variations occur in such long time spans as to appear as a bias during any one satellite pass. This results in a simplified error analysis that is believed to provide a conservative estimate of system error.

3.   Relative Synchronization System Error Sources

Comment 1: Satellite Rubidium (Rb) Reference — The satellite is provided with a rubidium atomic reference oscillator and epoch marker generator. Its performance is assumed to have a drift rate of 5×10^{-13} per day and a fractional frequency offset error $\Delta f/f$ of 5×10^{-13} (rms) for sampling intervals greater than 100 seconds.

It is assumed that an operational system will use polar satellites at low altitudes such that no less than 12 orbits per day occur; hence, any master ground station will have an opportunity to calibrate the satellite (likewise any slave station will observe the same satellite) within a 12-hour period. Therefore, relative time synchronization can be made with errors due to the Rb reference being typically 5 nanoseconds maximum bias because of aging rate and with a probability of up to 20 nanoseconds randomness because of offset or fractional frequency errors, as estimated from Figs. 1 and 2.

The characteristic of a typical rubidium frequency standard, as a function of sampling time, is shown in Fig. 3 from which systematic drift rate is calculated. Figure 4 gives the comparative performances of several types of primary and secondary standards. There are many literature references which give stability data on frequency
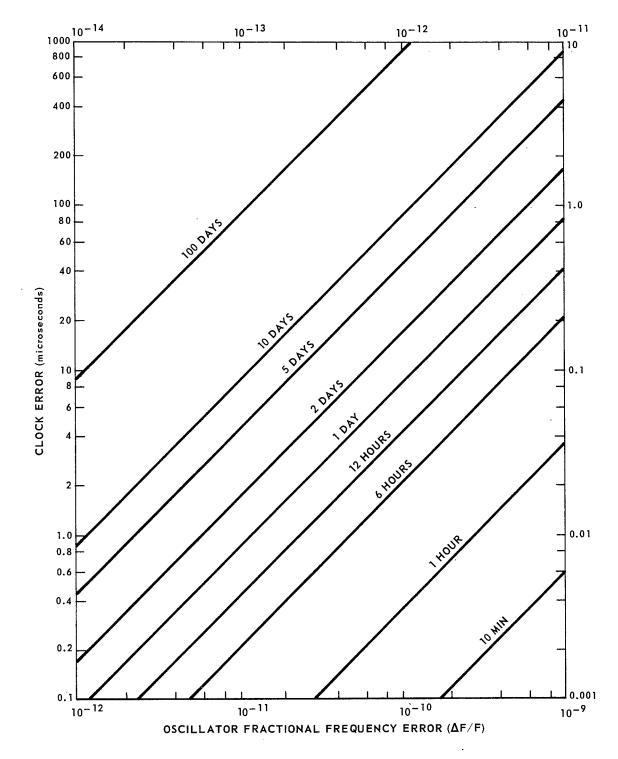
Fig. 1   CLOCK TIME ERROR VERSUS FREQUENCY OFFSET
FOR PERIODS FROM 10 MINUTES TO 100 DAYS
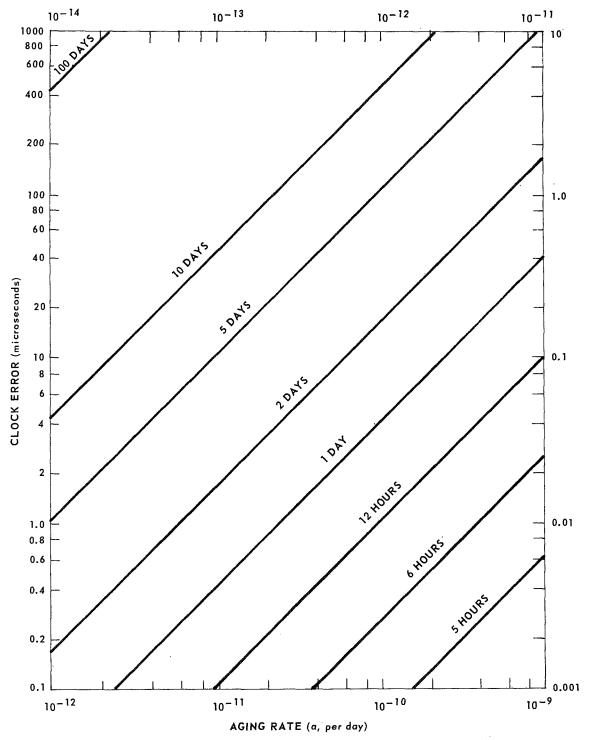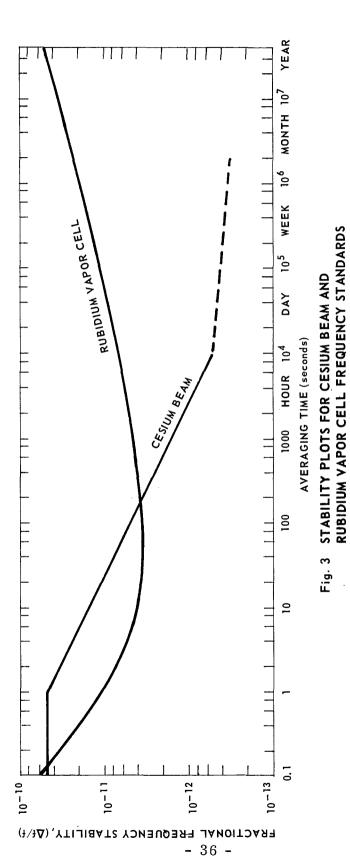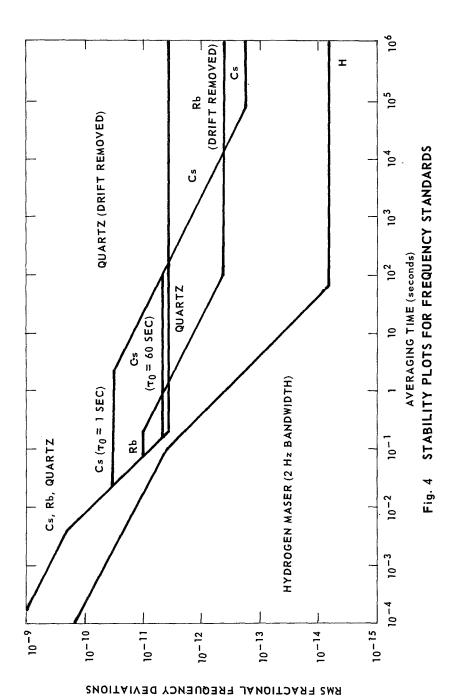
**Fig. 2   CLOCK TIME ERROR VERSUS OSCILLATOR AGING RATE
FOR PERIODS FROM 5 HOURS TO 100 DAYS**

Fig. 3 STABILITY PLOTS FOR CESIUM BEAM AND
RUBIDIUM VAPOR CELL FREQUENCY STANDARDS

Fig. 4   STABILITY PLOTS FOR FREQUENCY STANDARDS

standards (see, for example, Refs. 7, 14, 26, 32, 33, 42, and 48). Note that in this analysis circular orbits are assumed; therefore, relativistic timing drift due to velocity is constant and removable on calibration by the master ground station. If the satellite orbit is elliptical, systems desiring the ultimate accuracy must compensate for relativistic effects (see Refs. 2, 18, and 28).

Comment 2: Satellite Logic and Modulator — The satellite reference oscillator signal is operated on by a countdown divider chain, a waveform logic circuit, and switching type phase modulator. High speed components are suggested. It is estimated that a random jitter of 20 nanoseconds may be expected.

Comment 3: Satellite Transmitter Time Delay Stability — The satellite RF system following the phase modulator includes filtering and transmission line components whose electrical length and transmission time can be affected by environmental factors (for example, temperature changes during satellite eclipse). It is estimated that the shift in transmission time will produce a bias effect and that its magnitude will be no greater than one wavelength of the carrier frequency. In the extreme case at the 150-162 MHz VHF bands, a maximum of about 6 nanoseconds is estimated.

Comment 4: Satellite Position vs Time (see Refs. 15, 28, 29, and 34) — In a one-way (passive) radio system for timing it is necessary to compensate for range or distance traversed by the signal in the propagation path. In the low-altitude satellite system, slant range to the satellite from a ground station is dynamic with large systematic variations during the pass of the satellite through the cone of observation. Operational tracking stations determine the orbital parameters of the satellite from which a computer may calculate range (or time) vs time between the satellite and any other (using) ground station, assuming a standard coordinate system and a sufficient analytical model of the earth's geodesy. Based upon experience to date with geodetic and navigation satellite programs, it is

considered that satellite position vs time will be determined
by improved geodesy and navigation to within 10 meters (30
nanoseconds). For the particular ground station or user
this uncertainty must be considered as a bias.

Comment 5: User's Antenna Position — The deter-
mination of a proper range compensation for timing re-
quires accurate location of the user's antenna as well as
the satellite. In this analysis the user's location is pre-
sumed to be static, i.e., a fixed site installation. The
initial accuracy to which the antenna is located will be im-
proved by statistical averaging of a large number of satel-
lite passes and navigation fixes. The errors will converge
to a bias in position of about 6 meters (20 nanoseconds)
within the standard coordinate system.

Comment 6: Ionospheric Refraction — In propagation
from the satellite to the ground station antenna the radio
wave will be deviated from a straight line path by the refrac-
tive effect of nonuniform distribution of electrons in the
ionosphere. Refraction causes the path traversed by the
radio wave to be longer than the geometric range. It affects
the accuracy of range rate (doppler) measurements and the
transmission time for marker epochs between initiation at
the satellite and reception at a ground antenna.

For a time recovery system of either the relative
synchronization or normalized time dissemination type, the
significance of refraction is that the delays experienced by
signals arriving at a slave station will have a random dis-
tribution relative to the delays experienced by similar sig-
nals arriving at a master or calibrating station. For ob-
servation of the satellite over a particular orbit pass, the
comparative effect at the slave station relative to the mas-
ter is as if a direct bias error exists in time recovery.
Depending upon the instrumentation used, an indirect effect
may also exist in that refraction degrades the accuracy of
satellite position vs time determination which is necessary
for range compensation.

There are several effects (see Ref. 23) on the propagation of radio waves from space to earth caused by ionospheric electrons, each of which is dependent upon the frequency or frequencies of the transmitted signal. For accurate navigation by the doppler shift principle, the effect of primary importance is the ionosphere-introduced change in frequency. For accurate recovery of timing references the effect on group-path delay is of direct importance, while frequency change indirectly influences timing by way of error in navigation computations from which range compensation is inferred.

According to Ref. 23, the analytic expressions describing first-order effects are

Frequency Change
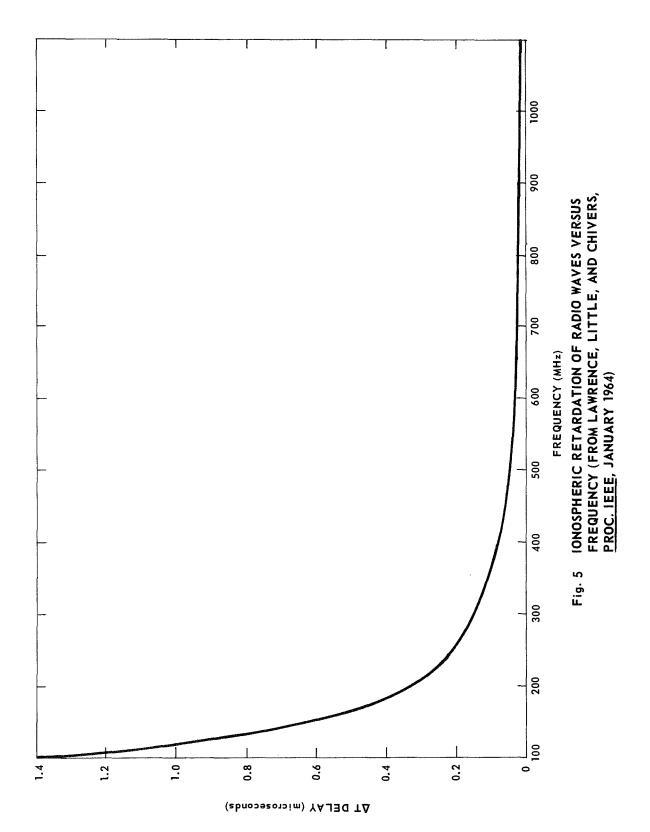
$$\Delta f = \frac{-b}{2\Pi WC} \; d \int_o^S Ndl/dt \qquad \text{and} \qquad (3)$$

Group-Path Delay

$$\Delta T = \frac{b}{W^2C} \int_o^S Ndl \qquad (4)$$

where N = number density of free electrons, C = velocity of propagation in free space, W = angular frequency of the radio wave, $b = 1.6 \times 10^3$ (mks units), and dl = increment of distance along the column O to S traversed by the radio wave from space transmitter to earth receiver.

For a typical case Lawrence has evaluated Eq. (4) for zenithal radio transmissions assuming a 10^{17} electrons/m^2 column giving ΔT = 1.3 microseconds at 100 MHz. As a function of frequency the group-path delay decreases as shown in Fig. 5. The curve suggests that for high timing accuracy a channel frequency of the order of 1 GHz might be chosen. However, it is desirable, even in the low-altitude satellite system, to accept data at lower elevation angles as well as near the zenith.

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Fig. 5   IONOSPHERIC RETARDATION OF RADIO WAVES VERSUS FREQUENCY (FROM LAWRENCE, LITTLE, AND CHIVERS, PROC. IEEE, JANUARY 1964)

In a separate analysis Feen et al. (see Ref. 11) have examined an extreme case of reception at elevation angles at and below 10° with results at least an order of magnitude less favorable than those estimated by Lawrence for single-channel transmissions.

As an alternative to the use of a very high frequency carrier, the system may transmit two coherently related radio frequencies to measure in real time a first-order refraction effect and thereby correct for ionospheric-introduced timing error. The direct use of the two-frequency concept in performing a real-time analog refraction adjustment of timing signals is impractical due to circuit complexity and conflicting system requirements on the choice of frequencies.

In the doppler navigation system, two carriers are coherently generated in the satellite so that

$$f_2 \equiv M f_1 \tag{5}$$

where M is a specific integer or ratio of integers. The values are chosen so that the frequency error due to ionospheric electrons (as shown in Eq. (3)) can be eliminated from doppler measurements. For the modulated signal necessary to define a high accuracy timing epoch

$$(f_2 \pm f_m) \neq M(f_1 \pm f_m). \tag{6}$$

In the doppler system let the first-order refraction frequency change given by Eq. (3) be described at a time, t, by the simple notation

$$\Delta f(t) = \frac{a(t)}{f} \tag{7}$$

so that the received signals are

$$f_r(t) = f\left(1 - \frac{1}{c}\frac{dR(t)}{dt}\right) + \frac{a(t)}{f},$$

$$f_{r1}(t) = f_1\left(1 - \frac{1}{c}\frac{dR(t)}{dt}\right) + \frac{a(t)}{f_1}, \quad \text{and} \tag{8}$$

$$f_{r2}(t) = Mf_1\left(1 - \frac{1}{c}\frac{dR(t)}{dt}\right) + \frac{a(t)}{Mf_1}.$$

By processing filtered signals in the receiving sub-system, cancellation of the refraction error terms is effected, and the equivalent doppler shift is obtained.

Doppler Shift

$$\frac{f_1}{c}\frac{dR(t)}{dt} = f_1' - \left(\frac{M}{M^2-1}\right)\left(f_{r2} - \frac{1}{M}f_{r1}\right). \tag{9}$$

By similar signal processing techniques the doppler shift may be extracted to permit a measurement of a refraction term representative of the cumulative ionospheric electrons along the radio path.

Refraction Term

$$a(t) = f_1\left(\frac{M}{M^2-1}\right)\left(Mf_{r1}(t) - f_{r2}(t)\right). \tag{10}$$

From Eqs. (3) and (4) it is seen that if the refraction term, a(t), is integrated (by a digital counting process) over a sampling interval T a measure of the average group delay for that sampling interval is obtained

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$$\overline{\Delta T} = -\frac{1}{f^2 T} \int^{T} a(t)\, dt \ . \tag{11}$$

These measured values based upon the two-frequency (carrier) method may be used for compensation of ionospheric error in timing.

To establish entries in Tables II and III representing system errors, it will be assumed that the time marker modulation is applied in a single channel RF transmission to a carrier near or above 1 GHz (972 MHz if a geodetic satellite) and that reception is limited to elevation angles greater than 45°. An alternative is also assumed for a navigation system which requires 150 and 400 MHz RF channels. In the coherent two-channel system it is assumed that timing is recovered from the highest frequency channel and that a compensating correction for error due to the ionosphere is derived from measurements of frequency error. Under either set of assumptions an allocation of a maximum bias error of 20 nanoseconds per station will be a sufficient and liberal entry for either the relative synchronization or normalized time budgets.

Comment 7: Tropospheric Refraction — In the lower atmosphere as the radio wave propagates, further refractive bending occurs as a result of climatic factors such as, pressure, temperature, and humidity in the space surrounding the ground receiving station. The tropospheric refraction is independent of the frequency of transmission.

As in the case of ionospheric refraction, the system error in a time transfer is the relative difference between the apparent effects at the master and slave ground stations rather than the absolute delay contribution.

If the satellite has a high inclination orbit, then the apparent timing system error can be minimized by truncation of data restricting acquisitions to elevation angles greater than 10° relative to the horizon. At the computing center it is possible to calculate a compensating function using a standardized model of the atmosphere along with

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local weather data. A first-order correction can be made in advance using standard surface refractivity maps published by the National Bureau of Standards (NBS) which give an average refractivity prediction for each month. A more accurate compensation may be made if each ground station is instrumented to actually measure the temperature, pressure, and humidity at least once during the period of satellite observation.

The typical computation of a correction for timing errors due to climatic refraction (see Ref. 16) can be made beginning with the basic relationship

$$\Delta T_c = \frac{\Delta S}{C} = \frac{1}{C} [\int_P nds - \int_G ds] \qquad (12)$$

where P is the radio path and G the geometric path between the satellite and the ground receiver, n being the refraction coefficient of the troposphere. From the time-varying geometry of the satellite-receiver orientation, the refraction range error (see Refs. 30 and 31) can be evaluated using the equation

$$\Delta s = \frac{10^{-6}N_t}{(h_{tro})^2} \left\{ \frac{1}{3} \left[(r_{tro})^2 - (r_T \cos E)^2 \right]^{\frac{1}{2}} \left[2(r_T \cos E)^2 + \right. \right.$$

$$(r_{tro})^2 \right] - \left[r_T \sin E \right] \left[\frac{2}{3} (r_T \cos E)^2 + (r_{tro})^2 + r_T(\frac{r_T}{3} - \right. \qquad (13)$$

$$\left. r_{tro} \right) + \left[r_{tro}(r_T \cos E)^2 \right] \ln \left[\frac{r_T(1+\sin E)}{r_{tro} + (r_{tro})^2 - (r_T \cos E)^{2\frac{1}{2}}} \right] \right\} .$$

Evaluation of the equation at discrete times T_1, T_2 $\cdots$ T_n requires the solution of the additional equations

$$\omega = \frac{r_o}{r_o th_s} \left[\frac{g}{r_o th_s} \right]^{\frac{1}{2}},$$

$$X_s(t) = \text{arc cos (cos } \omega t) \text{ cos } X_c,$$

$$E(t) = \text{arc tan } [\text{ctn } X_s - \frac{r_t}{r_s} \text{ csc } X_s], \text{ and}$$

$$N_T = \frac{77.6}{T_k} [p + 4810 \frac{e}{T_k}] . \tag{14}$$

In these equations:

C = velocity of propagation in free space,

ω = angular rate of the satellite in rps,

$X_s(t)$ = instantaneous spherical angle between the receiver and the projection from the satellite to the geoid,

E(t) = instantaneous elevation angle measured at the receiver from the horizon to the satellite,

N_T = tropospheric refractivity (as contrasted to the refraction coefficient) at the surface in the locality of the receiver,

r_o = radius from center of earth to geoid,

r_T = radius to the radio receiver at the terrain surface,

h_s = height of the satellite above the geoid,

r_{tro} = radius to the top of the troposphere,

r_s = radius to the satellite,

p = total atmospheric pressure (millibars) at the receiver,

X_c = spherical angle between the receiver and the projection from the satellite to the geoid measured normal to the subtrack at the point of closest geometric approach,

g = gravitational constant at the geoid,

T_K = surface temperature at the receiver in degrees Kelvin, and

e = partial pressure of water vapor (millibars) at the receiver.

The solution given by Eq. (13) for Δs is based upon an atmospheric model wherein it is assumed that

(a) N is continuous in the vertical profile and follows a quadratic relationship approximately,

(b) N is substantially invariant during the time interval of observation of the satellite,

(c) N has no horizontal gradient in the vicinity of a receiver during the time interval of observation of the satellite, and

(d) N decreases to a negligible value at a uniform height above the geoid.

Alternate solutions for Δs are possible depending upon the analytic model chosen to describe the lower atmosphere. To achieve greater accuracy in the computation at very low elevation angles (10° or less) a two-quartic profile model has been used in recent programs (see Ref. 17).

For purposes of this error analysis it is assumed that (as minimum procedure) the coarse correction based on the NBS prediction of surface refractivity, N, can be made. Therefore, it is expected that errors which could be as large as 250 nanoseconds at 10° elevation can, in the aggregate, be reduced to an effective bias timing error of less than 25 nanoseconds.

Comment 8: Ground Receiver Noise Jitter — An important system constraint is the limitation on power available at the satellite which may be apportioned between the RF carrier signal and its modulation. The effective transmitted powers, the channel frequency, slant range, antenna gains, system noise temperature, and the equivalent detection bandwidth establish an SNR for the time recovery mechanism.

Since the system is constrained by very low satellite powers, it will be assumed that digital angular modulation will be used for transmission of time marker epochs. It is also assumed that the carrier frequency and modulation format are universally known so that coherent reception and detection are possible at all ground receiving stations.

For large SNR the error in coherent time epoch recovery can be estimated using

$$T_{\epsilon N} = \frac{40.5}{360 \ f_m \ \sqrt{SNR}} \quad \text{or} \qquad (15)$$

$$T_{\epsilon N} = \frac{81 \ \tau_b}{360 \ \sqrt{SNR}} \qquad (16)$$

where SNR is a numeric ratio, τ_b is a digital bit interval (or chip width), and f_m (= $1/2\tau_b$) is the fundamental modulating frequency. These equations are derived from the signal and noise vector relationships

$$\frac{\theta_N}{57.3} = \sin^{-1} \frac{N_q}{\sqrt{N_q^2 + (A + N_I)^2}} \ . \qquad (17)$$

Here θ_N is the phase deviation due to noise, N_q is a noise component in quadrature with the signal vector, N_I is a noise component in phase with the signal vector, and A is the amplitude of the signal vector.

A typical example of SNR jitter in time recovery is given in Table IV using preliminary GEOS-C parameters. A timing error of 11 nanoseconds (rms) is indicated. In the time transfer systems this error is random with zero mean value.

Comment 9: Receiver Time Delay Uncertainty — The total propagation time between epoch generation in the satellite and epoch detection at the ground includes the time delay of the receiving subsystem. In any precision radio time recovery system it is necessary to calibrate the delay contribution of the receiver. In a system having high accuracy objectives, measurement of receiver time delay has major implications on equipment cost and operation. (A typical ground station configuration is given in Fig. 6, which shows the application of a modulated test signal to the receiver front end for delay calibration.) First there is the problem of adequate resolution of the calibrating instrumentation; then there is the problem of stability of the receiving equipment throughout the data acquisition interval. Instability of the receiving equipment during a data acquisition interval (satellite pass period) can be dependent on environmental factors such as temperature, physical orientation, and acceleration forces and on signal characteristics, particularly signal level and AGC control.

In any time recovery system, delay calibrations would be taken before and after data acquisition with minimum intervening time lapse. It is, however, proposed that significant relaxation can be made both in calibration resolution and in equipment stability by distributing time delay calibrations throughout the full data acquisition interval so that at least one calibration is obtained with each time marker received. If a single calibration is made at each ground station, the uncertainties in measurement will be equivalent to biases, and the expected error contribution to system timing error would be $\sqrt{2}$ times the uncertainty for a single station. However, if a large number of distributed delay measurements are made, one for each time epoch, then a random contribution to system timing error is expected having a zero mean distribution.

Table IV

GEOS-C Radio Link Characteristics

Assume

Satellite Orbit — Perigee 460 nmi, Apogee 620 nmi

Maximum Slant Range — 1850 nmi at 5° Elevation

RF Channel — 324 MHz

Satellite Antenna Gain — 0 dB

Ground Receiving Antenna Gain — +10 dB

Ground Receiver Noise Figure — + 5 dB

Satellite RF Power — 500 MW = +27 dBm

Satellite Modulation Power — + 20 dBm (for phase deviation = 26.5°)

Equivalent Detection Bandwidth ≤ 4 cycles

Compute

Free Space Loss ≤ 153.4 dB

Modulation Power Received, S_m = (-) 123.4 dBm

Noise Density N_0 = (-) 169 dBm/c

S_m/N_0 = +45.6 dB

SNR ≥ +40 dB

Timing Error, $T_{\epsilon N} = \dfrac{40.5}{360 \, f_m \, \sqrt{SNR}}$ = 11 nanoseconds with f_m = 100 kHz.
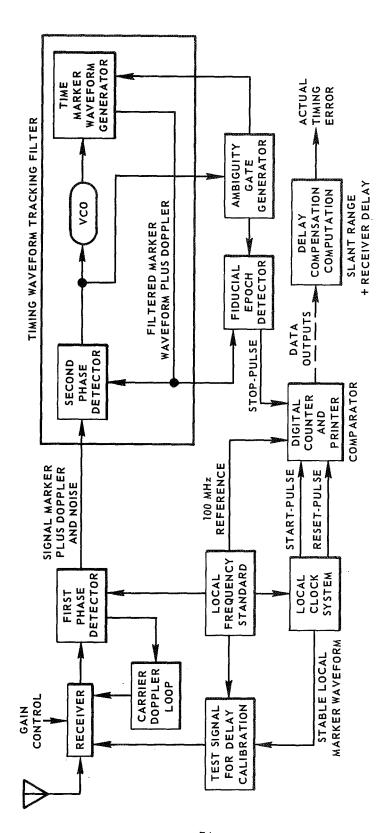
Fig. 6   GROUND STATION FOR HIGH ACCURACY TIME RECOVERY
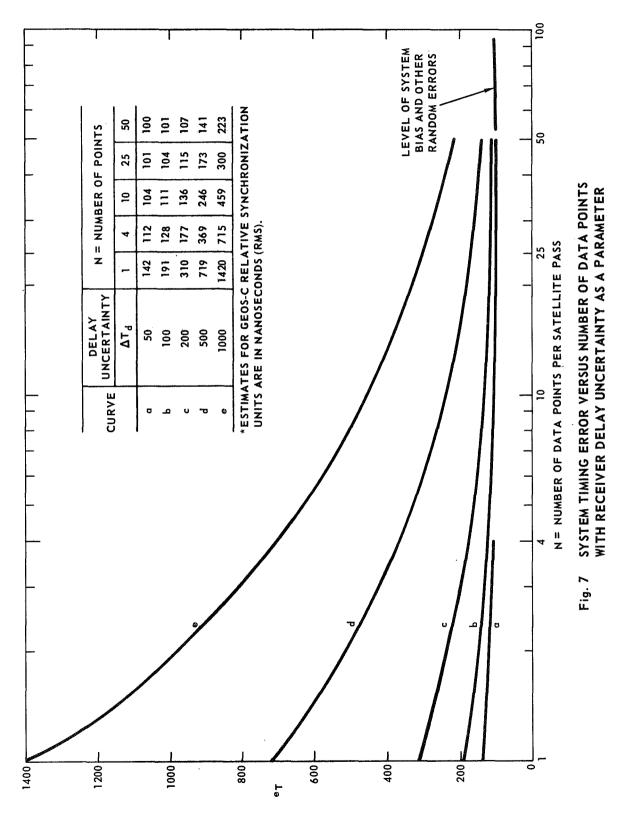
In the system timing error budget developed herein
(100 and 125 nanoseconds (rms) for the relative synchroni-
zation and normalized time systems, respectively) 50 data
points each with a receiver delay calibration to a resolution
of 50 nanoseconds are assumed. If fewer data points are
used and if delay calibration is less precise, then the sys-
tem error will degrade. Data are plotted in Fig. 7 to
show typically the degradation that may be expected.

With 50 nanoseconds receiver delay uncertainty and
50 data points, the system error is effectively that of the
bias and other random error sources. A typical represen-
tation of the opposite extreme is shown in curve (e) of Fig.
7 where a 1 microsecond error in a single delay calibration
completely masks all other error sources. The recom-
mendation for the receiver delay calibration mode of opera-
tion is to require a precision of at least 50 nanoseconds in
calibration distributed throughout the satellite pass with
time markers at approximately every 15 seconds.

Comment 10: Resolution of Receiver "Epoch" De-
cision Logic — With angular (phase) modulation, a time
epoch is represented by a change from phase state "A" to
phase state "B". In the receiving subsystem the epoch
may be identified by a zero crossing detector (ZCD) which
provides an output pulse indicating the epoch occurrence.
To fire the trigger circuit generating the output pulse re-
quires that voltage levels exceed nonzero threshold values.

Commensurate with reasonable circuit complexity
and cost objectives, the resolution of the detector should
be $\tau_b/100$ or 50 nanoseconds for a 100 kHz top fundamental
modulating frequency. This error source is classified in
the random category.

Comment 11: Dynamic Signal Tracking and Phase
Bias — The satellite carrier signal and its modulation are
received with doppler shift which, together with the ex-
tremely low power levels, require phase-locked tracking
to improve SNR and ultimate detection. At low orbital
heights for the satellite (in the 400-600 nmi range) doppler
shift can be as high as 25 ppm.

Fig. 7   SYSTEM TIMING ERROR VERSUS NUMBER OF DATA POINTS
WITH RECEIVER DELAY UNCERTAINTY AS A PARAMETER

Compensation by automatic tracking is required for both the carrier and modulation (see example in Fig. 6) since 25 ppm at a fundamental modulating frequency of 100 kHz is 2.50 Hz (representing 10 microseconds of error each 0.4 second relative to a local fixed 100 kHz signal). The time recovery is relatively insensitive to phase errors in carrier signal tracking since the timing error in that instance is inversely proportional to the carrier frequency.

The significant timing error due to dynamic (doppler) tracking is related to the subcarrier or top modulating frequency. It is assumed that a second or higher order phase-locked loop is used and that a maximum phase error of 1.8° can be achieved with continuous coherent tracking which represents a 50-nanosecond error at 100 kHz. This error source is classified as a bias.

Comment 12: Clock Comparator — After demodulation and recovery of time marker signals at a ground station receiver, use of the epoch requires further signal processing including pulse shaping, ambiguity gating, and triggering errors in the clock comparator. An allowance of 20 nanoseconds random error is credited to these sources in the system error budget.

Comment 13: Data Chopping Error — For a practical 125-nanosecond timing system the output instrumentation must be in the form of a digital counter and printer (or other data storage). It is well known that a digital counter will introduce a chopping or data round-off error or ±1 count ambiguity relative to the counter time base or clocking frequency. This error occurs because the counter reference time base and the input signals being measured are not synchronized.

Specification of a 100 MHz digital counter or its equivalent at each ground station limits this error source to 10 nanoseconds (rms) random.

Comment 14: Local Rb Reference and Clock Drift — The objective of the entire system is, of course, to synchronize and, in effect, calibrate the errors of the local

reference oscillator and clock at each station. For this to be accomplished with great accuracy it is necessary that instability of the local reference be negligible during the period of satellite observation (15 minutes maximum).

Assuming that an atomic reference whose perfor-mance is equal or superior to typical rubidium standards is appropriate and available at each ground station, a random error of about 1 nanosecond is anticipated.

4. Normalized Time System Error Sources

Comment 1: Error Sources Common to Relative Synchronization — Reference to Tables II and III indicates that error sources in the radio path and the user's subsys-tems are not dependent on the basic type of timing system. There are, however, additional sources associated with the satellite and its calibration.

Comment 2: Calibration of Satellite Injection Station to UT — In the normalized time system, UT will be trans-ferred from the national standard to the injection station of the operational network of supporting ground stations that are required for tracking and in-orbit maintenance of the satellite. It is anticipated that periodic time transfer will be scheduled using air transportable atomic clocks by which the injection station clock is maintained within 100 nano-seconds (rms) of the standard reference.

To each user of normalized time this error will ap-pear as a bias relative to UT. (NOTE: A possible system alternative would provide at the site of the national stand-ard a ground station and computing facility for direct mea-surement of satellite clock error after which a command could be sent to the injection station to advance or retard the satellite clock by a specific value and to reset the nor-malization rate if required.)

Comment 3: Satellite Epoch Calibration Via Radio Link — The operational ground support network must track the satellite and determine the error of its clock relative

to UT (for example, see Ref. 25). When proper instructions
are transmitted over a command radio link, the epoch of the
satellite clock is adjusted relative to the UT calibrated in-
jection station local clock. The accuracy to which this ad-
justment may be made in the period of a satellite orbital
pass over the injection station is estimated at 25 nanosec-
onds (rms). To the remote user, the error will have the
effect of a bias in overall system accuracy.

Comment 4: Satellite Normalizer Resolution — The
time and frequency subsystem of the satellite is subject to
drift and offset error of the reference oscillator and a basic
system inconvenience in that the reference oscillator and
system offset frequency specified for the allocated system
channel is generally related to a UT scale by a nonintegral
number. Variations from the exact system offset may also
be expected as a compromise in satellite synthesis of the
required atomic reference frequency (6834 MHz for rubidium).
To resolve these system incompatibilities a special circuit
will be required in the satellite so that time marker epochs
can be generated with a scale in normal units of minutes
and seconds as defined in an agreed-upon time scale. The
normalizer must have quasi-continuous action with incre-
mental steps being imperceptible at the user's station. A
resolution of ±10 nanoseconds is, therefore, specified for
the satellite time normalizer with the error contribution
being in the random category for the system.

5.   Conclusion

An identification and general classification of the
significant sources of error have been presented for rela-
tive synchronization and normalized time dissemination
systems, both of which make use of an orbiting clock in a
low-altitude satellite. Numerical estimates are given for
the specific error sources from which an aggregate system
error in timing was calculated, resulting in 100 and 125
nanoseconds (rms) for the relative synchronization and
normalized time systems, respectively.

III.   MODULATION TECHNIQUES FOR PRECISION TIMING

The transmission of timing references by radio re-
quires modulation having (1) unique epochs that constitute
a definite transition from state "A" to state "B", (2) rise
times for the transitions that are sufficiently short to per-
mit high resolution and accuracy, (3) a waveform structure
that permits identification, without ambiguity, of the fidu-
cial transition, (4) a frequent repetition rate of the fiducial
epochs for user's convenience and for smoothing of statisti-
cal errors, (5) high accuracy inherent within the signal in
terms of calibration, normalization, and stability relative
to atomic time, UT, or other reference, and (6) efficient
utilization of the radio channel (spectrum). In relation to
requirements 4 and 6, it should be noted that, from the
point of information flow, the number of transitions (or
timing data bits) is exceedingly small — on the order of one
every 15 seconds. The accuracy to which the transition
must be determined is, however, very stringent.

In addition to these requirements relating to timing
performance, the modulating waveforms should be derived
with minimum circuitry and with maximum efficiency and
reliability in both the satellite and ground station subsys-
tems. Timing modulation must provide the new high accu-
racy within the constraints of compatibility with primary
and other functional requirements and objectives of the
total satellite systems. The role of timing in the full sys-
tem, its compatibility and complementary interaction with
other system functions, cannot be overemphasized because
the success of the full system will establish the economic
value and feasibility of the program.

A.   CANDIDATE TIMING MODULATION WAVEFORMS

In the general sense there are many waveforms and
modulation techniques available that would be adequate for

high accuracy timing. A thorough discussion of a large number of the possible techniques would be lengthy and would be of dubious value in this report. However, a general outline listing of major concepts may be illustrative of techniques that might apply in particular satellite systems or experiments.

1.   Analog Modulation Concepts

a.   Continuous Wave Multiple Tone Systems

This concept is comparable to the well-known multiple tone ranging technique (see Ref. 36) where epoch is defined by coincidence of the zero phase crossings of coherently related tones. Accuracy is determined by the highest frequency signal, and range ambiguities are resolved by progressively lower frequency components.

Multiple tone modulation examples include single sideband suppressed carrier (SSB-SC) and double sideband phase or frequency modulation (PM or FM). The concepts may be useful in conjunction with radio relay timing synchronizations between cooperative ground stations where the satellite serves as a broadband communications repeater.

b.   Single Tone Phase Reversal System

A simple sinewave modulation is applied to the transmitter with epochs defined by properly phased and synchronized (to a recognized time scale) 180° reversals. The concept may be applicable to (frequency) multiplexed multichannel voice communication systems, where the highest frequency channel is coherently generated and recovered (relative to the carrier).

c.   Pulsed Modulation Systems

There are several possible mechanizations; however, these systems are generally comparable

to radar methods where the pulse repetition rate is less frequent but is accurately slaved to a precise time base. These concepts could be employed in conjunction with satellites having broadband communication repeaters or, in the special case of a geodetic satellite, pulse modulated timing might be derived from an on-board orbiting radar altimeter.

d. Television Systems (see Ref. 43)

The AM waveform of the composite TV signal has features quite useful for high accuracy timing provided that the source transmitter has a quality reference standard. The TV waveform is a specialized case of pulsed modulation. The composite waveform includes vertical and horizontal synchronizing pulses, and, in the case of color transmissions, each horizontal pulse carries a 3.579545 MHz ±10 Hz color synchronizing burst on its back porch.

A high accuracy time synchronization service could be supplied in conjunction with commercial TV transmissions via synchronous satellites which would give coverage to large regional areas of the earth.

2. Digital Modulation Concepts

a. General Types of Modulation

The transmission of information by digital signaling requires a finite set of discrete symbols (or waveforms), at least two for binary and with several waveform states or symbols in M-ary alphabets. Complex digital signaling can be constructed with coded sequences of binary or M-ary waveforms. Modulation of the radio wave itself is accomplished by two or more keying states such as

(1) On-Off Keying (OOK) which is a form of amplitude modulation,

(2) Frequency Shift Keying (FSK) where a unique frequency represents a digital state, and

(3) Phase Shift Keying (PSK) where each unique phase state relative to the unmodulated carrier signal represents a digital character or symbol. Generally, PSK infers binary operation with 0° and 180° representing the digital states. In M-ary PSK the full 360° phase space is divided into M equal parts, the phase center of each part representing a digital symbol.

In the flow of information over a radio channel, the great advantage of digital signaling is that the accuracy of reception is not dependent upon fidelity of waveform recovery in the receiving terminal but is rather dependent only on the probability of correct decisions as to digital state, character, or symbol vs time. Digital signaling is, without doubt, the primary modulation candidate for modern communications and telemetry via or from orbiting satellite subsystems.

b. Coherent Techniques

In electronic systems based upon radio transmissions from satellites, a dominating criterion for selection of a modulation method is its power efficiency. All satellites are power limited both in prime DC power and also in effective RF radiated power, since most lightweight solid-state components have low peak-to-average power ratios. The modulation should, therefore, be chosen to permit the use of simple coherent recovery techniques at the ground stations. Coherent PSK is often the logical choice since it provides the most favorable detection in terms of (digital) bit error rate as a function of SNR within the receiver.

c. Formating the Modulating Waveform

In arriving at a technical design plan (TDP) for the system, which includes timing, consideration must be given to determine whether a complete information channel can be justified for timing modulation alone or whether the channel should be shared with compatible transmissions of time-varying data or message elements. In the event the channel is shared, a format must be defined for the modulating waveform to subdivide the total data stream into a frame, word, and bit structure. The total number of bits in a frame would be organized by information content and would include typically the synchronizing word, the precision high accuracy timing word, identifiers, and data messages. In such an organization only the data messages are variable from frame to frame.

B. MODULATION PROPOSALS FOR LOW-ALTITUDE TIME-NAVIGATION OR TIME-GEODESY SERVICE

A discrete modified M-ary PSK modulation (where M = 3) is currently used in the navigation satellite system for the transmission of information including both message and timing. This modulation technique, amenable to generation and control by digital logic and simple circuitry and capable of high performance, continues as the logical choice for future improved navigation systems. Analog waveforms and amplitude modes of modulation may be immediately discarded as serious candidates on the grounds of circuit complexity, satellite power limitations, and general incompatibility with the primary functions of the satellite system.

For the navigation mission the total data stream is presently subdivided into sequential frames having a duration of exactly two minutes within tolerances of the time normalizer. Each frame contains 6103 data bits with 156 words of 39 bits each plus word No. 157 with only 19 bits.
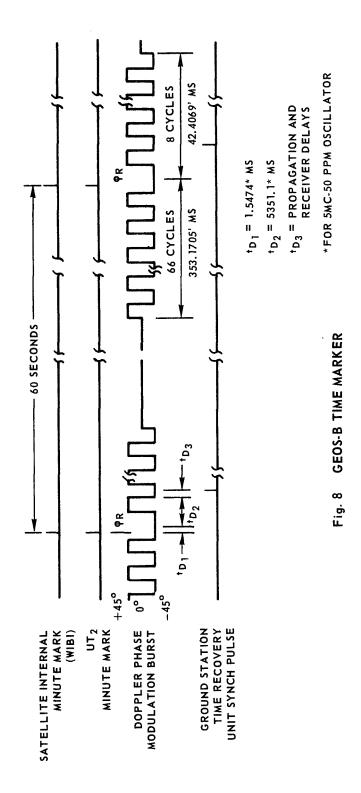
The end of word No. 2 marks fiducial time. Word No. 3 is a beep timing word. To achieve higher accuracy in timing recovery, the task remains to select an optimum modulation that will satisfy current as well as future requirements. The chief candidates for add-on to achieve a multi-function low-altitude time-navigation satellite system include the following:

1.   Compound Time Division Multiplexed (TDM) Waveform

The basic concept of this method is that the satellite message (orbital data, etc.) and timing information are sequentially applied in time to modulate the doppler carrier signals on a periodic basis, repeating every two minutes. Specific assignments are made within the 6103 bit frame format for message and timing data. Phase coherence is preserved throughout the composite waveform. Timing modulation would occupy the entire Word 3 generating markers every two minutes. It is also proposed that timing modulation would occupy bits 37, 38, and 39 in selected words to provide frequent markers at about every 10-15 seconds in order to obtain a good statistical measure of time over the period of the satellite pass. Bits 37, 38, and 39 are reserved for parity check (P), telemetry (T), and time normalizer (10 microseconds) corrections (C). The general concept is described in Appendix B; Fig. 1 of Appendix B shows the typical waveform structures. The concept improves the present modulation of the navigation system without departure from the basic format with minimum impact on satellite hardware.

2.   Simple (TDM) Phase Reversal Waveform

This basic concept for timing has been used in APL-designed satellites including ANNA, GEOS-A and -B, and DODGE. The modulating waveform is a gated square wave having a 180° phase reversal synchronized to a zero crossing point (of the initial pattern) near the end of the timing burst. Figure 8, representing the GEOS-B marker, is typical.

Fig. 8   GEOS-B TIME MARKER

- 63 -
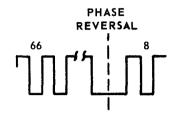
At a receiving ground station, fiducial time is recovered from the noise contaminated signal in a self-acquiring feed forward filtering and logic circuit illustrated in Fig. 9.

In principle, the first part of the timing burst (having 0° phase state) is used to ring up a high Q-tuned circuit. When the burst reverses in phase, the output of the tuned circuit continues at its original phase. An epoch is established by comparing the phase of the filtered output with the input to the tuned circuit and by using the indication of phase reversal to enable recording of the timing pulse from the next cycle of the waveform as generated by the Schmidt trigger. The AM burst detector serves to preclude false time points on noise alone. Since the Schmidt trigger operates from the output of the narrowband high Q circuit, the effective noise bandwidth and accuracy will correspond to that of the tuned circuit. The phase and the AM burst detectors serve as ambiguity resolving devices. The error of the phase detector due to drift, self-bias, or noise loading must not exceed a cycle of the modulation waveform. The recovery requires a separate doppler compensation (tracking) loop to stabilize the received signal at the center of the high Q-tuned circuit.

The possibility of achieving the desired nanosecond accuracy with the concept depends on component and environmental stability and also the extent to which the modulating square wave may be increased in frequency. GEOS-B uses 186.88 pps, while DODGE uses 325.5$^+$ pps for the timing burst.

3.   Randomly Encoded Digital Sequences

Maximum length, randomly encoded binary (or M) sequences have been proposed by various authors and organizations as a modulation technique for accurate timing. The modulation is frequently referred to as pseudo-noise (PN) or as pseudorandom (PR) and involves the spreading of energy into a broad spectrum relative to the bandwidth inherent within the initial information. Demodulation at a remote radio receiver usually involves a
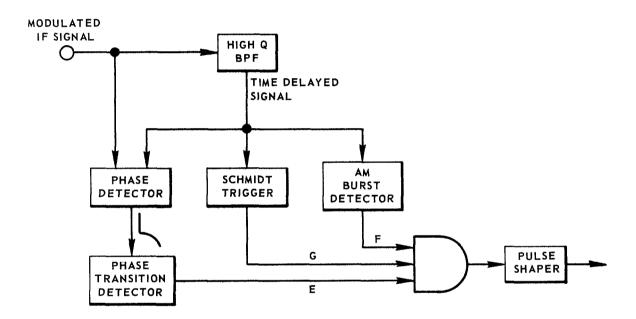
Fig. 9   TIME EPOCH RECOVERY – PULSE PHASE REVERSAL TECHNIQUE

matched filter (with doppler tracking capability if range is variable, as is the case between a ground station and an orbiting satellite). Therefore, the sequence of encoded phase states while randomly distributed in time must be known in advance by all users and ground receiving stations. A keystream generator, similar to that used in the satellite and capable of generating the identical code, is required at each receiving station.

Synchronization in the matched filter of the local random keystream generator to the signal received from the satellite permits the recovery of timing epochs that are coherently keyed to the repetition interval or word rate of the encoded sequence. Synchronization is accomplished by maximizing the magnitude of the output signal of a cross-correlator having the noise-contaminated received satellite signal as one input and the noise-free local encoded signal as the second correlator input. Since peak value detectors lack polarity or direction-sensing, a control problem is evident in achieving stable synchronization. One approach in optimizing the correlation function is to apply dither modulation to the locally generated sequence and to synchronously detect relative to the dither (thereby obtaining directional sensitivity).

If the worldwide timing system is to provide service to the international community, the use of random sequence may be for the purpose of sharing the radio channel with signals from other sources and systems by either (1) the interleaving of timing spectral components between spectra of other modulated signals (see Ref. 49), (2) the coincidence of like spectral components but with code division (i. e., delay-shifted)multiplexing, in the time domain, or (3) the general noncoherence between the timing waveforms and any other in-band signals. As such, the timing system would have a degree of discrimination against incidental or casual sources of interference.

If the low-altitude satellite timing system is to provide service to the military user and if discrimination against the deliberate jammer is required, programmable

sequences and nonreliance on carrier beacons or fixed
spectra must be provided if the random concept is to pro-
vide significant advantage over minimum bandwidth coher-
ent methods. A detailed analysis of intentional jamming
is beyond the scope of this study.

As an example of the application of random se-
quences to timing, the preliminary study reported in Appen-
dix C has considered modifications to the navigation sys-
tem. In the time-navigation system the random sequence
is generated coherently to the regular data message but
with short bit or chip size (τ_b) so that a composite data
message continuous PN waveform may be applied to the
phase modulator(s) of either the 150 or 400 MHz doppler
carriers. The satellite phase deviation vs time is the addi-
tive sum of the message and PN deviations in this illustra-
tion. In the example the PN sequence permits a uniform
distribution of epochs, independently and more frequently
than the regular 120-second frame rate of the 6103 bit
navigation data message.

4.   Auxiliary Channel for Timing

One or more of the above candidate modulation con-
cepts could be used on an isolated channel to provide high
accuracy timing. The auxiliary channel may also serve as
an information carrier for telemetry or for communications.
Several alternative mechanizations are possible. In one
auxiliary channel approach, a third and separate coherent
carrier at 1600 MHz (nominal) or higher, requiring a third
transmitter, would be used with appropriate new modula-
tion. In another approach an auxiliary channel is obtained
more simply by adding a relatively high-frequency continu-
ous wave (CW) square-wave subcarrier as additional phase
modulation of either of the regular 150 or 400 MHz car-
riers. Typically, the square wave must be at a fundamental
frequency greater than twice the maximum encountered
doppler shift and high enough to achieve the desired timing
accuracy. Information is transmitted on the square-wave
subcarrier by phase (delay) shifting according to a digital
code and waveform.
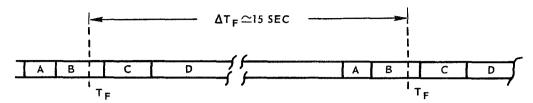
Typical formating for an auxiliary square-wave channel is shown in Fig. 10a and b. The time recovery technique of Fig. 10c is consistent with the general block diagram of a ground station shown in Fig. 6. Accuracy in time recovery is established by the rise time of the filtered square-wave subcarrier from which pulse P_1 is generated. Pulse P_2 is an intermediate ambiguity resolving function which is generated from the phase envelope function during format interval B. Pulse P_3 is a coarse ambiguity resolving function generated by delayed preset counting from the first half-cycle of the phase envelope during format interval B. After the first half-cycle of the phase envelope of the received signal (interval B), the local time marker waveform generator is enabled to reproduce a matching waveform for the remainder of the timing interval (b). The ambiguity pulses P_2 and P_3 enable the application of the fiducial timing pulse at T_f from the high accuracy pulse-stream P_1 to be used as a stop control in a digital counter time comparator.

If the square-wave subcarrier is transmitted as a CW then the ground station can effectively employ active coherent tracking filter techniques as suggested in Fig. 6 to gain large improvements in SNR with the minimum complication in signal acquisition and with a favorable distribution of loop gain under all conditions.
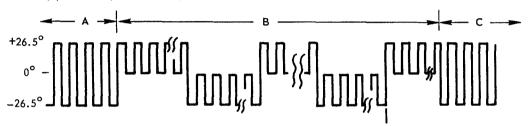
C.   ACCURACY CONSIDERATIONS

1.   Time Scale Normalization
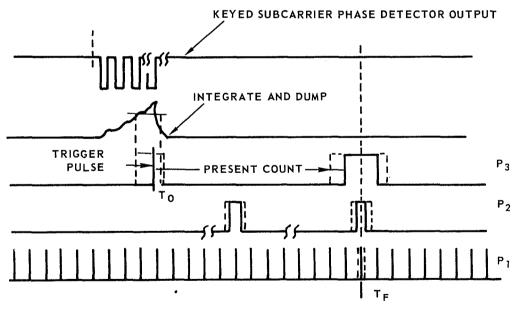
If the satellite time system is to service mobile ground stations and/or stations which must operate independently and passively for security reasons, then the modulation from which the time references are derived must be normalized to achieve high accuracy with reasonable operational procedures. Each epoch must be stable and calibrated to known standard units of time such as X minutes or Y seconds. The epochs of the modulation must be uniformly repetitive in the chosen standard time scale.

A = UNMODULATED SUBCARRIER FOR ALERT

B = PRECISION TIMING BURST (COHERENT)

C = UNMODULATED SUBCARRIER FOR STATION
TIME DELAY CALIBRATION

D = COHERENT SUBCARRIER WITH OR WITHOUT "DATA"

(a) MODULATION FORMATTING

(b) SATELLITE PHASE MODULATING WAVEFORM

P_1, P_2, P_3 ARE INPUTS TO TIME RECOVERY LOGIC

(c) TYPICAL TIME RECOVERY TECHNIQUE

Fig. 10   DIGITAL MODULATION AND RECOVERY TECHNIQUES
WITH AUXILIARY SUBCARRIER

For example, with the 6103 bits per 120 seconds message format of the navigation system, the satellite must be provided with an equivalent oscillator source frequency offset from a nominal 5 MHz by exactly -84.48 ppm. Since the practical satellite reference oscillator is operating at some other frequency either because of drift, a desire to center the RF carrier closer to -80 ppm offset for doppler tracking, or a desire to simplify the lock-up synthesizer in an atomic reference, an active system will be required in the satellite for adjusting the equivalent frequency as a function of time with the resolution of the adjustment being on the order of 10 nanoseconds per step or less.

Resolution of 10 nanoseconds has been shown in the summation of errors, Tables II and III, to be compatible with timing accuracy objectives in the 0.1 to 1.0 microsecond range. For more accurate timing or for applications in navigation by one-way ranging the resolution of the normalization adjustment should be even smaller.

Normalization is performed in the current series of navigation satellites by 10-microsecond pulse deletions (at 100 kHz) within the timing countdown divider chain under control of instructions injected into the satellite memory register. The potential ±10-microsecond error in epoch normalization is clearly incompatible with a total system objective of better than 1 microsecond (rms). An improvement in resolution of the normalization system of two to three orders is desired.

In addition to the pulse deletion technique, other concepts which have been applied to achieve normalization include devices which (1) control a parameter of the basic reference oscillator to change its frequency of oscillation, (2) adjust the subsystem output frequency by means of a programmable variable frequency synthesizer while preserving the natural undisturbed output of the reference oscillator, and (3) adjust the subsystem output frequency by phase addition or subtraction to the natural undisturbed reference signal.

Because of its versatility in operation with either crystal or atomic references, its uniformity, ease of control, and inherent reliability, the phase adjustment method is recommended for both the satellite and ground stations. A detailed discussion of the concept, several mechanizations, and advantages are given in Appendix D.

2.   Satellite Calibration Interval

For an effective worldwide timing system it is essential that accuracy in the generation and dissemination of reference markers from the satellite be maintained for prolonged periods. The satellite is recalibrated at injection intervals occurring every 12 hours at present; however, it would be operationally desirable to extend the interval to a much longer period to counter interference and temporary malfunctions and to effect savings in daily systems operations. The error of each time marker as transmitted will be an algebraic summation of (1) the initial calibration error which is limited by normalizer resolution, (2) an accumulated error due to improper offset frequency of the satellite oscillator, and (3) an accumulated error due to the aging rate of the satellite oscillator. Figures 3 and 4 show data representative of high quality frequency standards. The effects of frequency offset and aging rate on clock time error are shown in Figs. 1 and 2. Reference to these figures suggests that if the cumulative error in satellite timing as transmitted (between calibrations every 12 hours minimum) is to be kept compatible with objectives of high accuracy timing, then, clearly, an atomic reference will be required.

3.   Doppler Shift of Modulation Spectra

The ground station receiving subsystem, if it is to obtain the full accuracy of the timing system, must compensate for the doppler shift encountered by the complex spectrum of signals while propagating through the range-varying radio path from the satellite. A carrier (doppler) tracking loop permits narrowband filtering and signal demodulation against a local reference; however, this is inadequate for high accuracy timing since a residual doppler

shift would be present on each spectral component of the modulation. For example, if the fundamental modulating frequency were 100 kHz and the doppler shift reaches the maximum of 2.5 parts in 10^5, the residual doppler shift would be 2.5 Hz and a zero crossing relative to a local fixed reference would slip one full cycle of the 100 kHz in 0.4 second. Therefore, the reference for detection and decoding the precision time marker must be derived by signal tracking and not from the local reference oscillator. This applies to all modulation concepts, from the simplest phase reversal technique to the most elegant encoded pattern.

When using matched filter cross-correlation demodulation with wideband signals, as in spread spectrum random signaling techniques, a dispersion can be expected between the upper and lower modulation sideband spectra because of refraction by the electron density in the ionosphere and asymmetry of bandpass RF receiving equipment. Asymmetry of equipment is subject to design control; however, to ensure acceptable error in the refraction dispersion between the received signal and the locally generated matched filter waveform the signal bandwidth should not be excessive, and, again, the highest frequency radio channel available should be used for timing.

4.   Resolution of Ambiguities in the Time Marker
        Waveform

Another consideration in the recovery of a fiducial epoch with high accuracy is the resolution of ambiguities present in a waveform having a sequence of many similar epochs that are used for gaining coherence and synchronization. Time recovery logic can be used to resolve such ambiguities; however, a precaution must be taken to ensure that any delayed control to the gating circuits must possess a pulse width and accuracy compatible with the change in propagation time which has accrued between the detection of the ambiguity pulse and the later detection of the high accuracy pulse (see Fig. 10c or Fig. 8 of Appendix A).

For example, in the compound TDM method if the ambiguity pulse is detected at the end of Word 2 and the precision pulse is detected about 3/4 second later near the end of Word 3, there will be a differential time shift due to satellite motion over the 3/4-second interval which varies from 15 microseconds for the satellite at the horizon to 0 microseconds at closest approach (assuming an overhead pass at 600 nmi altitude).

D.   MODULATION CONCLUSIONS

In the selection of modulation to support high accuracy in time recovery from a low-altitude orbiting clock satellite it is clear that digital signaling techniques combined with a coherent PSK modulation and demodulation offer advantages in operation with the poorly received SNR that is characteristic of satellite systems.

The choice of a specific modulating waveform cannot, in general, be conclusively defined for all satellite systems. The specific waveform must be defined within the broad objectives of the total system with due weight being given to the primary system mission, whether it is navigation, geodesy, communications, or data sensing and acquisition. Several alternatives have been described, each of which has potential for application in a satellite timing system.

Of the digital signaling techniques described the phase reversal waveform is the simplest. In the DODGE experiment it is presently achieving better than 10-microsecond accuracies (rms) with a temperature-stabilized recovery receiver of the type illustrated in Fig. 9. Because of component instabilities, filter bandwidth limitations, and SRN requirements it does not appear on preliminary study that this method alone can be improved by two orders of magnitude.

The discretely organized and random modulating waveforms can be encoded with varying degrees of complexity depending on satellite power and bandwidth availability

and compatibility with primary system missions. Generally, for comparable performance, random encoding occupies a wider spectral bandwidth and is therefore limited in the receiver to demodulation by matched filter cross-correlation techniques applied at very low signal levels (near the RF) so that the loop gain and tracking performance become sensitive to both amplitude and phase noise components and to amplifier (IF) gain variations. The discrete code, on the other hand, can be demodulated with the more conventional phase-locked tracking demodulators since the information is basically narrowband (and the IF does not overload due to wideband noise), or the designer, if he so desires, may also apply the matched filter cross-correlation technique at the low level RF mixer.

In the case of a timing experiment on a future geodetic satellite of the GEOS series, one or more of the modulation waveforms could be considered for comparative tests since the 162, 324, and 972 MHz channels will carry only timing modulation. In consideration of future navigation satellites, modification to include an auxiliary information channel (a subcarrier wave on the 400 MHz carrier or a new channel near 1600 MHz) is preferred with either discrete or random encoding. If the auxiliary channel is to serve a dual purpose of timing plus TM or communications, then the discrete encoding with time division multiplexing offers the simplest high accuracy solution.

IV. STUDIES IN SATELLITE MECHANIZATIONS

Among the satellite programs that offer promise in achieving high accuracy in timing from low-altitude orbiting clock systems, the GEOS series of NASA and improved versions of navigation satellites are prominent examples. These are the prime candidates because one-way passive timing requires navigation capability for compensation of the propagation time. Future GEOS satellites can be particularly useful for early experimental proof and testing of advanced orbiting clock subsystems. The Navy navigation satellite program has the support necessary for regular operational service.

A.   TIMING EXPERIMENTS USING GEOS

Time and frequency parameters of GEOS-B are listed in Appendix E. The inclusion of high accuracy timing in future satellites of the GEOS series will obviously have some influence on the detailed parameters and exact mechanization. Tentative plans for GEOS-C call for an inclined orbit of 20° which is less than desired for a global timing experiment; however, useful tests can be performed that will lead to progressive development and qualification of accurate orbiting clock subsystems for inclusion in future satellites. Contingent upon final weight and power allocations for the satellite, the following experiments may be considered for ground stations located in the lower latitudes:

(1) Orbiting-clock transmissions to passive users

(a) Relative time synchronization,

(b) Normalized time dissemination,

(c) Atomic clock mode, and

(d) Crystal oscillator (only) mode.

(2) Master ground station via one-way satellite relay to passive slave users.

(3) Simultaneous two-way satellite relay synchronizations between a master and a slave station.

The radio relay experiments of (2) and (3) would use the unified S-band transceiver which is normally used for an alternate measurement of satellite range and range rate relative to a ground station. While the primary experiments pertain to the orbiting clock transmissions to passive users, the simultaneous performance of radio relay experiments would permit separation and evaluation of certain error sources in the special case where at least two ground station clocks have simultaneous radio visibility of the satellite. A generalized summary of a GEOS-C timing plan is presented in Appendix F.

B.   SATELLITE DESIGN CONSIDERATIONS AND
      EXAMPLES

An integrated design of the total satellite time and frequency subsystem will be required for each space program, whether it is GEOS, NAVSAT, or other system. The inclusion of an atomic reference in the advanced satellite design will have a major impact on the basic synthesis plans. The mere repackaging of an atomic clock design intended for ground-based applications is likely to be insufficient as a satellite subsystem. Uncertainties in performance of atomic references operating in the space environment remain to be clarified by experiment. The selection of a particular atomic reference requires more data on operational reliability, life, and stability than was available during the course of this study. At the present time the chief contenders for space flight in the near future are the rubidium (Rb) absorption cell and the cesium (Cs) beam resonator.

A problem is foreseen in obtaining a simple efficient design because of the inherent decimal relationship

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between the atomic reference frequency and both the system RF channel frequency allocation and a standard time scale having repetitive epochs at an integer number of seconds, minutes, etc.

If the navigation system becomes a vehicle for high accuracy timing and if the satellite uses an atomic reference, consideration must be given to potential system degradation caused by spectrum overlap of the system data modulating waveform about the (dither) modulation frequency that is required for servo slaving of the crystal oscillator to the atomic reference. As presently constituted the RF carrier signals are modulated by a waveform having frequency components extending from the subaudio region to at least 800 Hz. The dither frequency for servo control of the atomic standard is typically about 80-150 Hz. Care must be taken to minimize any residual dither modulation of the crystal oscillator since its output is frequency-multiplied by a factor of 80 to obtain the RF output signal.

Other systems whose minimum carrier modulating frequency (either the basic information wave or a subcarrier) is on the order of a kilohertz or more will be less sensitive to this type of problem.

1.   Control Characteristics of Atomic References

The physical principles and operation of atomic references (see, for example, Refs. 4, 14, 26, and 42) are beyond the scope of this study; however, it is useful to recall the general characteristics of the rubidium and cesium references in connection with combining the stabilization feedback circuits of the atomic standard into the satellite time and frequency synthesizer subsystem. The designer of the integrated satellite system might consider alternate feedback paths for stabilizing frequency including (1) direct feedback from the output of the slaved crystal oscillator, (2) feedback from an intermediate frequency in the system transmitter multiplier chain taken prior to the (information) modulator, and (3) feedback from an information modulated signal taken at or near the highest RF frequency of the transmitter. The motive for considering these possibilities

is twofold: (1) to include as much of the system within the control loop as possible to obtain maximum stabilization and smoothing of the output signal, and (2) to minimize the total circuitry required, thereby saving weight and prime power and increasing the total system reliability. The extent to which the feedback point can be advanced toward the system RF output depends on compatibility of the signals with the atomic reference control characteristics, which are shown schematically in Fig. 11.
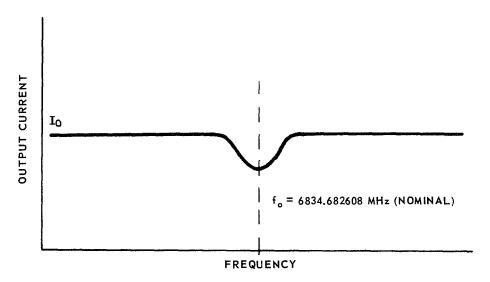
The control characteristic for either rubidium (Fig. 11a) or cesium (Fig. 11b) suggests that if the feedback signal, after multiplication to reach the microwave reference frequency, retains a high carrier-to-sideband ratio, then, indeed, it may be possible to enclose the entire system within the control.

References 3, 5, and 20 indicate that for certain types of atomic references the satellite designer may have options in selection of specific modulation for the crystal oscillator control servo. The options available include
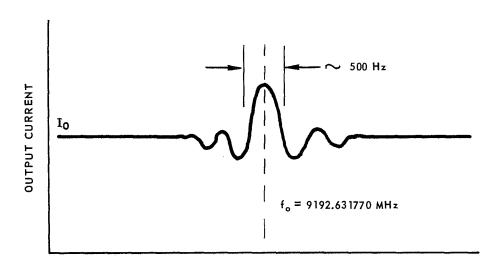
> (1) Independent sinewave modulation derived from separate audio oscillator,
>
> (2) Square-wave modulation derived either independently from a separate multivibrator oscillator or taken from the main satellite clocking countdown divider chain, and
>
> (3) Dual-purpose digital signaling using the satellite information waveform for control of the atomic clock as well as for modulation of the system RF output. This option assumes, of course, that the system carrier is audio waveform modulated (as is the case in the Navy navigation system).

2.   The Frequency Assignment of the RF Channel

The frequency of the signal received by a ground station from transmission by a low-altitude satellite is the frequency transmitted plus or minus a doppler shift due to the rate of change of slant range

OUTPUT CURRENT

I_0

$f_o = 6834.682608$ MHz (NOMINAL)

FREQUENCY

(a) RUBIDIUM (Rb) ABSORPTION CELL

OUTPUT CURRENT

I_0

$\sim$ 500 Hz

$f_o = 9192.631770$ MHz

(b) CESIUM (Cs) BEAM RESONATOR

Fig. 11   CONTROL CHARACTERISTICS OF ATOMIC REFERENCES

$$f_r = f_t \left(1 - \frac{1}{c} \frac{dR}{dt}\right) \tag{18}$$

where refraction and other anomalies are ignored. At satellite rise above the horizon, dR/dt is negative and $f_r >$ f_t. At the point of closest approach $dR/dt = 0$ and $f_r = f_t$. At satellite set on the horizon dR/dt is positive, hence $f_r < f_t$.

In the geodetic and navigation satellite systems the objective is to measure the doppler shift

$$f_d = \pm f_t \left(\frac{1}{c} \frac{dR}{dt}\right) \tag{19}$$

with accuracies in parts in 10^{11} or better. In order to maintain sufficient accuracy in the digital frequency counter instrumentation, it is necessary to provide an offset in frequency between the satellite and ground station oscillators so that the frequencies counted never change polarity and also have a large value (cycle count) during the counting interval.

In the geodetic and navigation satellite programs the offset has been provided always in the satellite oscillator subsystem because there are relatively few satellites while there are many ground receiving stations. The geodetic satellites are offset to the low side by 50 ppm with a tuning range of up to ±19 ppm. The navigation satellites are offset to the low side by 80 ppm with a tolerance of ±5 ppm. Since much has been expended in the user's receiving equipment, these offset constraints must remain for the primary transmission channels in the future, at least for the regular RF channels.

In advanced systems of the future it is therefore anticipated that some circuit complication will be required in the satellites, since the atomic reference frequencies,

9192.631770 MHz for the cesium beam and 6834.682608 MHz (approximately) for rubidium vapor cells, cannot be related to offsets near the nominal values by simple integral multiplying ratios.

3.   Examples of Satellite Time and Frequency Concepts

A number of block diagrams have been generated to illustrate the approaches to obtaining degrees of combined synthesis of frequencies and signals in the satellite. GEOS and navigation satellites are used as being representative.

a.   GEOS-C with Rubidium Reference

Figure 12 illustrates a synthesis technique applicable to relative synchronization timing with a rubidium absorption cell reference. A separate audio oscillator is used for detection and control of crystal oscillator drift from the atomic reference. Using parallel feedback of signals from the satellite doppler transmitter chain, it is possible to achieve stabilization of the output at an offset of -49.3 ppm compared to the system design center of -50 ppm.

In the GEOS satellites the coherent 162, 324, and 972 MHz doppler channels are conventionally modulated with timing only; TM is applied to the noncoherent 136 MHz channel. Timing modulation contemplated for GEOS initial experiments may be generated by a coherent clock divider without normalization to permit high accuracy in relative synchronization of ground stations.

The output of the stabilized crystal oscillator is also applied to the memory, control, and TM subsystems. Normalized time is also broadcast from the 136 MHz channel together with the TM data. The 1365 bit per minute data and timing formats of GEOS-B are expected to be used without alteration in order to service present equipments in the field via the 136 MHz telemetry channel.
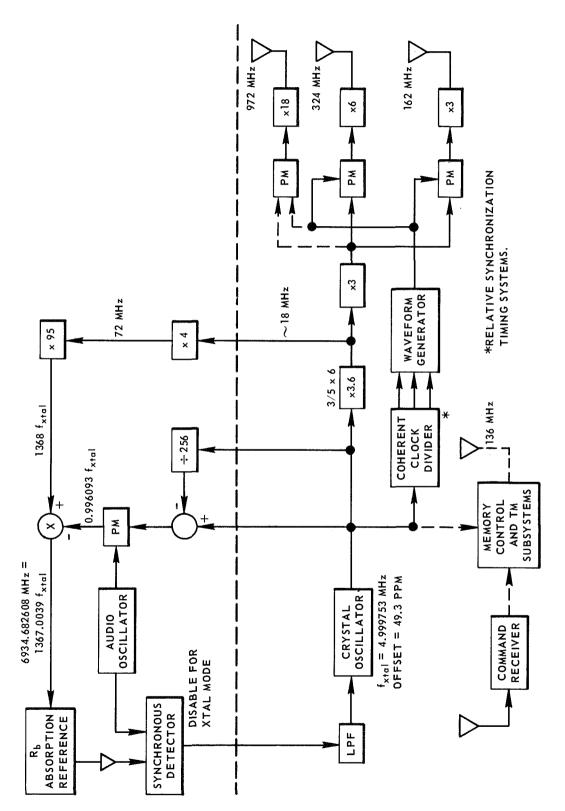
Fig. 12   GEOS-C WITH RUBIDIUM REFERENCE (TYPICAL SYNTHESIS PLAN)

On command a crystal-only mode of operation can be obtained by de-energizing the circuits above the heavy broken line shown in Fig. 12.

b. GEOS Satellite with Cesium Reference

Figure 13 illustrates a combined synthesis approach assuming the availability of a cesium beam reference. With the operations shown, the cesium frequency is synthesized with a system offset of -49.94 ppm compared to the -50 ppm design center for GEOS. The comments made in reference to Fig. 12 for rubidium generally apply.

c. NAVSAT with Rubidium Reference

Figure 14 is comparable to Fig. 12 but is for the application of the rubidium cell to the navigation satellite system which has a design center of -80 ppm for the transmitted coherent carrier signals. The tabular inset gives optional feedback multiplier and divider ratios which approach the design center. The illustration shows application of a sinewave audio oscillator for stabilization of the crystal oscillator to the atomic reference.

The timing in the navigation system requires normalization to the 6103 bits per 120 seconds format. The time normalizer circuit must therefore accept the crystal oscillator input and generate a reference, f_c, at a precise frequency offset by exactly -84.48 ppm. During injection, signals received via the command receiver load the memory with message data to be transmitted in 2-minute frames until the next injection. Instructions are also received to calibrate either in real or delayed time the operation of the normalizer to keep timing signals and epochs within tolerances.
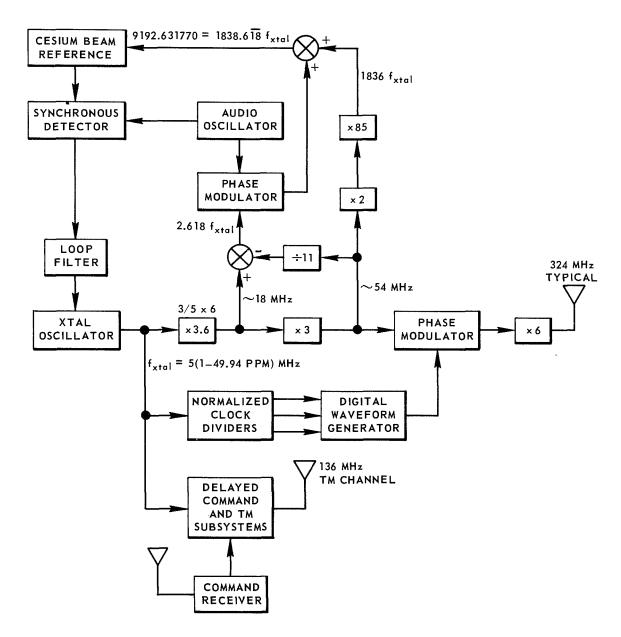
Fig. 13   GEOS SATELLITE WITH CESIUM REFERENCE
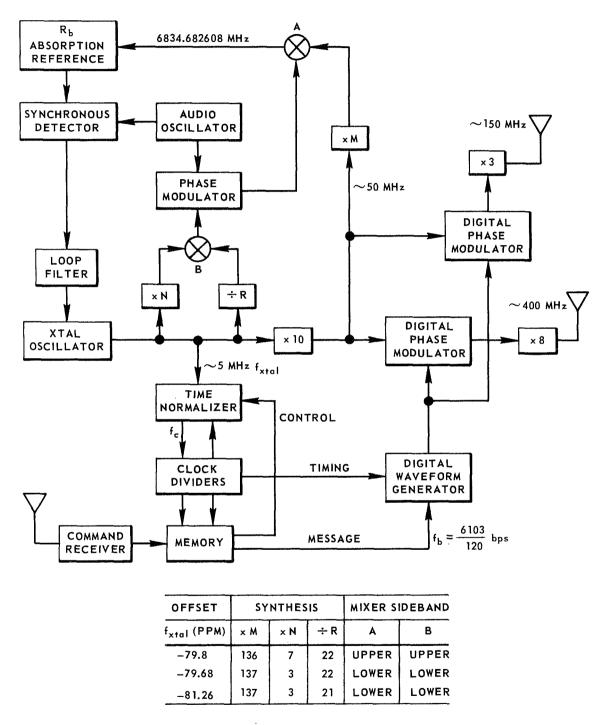
Fig. 14   NAVY NAVSAT WITH RUBIDIUM REFERENCE AND TYPICAL SYNTHESIS

OFFSET	SYNTHESIS			MIXER SIDEBAND	
f_{xtal} (PPM)	× M	× N	÷ R	A	B
−79.8	136	7	22	UPPER	UPPER
−79.68	137	3	22	LOWER	LOWER
−81.26	137	3	21	LOWER	LOWER

d.   NAVSAT with Independent Audio Control Oscil-
lator and Cesium Beam Reference

Figure 15 shows an approach that is the same as
that for rubidium as illustrated in Fig. 14. With
this typical configuration the crystal oscillator and
transmitted carrier frequencies are stabilized to
-79.94 ppm relative to the -80 ppm design center,
while assuming a cesium reference frequency.

e.   NAVSAT with Square-Wave Modulation of
Atomic Reference

Figure 16 illustrates only the technique in an
orbiting atomic clock of applying square-wave con-
trol modulation to control and stabilize the crystal
oscillator to the cesium reference.   According to
Ref. 3, control of cesium clocks by means of fre-
quency-impulse modulation has the following advan-
tages over sinewave analog:

"(1)   Any differential phase error between the
RF cavities can be measured and corrected.

(2)   The modulation on the RF signal is easily
generated with very low distortion.

(3)   The frequency at which the loop stabilizes
is insensitive to changes of modulation level.

(4)   Since the period of square-wave phase mod-
ulation need be no longer than that required to
accommodate the resultant beam-tube transients,
higher modulation rates than permissible in
other systems can be used.   This fact is par-
ticularly helpful for long beam tubes."

Of these advantages, (2) and (3) would certainly be
important in a satellite application.   The automated
self-tuning control implied by (1) should be consid-
ered in the satellite design in terms of its possible
functional and reliability features.

f.   NAVSAT with Common System/Atomic Refer-
ence Modulation

If the advantages of square-wave control modu-
lation are in fact confirmed, then, in the case of
the navigation satellite and other systems having
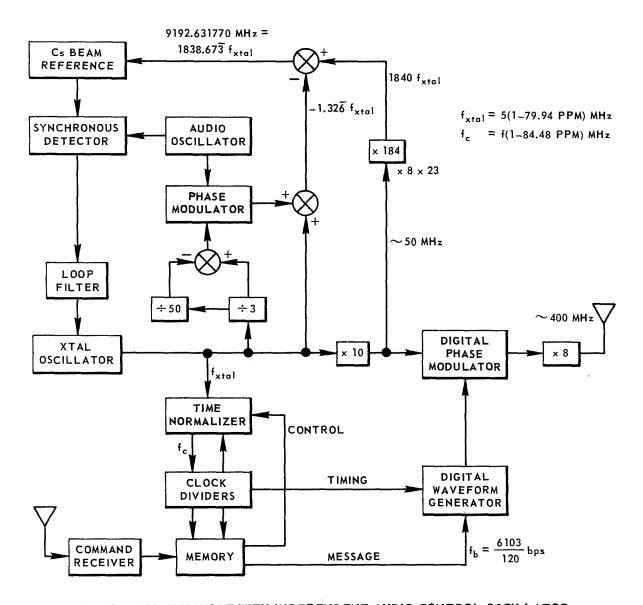
Fig. 15   NAVY NAVSAT WITH INDEPENDENT AUDIO CONTROL OSCILLATOR
AND CESIUM BEAM REFERENCE
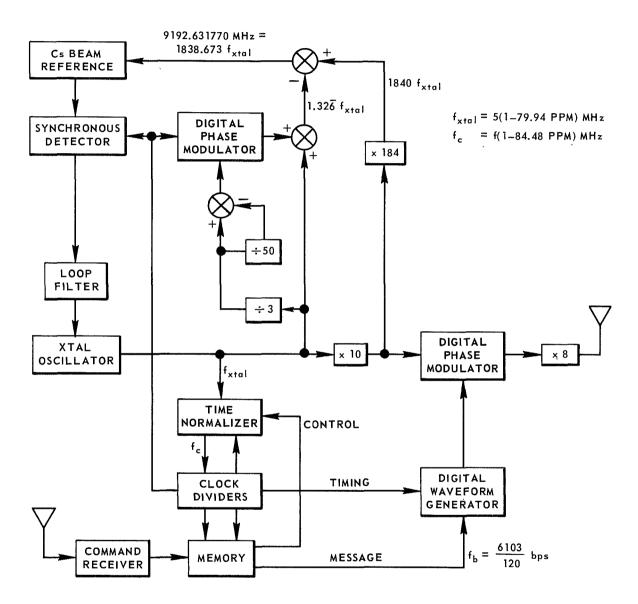
Fig. 16   NAVY NAVSAT WITH SQUARE-WAVE MODULATION OF ATOMIC REFERENCE
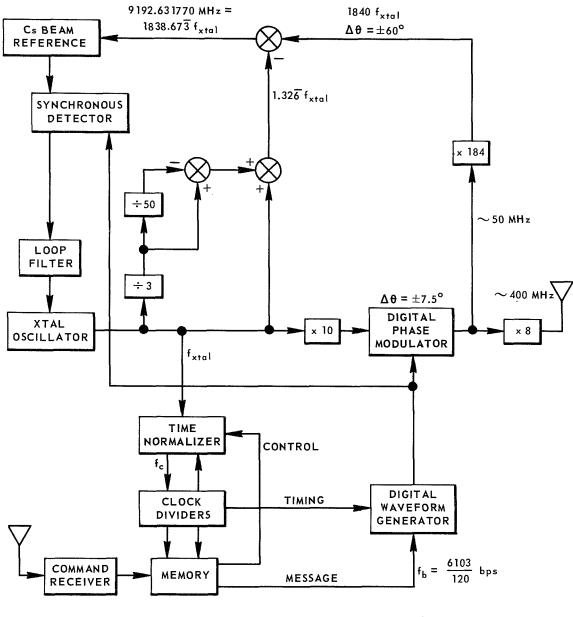
audio digital signaling of the transmitted carriers, overall system simplification may be possible by using feedback from a point following the system Digital Phase Modulator (DPM). The digital modulating waveform is also used to drive the synchronous (control) detector at the output of the cesium beam reference.

In addition to the advantages of frequency impulse modulation and simplification of hardware by elimination of an audio oscillator and phase modulator, this general concept would seem to offer a further advantage in that ground station recovery of the digitally modulated RF provides a monitoring technique for the control loops as well as message recovery.

In the general application of combined system/atomic reference modulation techniques, care must be exercised to preserve a satisfactory carrier-to-sideband ratio at the microwave atomic reference frequency. In the example given in Fig. 17 the square-wave phase deviation at the 50 MHz modulator is $\Delta\theta = \pm 7.5°$. After multiplication ($\times$ 184) to microwave, the deviation is $\pm 1380°$ which is equivalent to $\pm 300°$ placing the carrier vector with modulation at $\mp 60°$ (which is the inverse of the 400 MHz output). With the doublet bit structure of the navigation system modulation (see Fig. 1 of Appendix A) the average carrier-to-sideband power is +2.2 dB.

g.   Illustration of NAVSAT with Hypothetical Hydrogen Maser Reference

With the present level of development (see Ref. 45) Fig. 18 is purely academic; however, it is inserted to generally illustrate an ultimate orbiting clock mechanization where the radiated RF output signal is stabilized by true phase locking to the atomic reference. In constrast with the rubidium and cesium references of the prior illustrations, stabilization is limited by frequency control.

Fig. 17   NAVY NAVSAT WITH COMMON SYSTEM/ATOMIC REFERENCE MODULATION
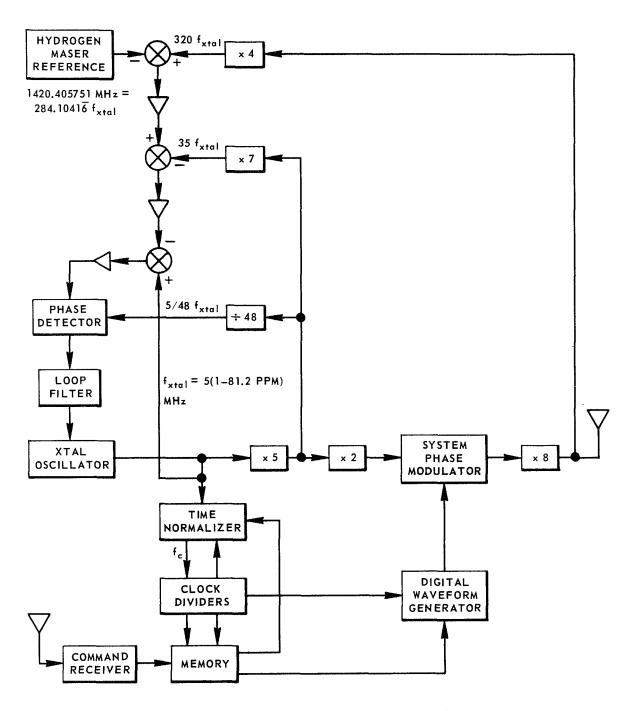
Fig. 18   ILLUSTRATION OF NAVY NAVSAT WITH HYPOTHETICAL
HYDROGEN MASER REFERENCE

V. CONCLUSIONS

A general survey of the application of artificial satellites to achieve accurate worldwide timing has been performed in this study. It is the opinion of the author that at the earliest possible date hardware development and experimental testing of specific subsystems should be initiated in conjunction with plans to implement accurate timing via a specific satellite program.

Other specific conclusions which are drawn and appear justified by the study include the following:

1. The findings from the survey of prior experiments and current systems are (from Appendix A):

   a. Two-way radio relay experiments have already reported intercontinental synchronizations of ground clocks to better than one microsecond.

   b. Orbiting one-way clock systems have not been designed for accurate (microsecond or better) timing; however, they have been in operation for several years and offer potentials for large improvements in accuracy.

2. User requirements for timing can be divided into two classes:

   a. Those that may be satisfied by relative synchronization between cooperative ground stations with interstation communications being permitted.

   b. Those that are satisfied only by reception of normalized calibrated references with station autonomy and prohibition of station communications (transmitting).

3.   Three specific systems were compared:

    a.   A low-altitude orbiting clock,

    b.   A near-synchronous orbiting clock, and

    c.   A near-synchronous radio relay satellite.

On the composite weight of advantages and disad-vantages, the low-altitude orbiting clock has supe-rior potential as a global system and provides accu-rate timing service to large numbers of passive users.

4.   Performance evaluations were made of low-altitude orbiting systems to generate estimates of system accuracy assuming moderately sophisticated equip-ment with data editing, qualification, and process-ing.   Global operations were assumed with up to 12 hours between satellite calibrations.   The results for fixed ground stations were the following:

    a.   For relative synchronization systems the rms accuracy was 100 nanoseconds per pass, and

    b.   For normalized time dissemination the rms accuracy was 125 nanoseconds per pass.   A more vigorous analysis, tighter specifications on subsys-tems, and careful data handling can permit growth to even better accuracies.

5.   In the area of modulation techniques for accurate timing, the supervening requirements of the multi-mission satellite systems will limit the choice and exact parameters.   Allocation of a complete satel-lite system or even a full modulation channel solely for the purpose of timing may not be justified on technical or economic grounds.

However, without doubt, an orbiting clock sys-tem should use digital signaling techniques to ob-tain maximum SNR improvement, circuit simplifi-cations, and reliability.   In the case of GEOS pro-grams a discrete binary sequence on the coherent

doppler channels is preferred. In the case of the navigation system the author prefers a discretely encoded binary sequence on an auxiliary information channel.

6.   In the orbiting clock satellite mechanization it is possible and profitable to combine in an integrated single design the frequency synthesis requirements of both the atomic reference and the satellite system.

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VI. APPENDIXES A – F

NOTE: These appendixes are supplied for background in-
formation. In cases of conflict, the body of the report is
to be considered as controlling.

APPENDIX A

EARLY HISTORY OF TIMING VIA SATELLITES

The concept of synchronization and/or calibration of remotely dispersed clock and timing systems by means of radio transmissions from satellites is not new. Several experiments and demonstrations have been performed but, as yet, there is no operational service available which has high inherent accuracy. Table A-1 lists some of the well known satellite programs which have supported experiments in point-to-point clock synchronization by two-way radio relay. The table also lists satellite programs which have included orbiting clocks from which timing has been disseminated as a secondary function without particular emphasis on high accuracy. Briefly, some of the significant features of these experiments and programs are as follows:

1.   Telstar Experiment — (August 1962) (see Ref. 40)

(a) Purpose: To relate the United States Naval Observatory (USNO) and the Royal Greenwich Observatory (RGO), United Kingdom clocks.

(b) Stated Accuracy: -1 microsecond.

(c) Type Experiment: Series two-way cooperative test from Andover, Maine, via Telstar to Goonhilly Downs, U.K.

(d) Techniques: Pulsed signals 5 microseconds long at 10 pps; visual comparisons to LORAN-C; channel frequencies near 6390 and 4120 MHz.

2.   Relay Experiment — (February 1965) (see Ref. 24)

(a) Purpose: To determine synchronization accuracies between transoceanic ground stations — USNO and Radio Research Laboratories (RRL), Japan.

(b) Stated Estimated Accuracy: ±0.1 microsecond each pass.

Table A-1

History of Timing via Satellites

Radio Relay Satellite Experiments

(1)   Telstar — August 1962

(2)   Relay — February 1965

(3)   ATS — June 1967

(4)   Lunar Orbiter — October 1967

Orbiting Clock Systems (APL/JHU)

(1)   Navy Navigation (TRANSIT) — June 1960-19____ ,
       Operational July 1964

(2)   ANNA — October 1962

(3)   GEOS — November 1965, January 1968

(4)   DODGE — July 1967

(c) Type Experiment: Simultaneous two-way cooperative test from Mojave, California, via Relay II to RRL, Kashima, Japan.

(d) Techniques: Pulsed modulation signals 11 and 5 microseconds long at Mojave and Kashima, respectively, at rates of 100, 1000, and 10,000 pps; visual comparisons using oscilloscopes and photography with system checks by portable cesium-beam atomic clocks and VLF transmissions; channel frequencies near 1725 and 4170 MHz.

3.   ATS Experiment — (June and July 1967) (see Refs. 13, 19, and 22)

(a) Purpose: To demonstrate synchronization of widely separated clocks using simple, low cost VHF equipment (in contrast to microwave) in conjunction with a transponder in a near-synchronous satellite.

(b) Typical Accuracies: 4 ±2 microseconds (rms) for a nominal receiver SNR at 26.6 dB.

(c) Type Experiment and Techniques: Sequential one-way measurements made at master station. First the master station measures the advance required in master station transmitted epochs to achieve coincidence at the remote slave station between the received signal and the slave clock. Second, the master station measures relative to the master clock the differential time interval to the reception at the master station of epochs transmitted from the slave station. A voice communications channel via the satellite was used to coordinate the test. Tone burst FM modulation was employed. A 10 kHz sinewave was initiated at zero phase first at 1 bps to remove ambiguities, then at 100 bps for accuracy and resolution; burst durations of 5×10^{-3} and 0.5 second. Channel frequencies were 149 and 135.6 MHz. Stations were located in Colorado, California, and Hawaii.

4.   Lunar Orbiter Experiment — (October — December 1967) (see Ref. 50)

(a) Purpose: To calibrate clocks at Manned Space Flight Network (MSFN) stations for the Apollo Program and measure errors of the HF-WWV method by means of correlation between master and slave station's receptions of the range code transponded by the Lunar Orbiter space probe.

(b) Accuracy: The estimated (additive) error budget was ±3.82 microseconds.

(c) Type Experiment and Techniques: A relative intrastation cooperative time synchronization experiment uses a lunar space probe as a relay transponder; the modulation concept uses a time-referenced digital ranging code; measurements were made with time interval counters; the master station transmits and receives back from the satellite the digital code which was time-referenced to the master clock. Slave stations receive only the transponded code for measurement relative to their own local clocks. With knowledge of the location of the satellite and each receiving station it is possible to compute the error of each slave clock. LORAN-C and flying clocks were used as references for comparison.

5.   Navy Navigation (TRANSIT) System (Prototype 1960, Operational 1964) (see Refs. 10 and 46)

(a) Purpose: To provide reference signals from low-altitude satellites that are used by submarines, ships, and others in providing all-weather global high accuracy navigation fixes. As a secondary function each satellite also transmits timing epochs which are normalized in scale and are calibrated to UT by a ground support network.

(b) Accuracy: The system requirements for timing are very modest and allow up to a 500-microsecond error relative to UT. According to Ref. 10 the

current system and management practices are
achieving about 40 microseconds (rms) at the OPNET
ground stations (which have high gain antennas). As
an absolute time reference, accuracy is inherently
limited by a -10-microsecond pulse deletion norma-
lizing circuit in the satellite epoch generator.

(c) Type system: Normalized time dissemination
worldwide from the orbiting satellite clock; inde-
pendent passive users.

(d) Technique: Timing epochs are transmitted
periodically every 2 minutes using a digital data and
beep word format with phase modulation of coherent
carriers. Doppler shift of the carriers plus timing
and orbital parameters of the satellite obtained from
the transmitted digital data format permit accurate
navigation. After computation of position of both
satellite and user, then (range compensated) high
accuracy time recovery is theoretically possible.

6.   ANNA 1B Satellite (October 1962-June 1965)
        (see Ref. 33)

(a) Purpose: To determine precisely the location
of land masses relative to each other and the earth's
center of mass, and to determine the detailed struc-
ture of the earth's gravitational potential. Inciden-
tal to these system objectives, the satellite trans-
mitted from an orbiting reference oscillator and
waveform generator markers which were useful for
timing by means of cooperative ground station syn-
chronizations.

(b) Accuracy: A cursory check made between two
nearby ground stations indicated an error of 250
microseconds. The major source of error was
attributed to the ground recovery equipment.

(c) Techniques: The satellite subsystem incor-
porated a high quality crystal reference oscillator
from which combinations of coherent carriers and

phase modulating time bursts were derived. The carriers were used for fixed ground station tracking from which orbital and geodetic parameters are computed. Time transfers between ground stations were possible by relative synchronization to the satellite signals. Marker epochs were coherent with carrier; no attempt was made to scale or calibrate to UT. Epoch is identified by phase reversal of the square-wave modulating function near the end of the timing burst.

7. GEOS Satellite (November 1965 and January 1968)
    (see Refs. 9, 21, and 38)

(a) Comments for ANNA-1B apply except that the satellite time and frequency subsystem incorporated a two-level pulse deletion type of clock normalizer that was controlled by a delayed command (memory) to hold every 1 minute marker epoch to within ±10 microseconds of UT_2.

(b) Accuracy: GEOS has been regularly used to time-synchronize the NASA Space Tracking and Data Acquisition Network (STADAN). Relative to VLF techniques the accuracies achieved are reported to be better than 50 microseconds. The techniques are described in Refs. 9 and 38. Accuracy is reported in Ref. 21.

8. DODGE Satellite (July 1967) (see Ref. 37)

(a) Purpose: To perform an experiment in gravity-gradient stabilization at synchronous altitudes. A supporting feature of the system was the transmission of timing references from an on-board crystal clock system. Observation of the timing epochs by several VLF calibrated ground stations provided a means for tracking the satellite position.

(b) Accuracy: Preliminary tests suggest a capability within 7. 7 microseconds (rms). A detailed analysis of data is currently in progress.

(c) Technique: Generally the comments stated above for ANNA and GEOS apply. In addition the time recovery subsystem of the ground station was designed with temperature stabilization of (time delay) critical components.

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APPENDIX B

S3E-68-084
S1QO
March 21, 1968

TO: R. B. Kershner

FROM: E. F. Osborne and L. J. Rueger

SUBJECT: Precision Time Synchronization by Satellites Using
           a Time-Multiplexed Recovery System.

The enclosed report describes in detail the satellite
and user equipment design changes required to provide 0.1 micro-
second time synchronization via the Navy Navigation Satellite
System. The basic change involves the addition of two modulation
frequencies in the satellite beep-tone word that are coherent in
time and frequency with the bit rate modulation on the RF carriers.
These tones are recovered by narrow band receiving techniques in
circuits added onto existing navigation equipments. All present
navigation equipments will be blind to this modification unless
specially equipped to recover the new tones.

Although the present methods of satellite time synchro-
nization to UTC have epoch steps of 10 microseconds, this proposed
technique will permit full system synchronization accuracy to all
users who are within radio range of the same satellite and can
mutually observe a specific beep word. Future methods of satellite
time synchronization using drift corrected oscillator or atomic
frequency standards will permit time synchronization to this pre-
cision on a world wide basis rather than only within line-of-sight
to the same satellite.

A Time-Multiplexed Time Recovery Satellite System

The Objective

It is desired to develop a satellite radio TIME-
RECOVERY system for (1) the calibration of clocks to a universal
time standard, or (2) the relative synchronization of clocks at
several stations each to a common reference by the simultaneous
reception of satellite reference signals. The design goal for World-
Wide coverage is 0.1 μsec accuracy. The use of the Navy Navigation
Satellite System, with minimum modification or change is desired.

The Proposed System

There are several concepts which have promise, however,
the Time-Multiplexed System described herein is recommended because
its accuracy is achieved with minimum impact on the equipment,
software programs, system operation, and management procedures
which are now operational or planned for the foreseeable future.
This claim is made both with respect to satellite and user facilities.

The Time-Multiplexed system uses the present time re-
covery features of the Satellite Navigation System and improves
its accuracy by one to two orders of magnitude depending upon the
components to be chosen in the final design. The improved accuracy
is obtained by the time-multiplexed transmission of new PSK modula-
tion possessing higher information rates in order to achieve time
resolution of 2 minute epochs to smaller increments.

The new modulation is confined to the "Beep" doublet
intervals of Word 3 of the normal message wave immediately follow-
ing its fiducial time epoch. The present "400 Hz" Beep doublet

would be replaced by a complex wave generated by logic combining

of 26 KHz and 3.25 KHz wave trains. The time multiplexing principle

is illustrated in Figure 1.

The 26 KHz information rate is used to obtain the

required time accuracy (resolution). The 3.25 KHz information and

the fiducial time as now obtained from the decoder by synchronization

to Word 2 are required for ambiguity resolution.

In the basic concept the 3.25 and 26 KHz components are

generated coherently with respect to each other and also to the

carrier at least for the time interval of Word 3 and are transmitted

by the satellite at power levels normal for $\pm$ 60° PM. During Word

3 there are 78 information bursts uniformly distributed at 1/4 the

standard bit rate, each burst consisting of 16 and 128 cycles of

3.25 and 26 KHz respectively. There are therefore a total of 1248

and 9984 positive going excursions during Word 3 of the initial

3.25 and 26 KHz components. A suggested modulation wave is shown

in Figure 1. Other waveforms are also visualized.

At the ground station the received signals are amplified

and translated to a satisfactory IF and bandwidth for coherent

demodulation and post detection analog filtering. Post detection

filtering by means of digital data processing techniques is possible;

however, the analog method is described as a representative approach.

The recovery of accurate timing information is accomplished by

measurement of selected coherent 3.25 and 26 KHz positive zero

crossings. Accuracy is limited by the resolution of the 26 KHz zero
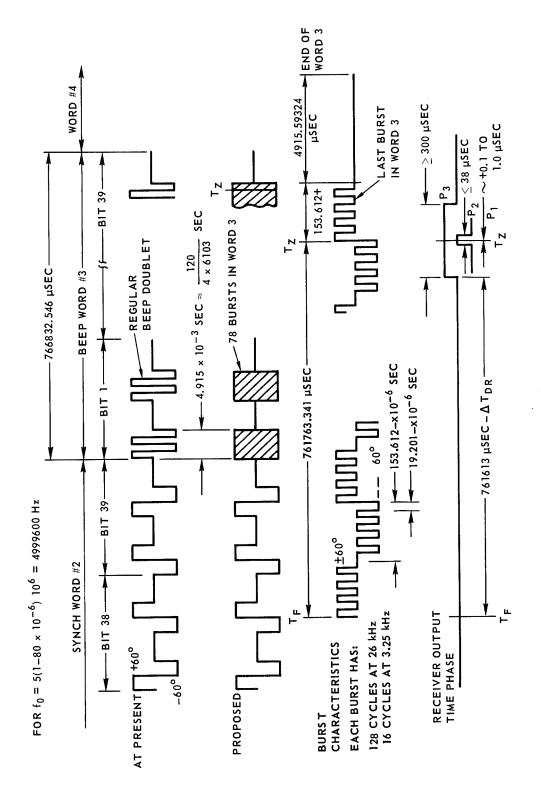
Fig. 1   MODULATION WAVEFORMS

crossing detector (and by other factors including jitter due to thermal noise, reference oscillator instability, counter resolution, etc.). Ambiguity is resolved by the logical combination of gating pulses so that an output is accepted only during the last (78th) burst at its last (16th) -60° to $+60^O$ phase excursion as indicated at T_z in Figure 1. Coincidence between pulses P_1, P_2, and P_3 occur only once per each two minute interval. P_1 provides the accuracy, P_2 and P_3 the ambiguity resolution.

The selection of the 78th modulation burst (of Word 3) for a delayed time measurement is not critical but is recommended to permit complete transient recovery and maximum averaging (smoothing) by the analog recovery filter. The pulse, P_3, which performs this selection is generated from fiducial time epochs T_f (at end of each Word 2) by counting the local clock from T_f to a time at least $(761613 - \Delta T_{DR})$ μsec later at which time P_3 changes state for no more than 300 μsec. The value ΔT_{DR} is the differential time delay of the ground station instrumentation in its detection of P_1 (and P_2) relative to the detection of fiducial time T_f. The pulse widths indicated in Figure 1 for P_2 and P_3 are the maximum values permissible for the proposed Word 3 modulation format.

(It should be noted that at the time of satellite rise and set, assuming 600 n. mi. orbits, the change in propagation time over the 3/4 second interval between T_f and T_z can be as large as 125 μsec leaving about $\pm$ 25 μsec system tolerance on P_3. If T_f and T_z are centered about TCA the change in propagation is effectively zero.)

The results of this preliminary study indicates an optimistic expectation of achieving 1 μsec timing with relatively simple satellite modification and ground station add-on equipment. While a 0.1 μsec accuracy appears possible a more detailed and comprehensive study is recommended.

Assumptions and Constraints

Full comprehension of the proposed method is aided by the following listing and outline of assumptions and constraints:

1. Navy Navigation Satellite Constellation at low orbital altitude at 600 n.mi. (minimum).

2. All time recovery users will have both navigation and timing capability, however, the user may elect to use or outfit for navigation only capability.

3. Compensation in the data processing is assumed for the variation in propagation time (from the orbiting satellite to the user). For 600 n.mi. orbits the variation ranges between 3.2 to 12.4 x 10^{-3} seconds due to change in slant range over the pass interval.

4. Approved Navigation System (Satellite) Transmission Channels.

$$400 \ MH_z \pm 50 \ KH_z$$
$$150 \ MH_z \pm 50 \ KH_z$$

5. Maximum Doppler shift observable at ground stations for 600 n. mi. orbits is 2.2 parts in 10^5..

6. Satellite Modulation Characteristics.

    a) PSK deviation: $+60^O$, -60°, 0° (doublet)

    b) Message Format: 6103 bits in 120 sec. constituting 156 words of 39 bits each plus Word #157 with 19 bits.

    c) Two minute fiducial time epochs coincident with end of Word #2: All receivers presently recover to an accuracy better than 100 μsec

    d) Modulation-Carrier signal coherence: Carrier and modulation frequencies are <u>at present</u> coherently derived during word intervals 1, 2, 3 and 136-157. Time offset and corrections are constrained by the Memory system to Bit 39 of some but not necessarily all of the remaining Words.

    e) Word #3 (the Beep Interval) has negligible significance to current Navigation systems. Modified transmissions during Word 3 are acceptable in the implementation of advanced time recovery.

    f) Any new modulation during Word 3 for enhancement of time recovery must be confined to the current $\pm 60^O$ deviated intervals and cannot continue in the intervals of 0° phase position of the carrier. Therefore a maximum of 78 modulation bursts can alternate with 78 spaces where the mark-space interval is exactly one quarter of the bit interval.

g) The use of a compensated frequency standard
in the satellite to permit coherent derivation
of modulation signal components relative to
the transmitted carrier signals 100% of the
time (rather than during words 1, 2, 3, and 136-157
only) is acceptable in principle. The calibra-
tion of the tuneable frequency standard would
be by control during injection (or by Memory
register during orbit if required).

With a compensated standard the criterion
for tuning shall be 6103 bits per 120 sec. and
the coherent carrier offset from the nominal
80 parts per million shall not deviate by
not more than 0.1 part per million as accomplished
by coherent synthesis.

h) It is assumed that all users of timing will
have a local frequency standard and clock of
sufficient stability and accuracy to maintain
operation between successive satellite passes
as provided by the low altitude Navigation
satellite constellation.

Description and Analysis

In the paragraphs to follow an effort is made to de-
scribe the concept, determine certain critical parameters, and
illustrate functionally the satellite and typical ground station
time recovery receivers.

In several areas there are technical trade-offs which can influence

the numerical parameters, however those presented demonstrate

clearly that the Navigation System can be improved for practical

Time Recovery with modest modifications.

Satellite Configuration

Two configurations are presented for examination and

analysis. As an introduction to the concept of Time-Multiplexed

time recovery consider the semi-coherent satellite of Figure 2.

This concept represents a rather minor variation of the present

OSCAR design that can be implemented promptly to satisfy the second

objective-the synchronization of clocks over a large tactical area

as determined by mutual radio visibility of the satellite. The

use of the semi-coherent satellite for time calibration to a

STANDARD (UTC) will require accurate accounting procedures by the

TRANET and INJECTION stations (or by the users themselves) in order

to maintain calibration of the modulation epoch, T_z of Figure 1,

relative to UTC. Epoch drift is caused by the frequency error of

the satellite oscillator.

In the "Semi-Coherent" satellite the only departure

from present designs is the substitution for the present "Beep"

the new modulation waveform proposed for Word 3 (shown typically

in Figure 1). The primary message of 6064 bits is unchanged, and

39 bits of (f_1, f_2) modulation retain 6103 bit intervals in 120 sec-

onds. During Words 1, 2, and 3 the frequencies f_1 and f_2 are both ob-

tained by the direct division from the regular uncompensated 5 MHz re-

$f_1 = 26039.58\bar{3}$ Hz

$$f_2 = \frac{f_1}{8} = 3{,}524.94791 \text{ Hz}$$

$$f_o = 5 \, (1{-}80 \times 10^{-6}) \, 10^6$$
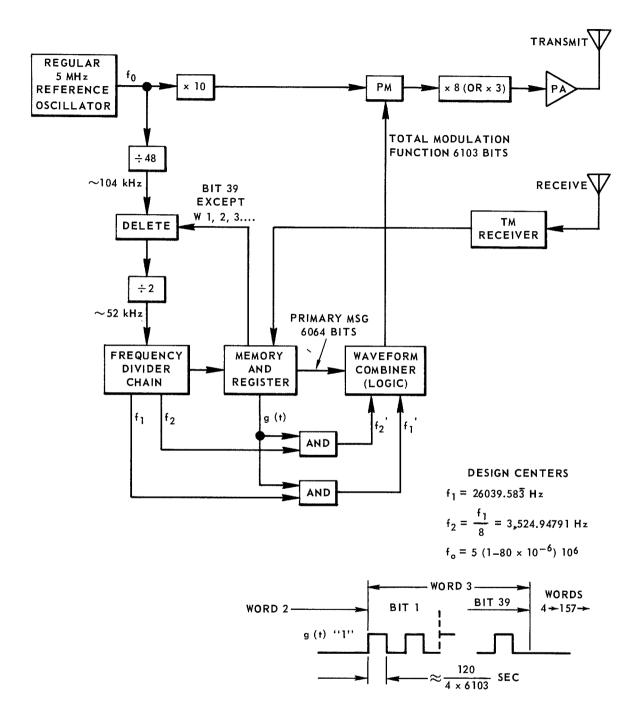
Fig. 2 SEMI-COHERENT SYSTEM

ference oscillator. During many of the remaining 157 words the

carrier and the modulation waves will not be coherently related

due to the action of the "Delete" gate under Bit 39 control by the

Memory Register. At the nominal design center the oscillator

frequency is f_o = 5 (1-80 x 10^{-6}) 10^6 H_z, while f_1 and f_2 are

26039.583̄ H_z and 3,254.94791 H_z respectively. Minor changes would

be necessary to bring out and combine existing f_1 and f_2 signals

for a modified modulation waveform.

For the synchronization of clocks in a tactical

zone the ground station must compensate for propagation time

delays between the satellite and the output of the user's time

recovery receiver. For calibration with respect to UTC or other

STANDARDS the ground station must also compensate for the error

of the modulation epoch, T_z due to satellite oscillator drift.

It is suggested that this correction may be accomplished by coded

instructions via the satellite memory register with the calibration

of T_z relative to UTC being performed by the TRANET facilities.

On cursory examination these compensations do not appear as un-

surmountable problems.

Further improvements of the Time-Multiplexed complex

are visualized if a totally coherent satellite is used. Figure 3

illustrates such a satellite. Again the basic OSCAR design is

apparent however the modifications of its oscillator require more

development. The coherent system requires a compensated reference

oscillator, a fixed divider chain, and the substitution of (f_1, f_2)

Fig. 3   COHERENT CARRIER-MODULATION SYSTEM

$$\underline{\text{FREQUENCIES}}$$

$$f_b = \frac{6103}{120} \qquad = 50.8583 \text{ bps}$$

$$f_2 = 64 f_b \qquad = 3.25493 \text{ kHz}$$

$$f_1 = 512 f_b \qquad = 26.03946 \text{ kHz}$$

$$f_3 = 2048 f_b \qquad = 104,157.86 \text{ Hz}$$

$$f_i = f_3 + \frac{f_b}{109} \qquad = 104,158.3332+ \text{ Hz}$$

$$F_0 = 48 f_i \qquad = 4,999,599.9936.. \text{ Hz}$$

$$F_0 = 5(1-80.0013...\times 10^{-6})\, 10^6 \text{ Hz}$$
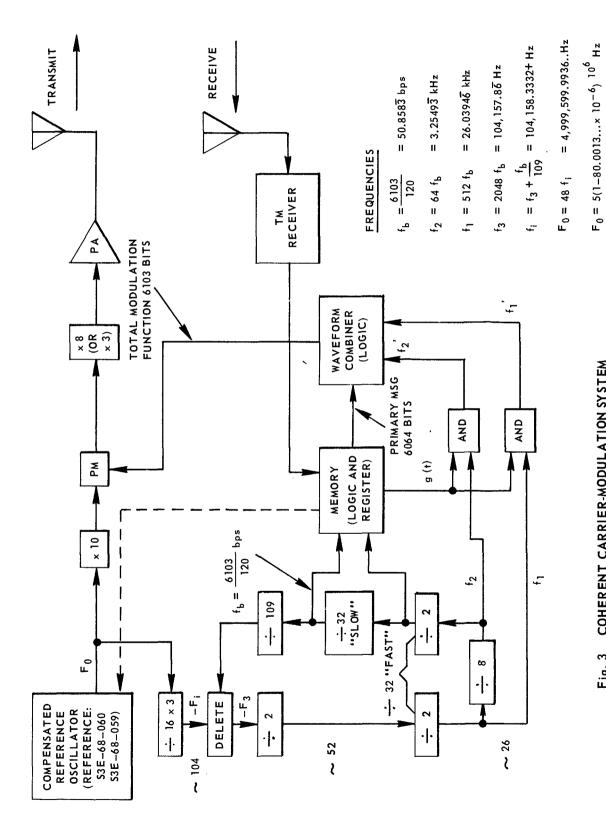
modulation for the normal "Beep" of Word 3. In the totally coherent

system there is no correction from the Memory register of the bit

interval to adjust timing as a fixed divider ratio is provided to

guarantee the correct bit frequency (6103/120), with a controlled

reference oscillator frequency near the specified nominal offset.

Depending upon the compensated reference oscillator design (see

for example S3E-68-059, and S3E-68-060), the control may be either

from the Memory Register or by direct TM injection.

Calculations were made in Figure 4 (using a desk calcu-

lator) to establish the frequency divider parameters and the exact

frequency for reference oscillator tuning. The best compromise

based upon pulse deletion (at 104 Kc) and integral numerical divi-

sion achieves the exact bit rate if the reference oscillator is

tuned to $f_o = 5 (1-80.0013 \times 10^{-6})$ MH_z. This requires division of

the bit frequency F_B by the integer 109 and deletion at the 104 Kc

level.

Reference to the current OSCAR design indicates that

except for the compensated reference oscillator the impact on

satellite equipment for a totally coherent carrier-modulation

system can be rather trivial.

Ground Station Receiver Configurations

Those ground stations which have or plan to have a

Navigation capability will not be affected by the improved

Time-Multiplexed Time Recovery system except that certain acquisi-

tion problems, data processing, computations, and generation (in

$$\text{Bit Rate} = \frac{6103}{120} = 50.858\overline{3} \text{ H}_z$$

$$\text{Division Ratio at Spec. } F_o = \frac{4,999,600}{50.858\overline{3}} = 98304.4404$$

$$\text{Division Ratio in Satellite} = 16 \times 3 \times 2 \times 32 \times 32 = 98304$$

$$F_o/48 = 104158.\overline{3} \text{ H}_z = \text{Nominal Input to Delete Circuit}$$

$$50.858\overline{3} \times \frac{98304}{48} = \underline{104157.8\overline{6}} \text{ H}_z = \begin{array}{l}\text{Required Delete Circuit Output}\\ \text{Frequency}\end{array}$$

$$\text{Difference} = \qquad\qquad 0.4\overline{6} \text{ H}_z = \text{Nominal Correction Frequency}$$

$$\frac{50.858\overline{3} \text{ H}_z}{0.4\overline{6} \text{ H}_z} = 108.982 = \text{New Divider Ratio} - \text{Round off to } \underline{109}$$

$$\frac{50.858\overline{3} \text{ H}_z}{109} = 0.466590214 = \text{Actual Correction Frequency}$$

$$\text{Sum} = \frac{104,157.866666666}{104,158.333256880} = \text{New Input Frequency to Delete Circuit}$$

$$\frac{\times 48}{}$$

$$\text{Product} = 4,999,599.9936\ldots\ldots$$

$$\therefore \quad F_o = 5\ (1-80.0013 \times 10^{-6})\ 10^6 = \begin{array}{l}\text{Compensated Reference Oscillator}\\ \text{Frequency.}\end{array}$$

FIGURE 4

OSCILLATOR AND DIVIDER PARAMETER FOR COHERENT TIME
NAVIGATION SIGNALS

the AN/BRN-3) of tracking aids could become easier by virtue of tighter satellite oscillator frequency control. There are no changes required for the user who desires a navigation capability only.
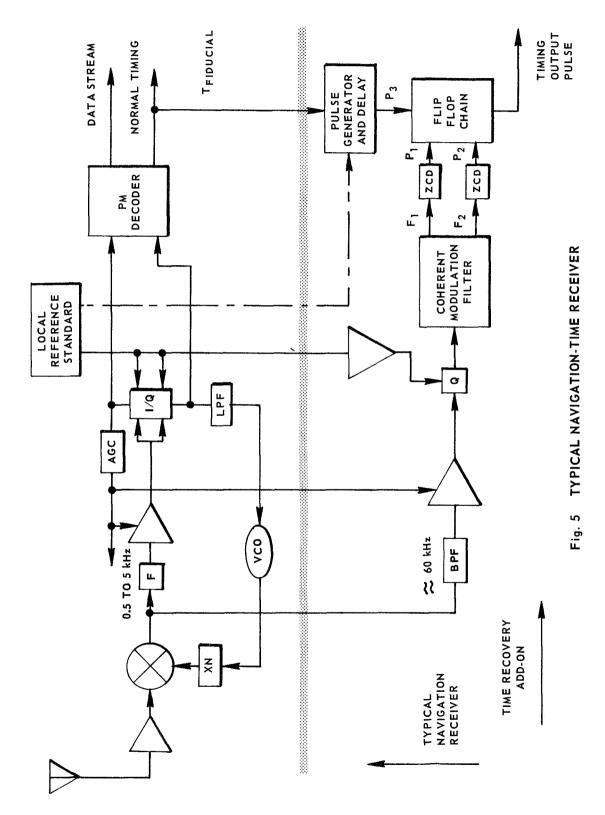
The ground station desiring Precision Time Recovery is required to also have navigation capability in order to make the compensation for variation in propagation time due to changing slant range which occurs with the passing of the low altitude satellite. Any user with a Doppler Navigation system (AN/BRN-3, AN/SRN-9, etc.) may upgrade his present facility by additional circuitry tailored to his particular type of receiving system. The fine distinctions in circuitry of the current receivers is of secondary interest to the recovery of Precision Timing. The functional requirements of a typical NAVIGATION-TIME receiver are illustrated by the diagram of Figure 5.

The add-on equipment for the recovery of Precision timing pulses consists of three basic sub-groups, namely:

    (1) A wideband (relative) IF channel and carrier demodulator;

    (2) A coherent modulation filter; and

    (3) A time recovery logic unit.

Equipment which may be required for data processing, propagation compensation, and control of local clocks should be treated separately from the receiver.

Three signals from the Navigation receiver are required and two may be optional. The required signals include (1) a doppler

Fig. 5   TYPICAL NAVIGATION-TIME RECEIVER

corrected IF signal of sufficient bandwidth to sustain the new

f_1 and f_2 phase modulation (approximately 60 KHz), (2) a coherent

reference signal from the local frequency standard for carrier

demodulation, and (3) an output timing pulse from the PM decoder

generated at the end of Word 2 (or at a known time shift) represent-

ing fiducial time epochs. Optional signals which may be used

include the coherently derived AGC bus voltage and a gating pulse

from the Decoder representing the received Word 3 time interval.

In the AN/BRN-3 the IF signal would be taken from the

4.5 MHz strip prior to the 5 KHz filter. In AN/SRN-9 (XN-5) designs

the IF signal would be taken from the final(5MHz) IF strip prior to

its predetection filter. To make these signal outputs available

for time recovery an adjustment in receiver gain will be necessary

which may require the addition of a buffer or distribution amplifier.

A preliminary estimate of system performance is pre-

sented in Figure 6 which is based upon coherent signals described

for the satellite transmission. Modulation filtering is performed

by the synchronous system shown in Figure 7. Ambiguity resolu-

tion and formation of the precision output timing pulse is accomp-

lished by the logic circuitry of Figure 8.

The critical parameters of the system are developed

in Figure 6 for the assumptions stated and in keeping with the

constraints listed earlier in this memorandum. For a received

satellite signal at a carrier level of -130 dBm, the highest modula-

tion frequency at a nominal 26 KHz, and with 1/3 of the allowable

error assigned to noise induced phase jitter, the calculations show

that the tracking bandwidth of the modulation recovery filter must

Assume:

C = Received Carrier Level = -130 dBm

S = Received Modulation Level = -140 dBm

Noise Density (KT) = -174 dBm/cycle

Receiver Noise Figure = +10 dB

Effective Noise Density = -164 dBm/cycle

KTB in (60 KHz = 48 dB) = -116 dBm

CNR to Q detector = -14 dB

SNR from Q detector = -24 dB

at: $f_1 = 26.0394\overline{6} \times 10^3$ H$_z$

$$T_1 = \frac{1}{f_1} = 38.40 \ \mu sec$$

$$\frac{360°}{T_1} = 9.3742\ldots \text{ degrees}/\mu sec$$

Error of Zero Crossing Detector due to Noise:

$$\phi = \frac{40.5}{\sqrt{SNR}}$$

Eq. (A)

	0.1 μsec System	1.0 μsec System
a) Required Angular Resolution ≤	0.9374 degrees	9.374 degrees
b) Allocate 1/3 Resolution to Thermal Noise	0.3124 degrees	3.124 degrees
c) Calculate from Eq. (A) the Required SNR at ZCD	42.25 dB	22.25 dB
d) Additional Bandwidth Reduction (Relative to 60 KHz)	66.25 dB	46.25 dB
e) Final Bandwidth (Prior to ZCD)	.015 H$_z$	1.5 H$_z$
(1) Allocate ZCD Resolution Error	0.360 degrees (rms) = millicyc.	3.60 degrees = centicyc.
(2) Residual Allowable Error (X)	0.807 degrees	8.07 degrees
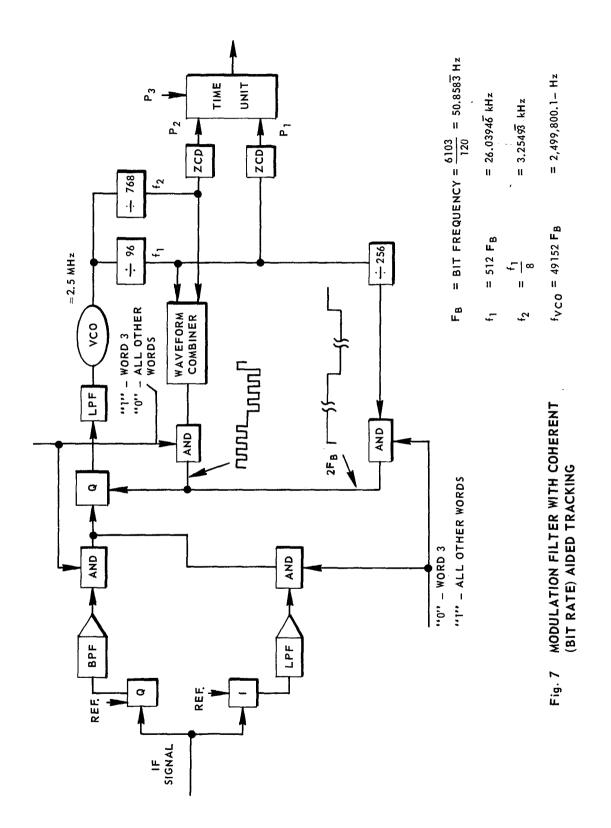
$$.9374 = \sqrt{(.3124)^2 + (.36)^2 + X^2}$$

FIGURE 6

ESTIMATE OF MODULATION FILTER BANDWIDTH

- 122 -

Fig. 7   MODULATION FILTER WITH COHERENT
(BIT RATE) AIDED TRACKING

F_B = BIT FREQUENCY = $\dfrac{6103}{120}$ = 50.8583 Hz

f_1 = 512 F_B = 26.03946 kHz

f_2 = $\dfrac{f_1}{8}$ = 3.25493 kHz

f_{VCO} = 49152 F_B = 2,499,800.1– Hz
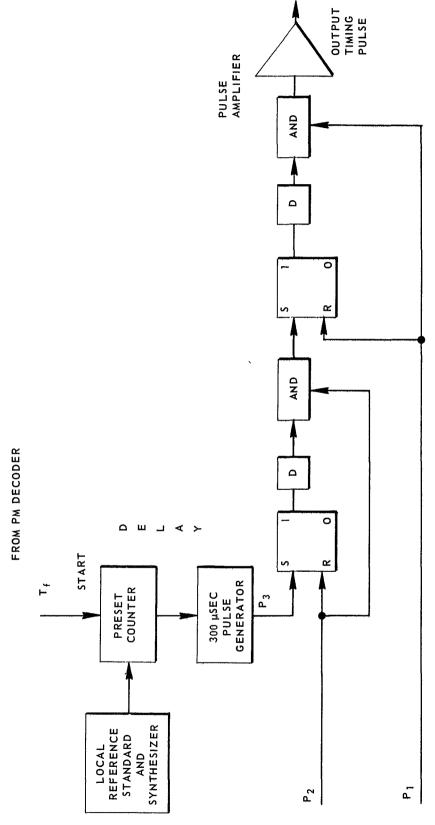
Fig. 8   TIME RECOVERY LOGIC

be no greater than 0.015 Hz or 1.5 Hz respectively for 0.1 μsec or 1.0 μsec accuracies. Typically, the further allocation of error will require millicycle resolution of the zero crossing of f_1 for 0.1 μsec and only centicycle resolution for 1.0 μsec. This leaves a residual (rss) error of 0.807 or 8.07 degrees for allotment to the remainder of the system.

The calculations in these examples clearly demonstrate the feasibility of a 1.0 μsec system. Whether a 0.1 μsec or a 1.0 μsec system is obtained depends upon the ground equipment design and cost rather than the satellite. It should be noted that the theoretical limit on bandwidth reduction in the modulation recovery filter is the Doppler curve itself which approximates a segment of a sine wave having a frequency of about .0007 Hz assuming a 12 minute pass. Thus even for the 0.1 μsec system the indicated bandwidth (.015 Hz) has an order of magnitude margin.

To supplement understanding of the proposed system further comment is in order to explain the functional operation of the modulation filter and recovery logic.

In Figure 7 a modulation recovery filter is shown which operates 100% of the time during a satellite orbital pass to track and filter the new high speed information during Word 3 reception and to track the coherently related half-bit waveform derived from an in-phase (I) carrier phase detector during the remainder of the time. With regard to modulation acquisition with ı inimum lock-up time a dual mode (two bandwidth) design of the tracking filter

should be considered since a positive SNR of 10 dB is quite
sufficient for acquisition. With the values assumed in Figure 6
a 34 dB bandwidth reduction would be used resulting in a tracking
filter bandwidth for acquisition modes as large as 24 Hz.

In the selection of the VCO for the modulation filter
a center frequency should be chosen for convenience in component
procurement and for minimum instability over short time intervals.
The oscillator output frequency range is still 2.5 parts in 10^6.
The frequency dividers must preserve the exact ratio of f_2/f_1
used in the satellite design.

Since f_2 and P_2 serve merely to resolve ambiguities as
illustrated by Figures 1 and 8 a more liberal tolerance is permitted
for the f_2 zero crossing detector (ZCD). A resolution of $\pm 1/20$
cycle would appear to be sufficient for f_2.

Conclusion

This study has identified the functional characteristics
of a Time Recovery concept which can be incorporated within the
Navy Navigation Satellite System with minor modifications and
simple additions at the ground stations. Performance estimates
and critical parameter values obtained in the study justify an
expectation of a 0.1 μsec eventual accuracy.

APPENDIX C

S3R-68-202
S1Q0S3RO
May 10, 1968

TO: A. C. Schultheis

FROM: E. F. Prozeller and T. A. Stansell

SUBJECT: Pseudorandom Time Signal Modulation for the S/N-17
                 Satellite

REFERENCES: (1) S3R-68-184, R. Grant and T. A. Stansell,
                     "Definition of a Digitally Controlled
                     Oscillator for the S/N-17 Satellite",
                     dated 4/23/68.

                 (2) S3R-68-171, T. A. Stansell, "Inclusion of
                     a Pseudorandom Modulation Capability in the
                     S/N-17 Satellite for Accurate Time Distribution
                     and Elimination of Cross-Satellite Interference,"
                     dated 4/12/68.

                 (3) S3R-66-201, S. F. Oden, "Special Application
                     Pseudorandom Code Generator," dated 11/8/66.

                 (4) S3R-66-170, T. A. Stansell, "Compatible
                     Technique for Eliminating Cross-Satellite
                     Interference," dated 4/66, Confidential.

1.0 INTRODUCTION

The use of pseudorandom noise (PN) phase modulation

on Navy navigation satellite signals was first proposed in

Reference (4) as a way to eliminate cross-satellite inter-

ference. More recently, the concept of having the satellites

provide a one microsecond or better world-wide time reference

has been introduced. The PN modulation technique also happens

to be very well suited for time distribution, and this memo-

randum proposes its inclusion in the S/N-17 Oscar satellite.

Although used primarily for time transmission, the rejection

of cross-satellite interference can be an important secondary benefit.

The PN modulation capability could be added to existing satellites, but much better performance will be demonstrated if the satellite's clock is kept accurate by means of a controlled oscillator rather than by discrete 9.6 microsecond time jumps, as is now the case. This is because the time recovery technique requires that a receiver synchronize its PN code generator with the PN modulation being received from the satellite. Relatively large time jumps occurring randomly make the time recovery job much more difficult. Therefore, it will be assumed that a controlled oscillator, such as the one proposed in Reference (1), will be used.

At this time, it is not clear what set of design parameters are best for the time distribution system. Specifically, time recovery precision must be balanced against allowable or desirable bandwidth spread. Fortunately, the hardware implications of changing the design parameters are trivial, and all interfaces would remain the same. Therefore, three specific designs will be discussed in this memorandum. All of the design parameters, however, are subject to review and they may be changed quite easily if such changes prove desirable.

Table I summarizes the three sets of PN time modulation characteristics. It is important to note that the PN code is proposed to be synchronous with message bit rate. In this way, the receiver can limit the number of code bits over which it must search for synchronization after first acquiring doublet and bit synchronization. Note also that there must be a time correction of just over 441 microseconds every 120 seconds. It is proposed that this time correction be made in a single step immediately after the two-minute time mark. A receiver with message synchronization can anticipate the step and compensate for it. A receiver without message synchronization will have nearly two minutes after the time correction in which to acquire time synchronization before receiving the next two-minute time mark. The time correction represents only a 16 degree phase step in the doublet-rate signal, which can be tracked out quite easily by current receivers with no adverse affect on doppler recovery accuracy.

(The requirement for a time correction step is influenced by the reference oscillator offset. For instance, with an offset of -84.48 ppm, no time correction step is required at all. With an offset of -80.0 ppm, a step of just over 537 microseconds is required.)

One interesting aspect of providing very accurate time marks throughout the satellite's message, but especially

TABLE I

PN TIME MODULATION CHARACTERISTICS

	Set 1	Set 2	Set 3
Controlled Oscillator Frequency	4,999,596 Hz	4,999,596 Hz	4,999,596 Hz
Oscillator Frequency Offset	-80.8 ppm	-80.8 ppm	-80.8 ppm
PN Modulation Angle	$\pm 27^{\circ}$	$\pm 27^{\circ}$	$\pm 27^{\circ}$
Reduction of Normal, Narrowband Power	1 db	1 db	1 db
PN Clock Frequency	416,633 Hz	$52,079\frac{1}{8}$ Hz	$26,039\frac{9}{16}$ Hz
Clock Cycles per Code Period	8192	1024	512
Code Repetition Frequency = Bit Rate =	50.8585205 Hz	50.8585205 Hz	50.8585205 Hz
Clock Cycles per 120 Sec.	49,995,960	6,249,495	3,124,747.5
Clock Cycles per 6103 Bits	49,995,776	6,249,472	3,124,736
Extra Clock Cycles each 120 Sec.	184	23	11.5
Time Correction each 120 Sec. (immediately after 2-min. time mark)	441.6 μsec.	441.6 μsec.	441.6 μsec.
Equivalent Doublet Phase Step Error	16°	16°	16°

at the two-minute time mark, is that it will improve the
ultimate navigation accuracy of integrated doppler receivers.
These receivers depend on the received time marks to start
and stop the doppler counts. The largest source of doppler
count noise today is due to random time recovery jitter.
More accurate time recovery would thus contribute to nav-
igation accuracy, especially for higher order solutions,
e.g., the 4 x 4.

2.0   PRINCIPLES OF ACCURATE TIME RECOVERY

The precision with which it is possible to
recover absolute time on the ground from a satellite con-
taining a universal time standard is dependent on a number
of factors. The following are most pertinent to this
discussion:

1) The time resolution properties of the
modulation waveform must be very high.

2) The time delay properties of the observer's
receiver from the antenna to the point of
time mark detection must be calibrated precisely.

3) Tracking of the time signal must be made in
as narrow a BW as possible in order to
minimize receiver noise errors.

4) Many independent time marks should be
received and averaged to further reduce
the effect of random error sources.

The above factors give rise to the following rules for designing an accurate time recovery system:

1) Use of as high a modulation frequency as allowable.

2) Detection of the timing modulation early in the receiver (near the antenna) before the signal passes through narrow band filters or many amplifier stages. Otherwise, a very accurate calibration of receiver time delay must be made frequently.

3) Use of long integration times (narrow bandwidths) in the time recovery tracking circuits. This is greatly enhanced if the time modulation is coherent with the doppler carrier frequency, permitting the receiver's doppler tracking loop to rate-aid the time recovery loop.

4) Provide more than 10 time marks per satellite pass, e.g., perhaps 100.

It will be shown in what follows that a PN phase modulation of the present satellite signal is extremely well suited to meeting the above conditions for accurate time recovery.

3.0 PN MODULATION OF SATELLITE SIGNAL

3.1 Time Characteristics of Proposed PN Modulation

It would seem desirable for the PN sequence to be time synchronous with message bit rate. In this way, the receiver can have a combined and complimentary time recovery system rather than have two independent systems. For instance, the receiver would initially synchronize with bit rate; then, by using the known bit phase to confine the PN search region, much more rapid PN synchronization can be achieved. Integrated doppler receivers also can improve measurement accuracy by starting and stopping doppler counts with the more accurate bit time marks derived from the PN code.

It is also desired that the PN clock rate be coherent with the doppler carrier frequencies, which means that it, too, will be derived from the 5 MHz reference oscillator. The problem is that unless the reference oscillator is offset by -84.48 ppm, there is no possible integer division of the oscillator frequency to the required bit rate of 6103 bits per 120 seconds. Therefore, at least one bit must be longer than all the others, which means that at least one PN sequence must be longer than the others if the PN sequence is to be time-synchronous with bit rate.

The technique proposed here is to stretch the length of just one bit (and one PN sequence) located just after the even-minute time mark. As shown by Table I, the amount of stretch is about 441.7 μsec when the reference oscillator is offset by -80.8 ppm. By coming just after

the even-minute time mark, the effect on any user will be trivial. If message sync has been acquired, a receiver equipped to extract the PN time marks will simply anticipate and match the extended PN sequence.

3.2 Functional Block Diagram Description
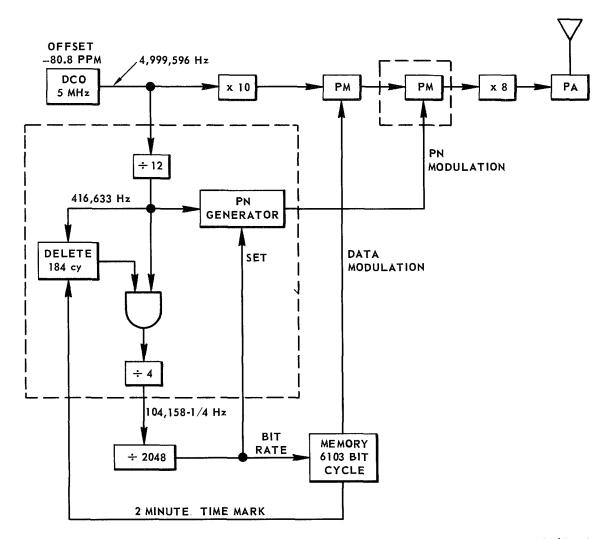
A block diagram of the satellite electronics required to achieve PN phase modulation is shown in Figure 1. All of the new circuitry has been enclosed by dashed lines.

It is assumed that the digitally controlled oscillator (DCO) described by Reference (1) is used to hold the reference frequency at 80.8 ppm below 5 MHz. The reference frequency is multiplied to 50 MHz and phase modulated by data from the memory system in the normal way. At that point, however, a second phase modulator circuit inserts the PN binary code as a two-state phase modulation. Thus, the new phase modulator can be identical to the one used for the message data, or it can be somewhat simpler because it has to produce only two phase states rather than three.

The PN sequence is generated by means of a simple shift counter driven at an appropriate clock rate obtained by division of the reference oscillator frequency. A bit-rate feedback from the memory drive assures that the PN sequence is always in the proper state at the beginning and at the end of each memory bit.

Just after the even-minute time mark, digital circuits are triggered to delete precisely the right number

NOTE: IMPLEMENTATION FOR PN MODULATION AT LOWER RATES, e.g., 52 OR 26 kHz, IS
ESSENTIALLY THE SAME, EXCEPT THAT THE PN CLOCK FREQUENCY AND THE
CYCLE DELETION GATE ARE FURTHER DOWN THE DIGITAL DIVIDER CHAIN.

Fig. 1   SATELLITE IMPLEMENTATION OF 400 MHz CHANNEL
FOR PN MODULATION AT 416 kHz

of clock pulses from the memory divider chain in order that the 6103 bit message will cycle in precisely two minutes. For the case shown in Figure 1, exactly 184 cycles at 416,633 Hz are deleted. If the PN clock frequency were $52,079\frac{1}{8}$ Hz, Table I shows that a deletion of exactly 23 clock pulses at that frequency would be required.

3.3 <u>Interface with Existing Hardware</u>

The interface between the PN modulation circuitry and the other satellite electronics is as follows:

1) The PN circuitry accepts as input the reference oscillator frequency of 4.999596 MHz from the DCO.

2) From this, it synthesizes $\approx$ 104 kHz required by the memory dividers.

3) In addition, the PN circuits require inputs of bit rate and the even-minute time from the memory for synchronization purposes.

The required PN digital hardware is about 25 flat packs of which 17 or so comprise the code generator. The PN digital circuitry will fit nicely within the DCO electronics package. The additional phase modulator will go in the satellite RF chain as another stage in the existing modulator/multiplier module.
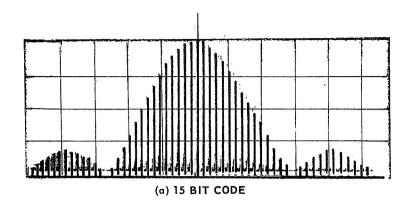
3.4 <u>Spectral Characteristics of the Transmitted Signal</u>
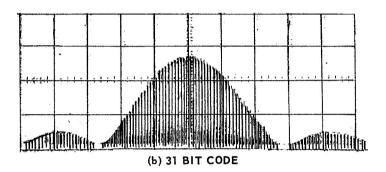
3.4.1 <u>General Characteristics</u>

Two important numbers in describing a PN sequence are its clock rate and the number of bits in the sequence, N.

Naturally, the clock rate divided by N gives the overall sequence repetition rate.

Figure 2 is a set of oscilloscope photographs showing the spectral output of three PN generators of different length N but all driven at the same clock frequency. Because the spectrum analyzer responds to voltage amplitude rather than to power, the envelope of the spectrum is described by $\left| \dfrac{1}{\sqrt{N}} \left(\dfrac{\sin x}{x} \right) \right|$. The first spectral envelope null occurs at $\pm$ the clock drive frequency, in this case $\sim$13 kHz. Note that as N increases, the number of spectral lines increases and the envelope voltage amplitude decreases proportionally to keep the total spectral power constant. In other words, the amount of _power_ in each spectral line decreases in direct proportion to an increase in N. The spacing between the spectral lines is just the PN sequence repetition frequency, i.e., the clock rate divided by N.

If the satellite signal is phase modulated $\pm$ α degrees by a PN sequence, then the total transmitted power will be divided into two components: a normal, narrowband signal component and a spread spectral signal component. The normal component will have $\cos^2 \alpha$ of the total transmitted power, and the spread spectral component will have $\sin^2 \alpha$. These power relationships are plotted in Figure 3 as a function of the PN modulation angle.

(a) 15 BIT CODE

(b) 31 BIT CODE

(c) 63 BIT CODE
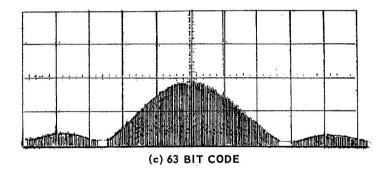
Fig. 2   AMPLITUDE SPECTRA OF PN CODES (CLOCK RATE = 13 kHz)

TOTAL TRANSMITTED POWER
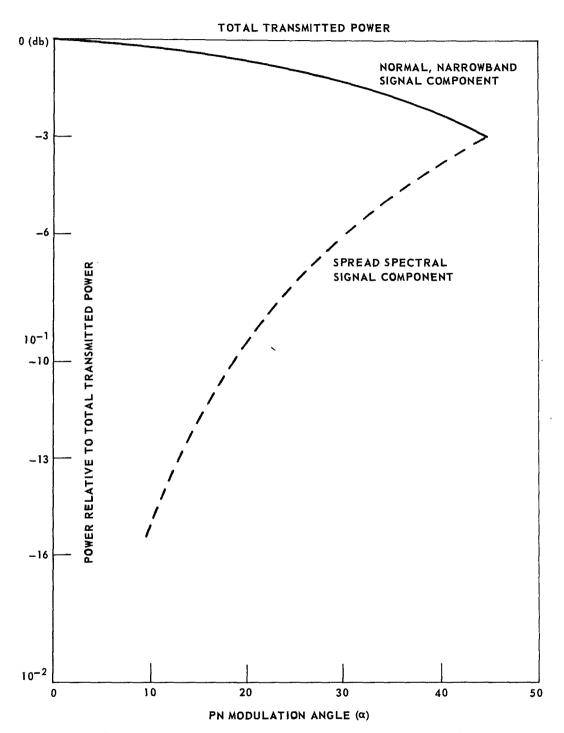
Fig. 3   DIVISION OF SATELLITE SIGNAL POWER BETWEEN
SPREAD SPECTRAL AND NORMAL COMPONENTS

Although as much as $\sin^2\alpha$ of the total transmitted power will be in the spread spectral component, the power in any one spectral line is never more than 1/N-th of the total spread spectral power. This relationship is shown mathematically and pictorially by Figure 4.

3.4.2 Proposed Time Modulation Characteristics

The S/N-17 satellite is primarily intended for doppler navigation and only secondarily intended for accurate time distribution. Therefore, it is proposed that the normal, narrowband signal component be reduced by only one db in providing for PN time modulation. From Figure 3, this is achieved at a PN modulation angle of $\pm$27 degrees. The spread spectral signal component will be seven db below the total power, or six db below the narrowband signal power.

Figure 5 summarizes the important spectral characteristics of the proposed satellite signal. In this table, all signals are referenced to a typically good received signal level of -120 dbm. In this way, it becomes obvious that the individual PN spectral lines as received will be below the acquisition and tracking threshold of doppler receivers.

3.4.3 Spectral Bandwidth Considerations

As discussed in later sections of this memorandum, a high PN clock frequency is desirable for the most accurate time recovery. On the other hand, a high clock frequency spreads the time signal modulation over a correspondingly wide frequency band. Although there is little or no chance of interfering with other users of the nearby spectrum, there is the chance

Carrier with Data Mod: $V(t) = A \cos \left[\omega_c t + \Psi M(t) \right]$

Carrier with Data and PN Mod: $V(t) = A \cos \left[\omega_c t + \Psi M(t) + \alpha P(t) \right]$

$$\text{where} \quad M(t) = +1, \ 0, \ -1$$
$$\Psi = 60^\circ$$
$$P(t) = \pm 1$$
$$\alpha = \text{PN modulation angle}$$

Composite signal becomes:

$$V(t) = \underbrace{\cos \alpha \left[A \cos(\omega_c t + \Psi M(t)) \right]}_{\text{Normal Component}} + \underbrace{P(t) \sin \alpha \left[A \sin(\omega_c t + \Psi M(t) \right]}_{\text{Spread Spectral Component}}$$

Composite Power
Spectrum
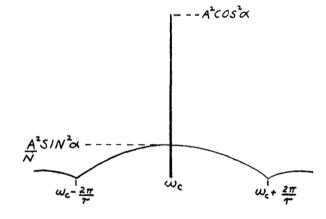
Figure 4

Phase Modulating a Carrier with a PN Code

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Figure 5

SPECTRAL CHARACTERISTICS OF PROPOSED MODULATION

(Referenced to Total Received Power of -120 dbm)

	Set 1	Set 2	Set 3
PN Clock Frequency	≈416 KHz	≈52 KHz	≈26 KHz
PN Sequence Length, N	8192	1024	512
PN Modulation Angle, α	27°	27°	27°
Total Received Power	-120 dbm	-120 dbm	-120 dbm
Received Narrowband Power	-121 dbm	-121 dbm	-121 dbm
Received Spread Spectral Power	-127 dbm	-127 dbm	-127 dbm
Strongest PN Spectral Line	-166 dbm	-157 dbm	-154 dbm
Spectral Line Spacing	50 Hz	50 Hz	50 Hz
First Spectral Envelope Null	±416 KHz	±52 KHz	±26 KHz

that signals outside the $^\pm$60 kHz guard band (about exactly

400 MHz) but within the PN spread spectral bandwidth could

become a source of interference when the navigation receiver

attempts to demodulate the PN time modulation. In such a

case, the PN demodulator simply could be turned off, eliminating

the interference along with the time signals. However, the

more general question is how the chance of or severity of

such interference would be influenced by the spread spectral

bandwidth. On one hand, the wider the spectrum the more likely

it will be to encompass a source of interference. On the other

hand, in demodulating a very wide spectrum, only a minute amount

of power is accepted from any one portion of that spectrum ,

so the severity of an interfering signal would be minimized.

At this time, there is no clear answer to the

interference question. Therefore, it is proposed that a "best

guess" of all interested parties be made, and the question be

settled eventually by a series of experiments, some of them

involving actual use of PN modulation radiated by the S/N-17

satellite.

4.0 TIME RECOVERY

4.1 General Concepts

The time recovery receiver design problem is to

recover, with minimum error, the PN sidebands of the transmitted

satellite signal which contain the fine-grain timing information.

There are two types of errors to consider. One is a static

error in the sense that it remains constant throughout

a satellite pass but it can vary both with receiver environment
and with age and therefore must be calibrated often. Two main
causes of static error are:

      1)   Time delay between reception and detection
          of the timing signal in the receiver.

      2)   Hardware limitations such as operational
          amplifier offsets and analog switch
          imperfections.

Accurate measurement of a time interval (e.g., 2 minutes) is
relatively independent of static error. However measurement
of time epoch requires a precise knowledge of the total static
time error.
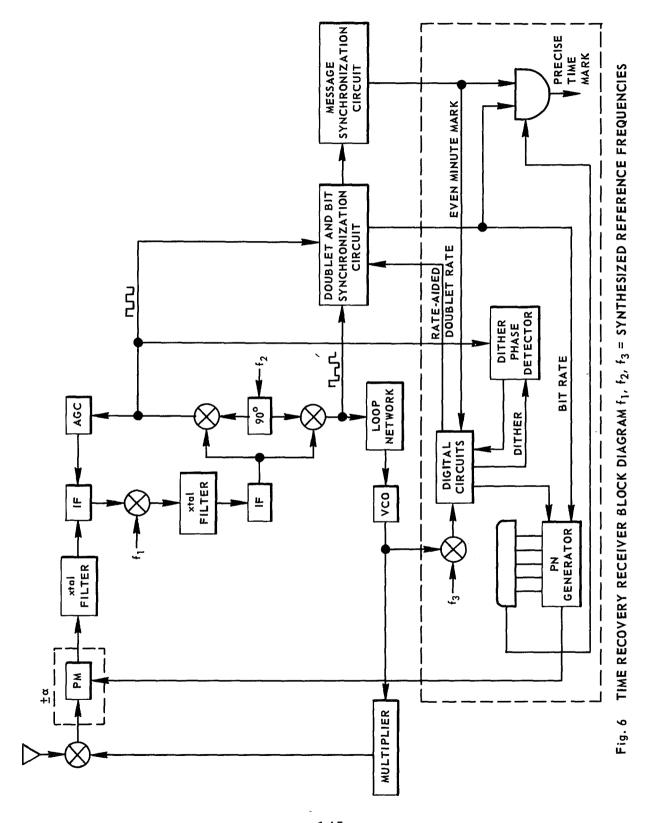
The second error to consider is dynamic error.
This is caused mainly by receiver noise degrading the detection
and tracking of the timing modulation. Dynamic errors affect
the measurement of time interval and epoch about equally.

4.2   A Time Recovery Receiver

4.2.1   Implementation

One possible implementation of a receiver which
is capable of highly accurate time recovery is shown in Figure 6.
The new circuitry required for PN demodulation and tracking
is enclosed in dashed lines. The added time recovery circuitry
consists of:

Fig. 6   TIME RECOVERY RECEIVER BLOCK DIAGRAM f_1, f_2, f_3 = SYNTHESIZED REFERENCE FREQUENCIES

1) A phase modulator immediately following the first mixer.

2) A local PN generator which is identical to the generator in the satellite.

3) An auxiliary mixer which removes from the VCO frequency the fixed IF frequency component.

4) A block of digital circuitry which generates:

   (a) a "rate-aided" reference signal for the normal receiver time-recovery circuits

   (b) a coherent clock for the local PN generator which by means of pulse-addition/deletion circuits can be phase shifted with respect to the received PN clock phase

   (c) a periodic phase dither of the local PN code

5) A synchronous dither detector circuit for generation of a timing-signal error function.

The receiver operates in the following manner.

The signal at the antenna consists of a narrowband "normal" component and a wideband "spread spectral" component. Initially

the PN generator and phase modulator are inactive and the
phase-locked loop acquires the normal signal component. The
spread spectral component is rejected by the narrowband
filters in the receiver. Following carrier acquisition,
the normal processes of doublet-rate and bit-rate synchronization
are initiated. The coherent reference for this "course" time
recovery is derived from the main carrier-loop VCO (via the
auxiliary mixer) and, because the resulting frequency is phase
coherent with the received carrier, it will vary with doppler
frequency. Use of this "rate aided" timing signal as a
reference in the normal time recovery loop (instead of a
separate VCO as is now used) allows the bandwidth of this loop
to be made very narrow and therefore greatly reduces phase
jitter in the "course" time recovery.

When bit-rate synchronization has been achieved,
a bit sync signal is generated and used to preset the code
generator and turn on the local phase modulator, which impresses
a PN phase modulation of $\pm$ α degrees on the output of the first
mixer. The PN code has been designed to cycle at bit rate;
therefore, since bit rate phase is accurately known to within
.1 msec or so, only 100 microseconds worth of bits need be
investigated in search for proper PN phase. For a code of
length 8192 this involves searching about 40 bits.

Calculations have been made to determine the
acquisition times for codes of lengths 8192, 1024, and 512

bits and the results are tabulated in Figure 7. It should

be noted that these acquisition times are "worst case" and

that normally much faster PN synchronization could be expected.

Phase modulation of the first mixer output causes

about a 1 db loss of normal signal power when the received

and local PN codes are uncorrelated. The normal, narrowband

signal component increases to a maximum and then decreases

as the codes draw into and then out of correlation. This is

shown by the dashed curve of Figure 8(a) where the numbers are

based on a PN modulation angle of $\alpha = 27^\circ$. In order to generate

an error function which is zero at the point of maximum correlation,

the local PN code is dithered in phase $\pm$ $\tau/2$ at a rate which will

not be tracked out by the AGC loop but will pass unattenuated

through the crystal filters. The dithered correlation functions

are shown by the solid curves of Figure 8(a). The dither detector

synchronously detects the difference in carrier signal into the

phase comparator between the two dither conditions (Figure 7(c)).

Incorporation of a PN phase dither enables location

of PN correlation without actually detecting the PN modulation

(this would require a separate wideband IF strip and all of the

accompanying delay problems). The consequence of using a dither

is that the average increase in signal strength when the codes

are correlated is about 1 db less than if the PN phase were not

dithered. This is shown in Figure 8(b).

If the AGC reference voltage is .75v, as it is in

Geoceiver, then the error function of Figure 8(c) must be

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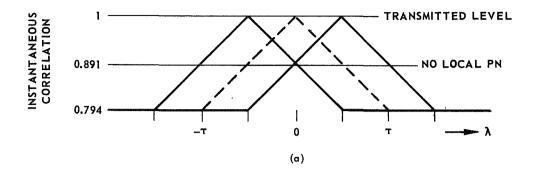
TOTAL RECEIVED POWER
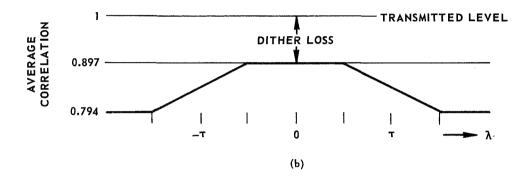
		−120 dbm	−130 dbm	−140 dbm
(CLOCK RATE)	8192 bits (416 kHz)	5.4 sec	54 sec	540 sec
	1024 bits (52 kHz)	.68 sec	6.8 sec	68 sec
	512 bits (26 kHz)	.34 sec	3.4 sec	34 sec
	Acquisition bandwidths →	29.3 Hz	2.93 Hz	.293 Hz

Figure 7

Maximum times and bandwidths required for synchronization of PN codes. ($\alpha = 27°$, AGC correlation = .75v, 10 db noise figure, probability of acquisition > 99%)
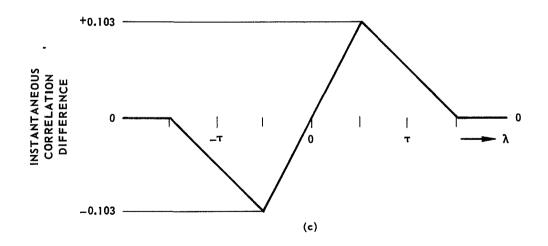
Fig. 8   INSTANTANEOUS CORRELATION (a),AVERAGE CORRELATION
(b),AND ERROR FUNCTION (c) VERSUS RELATIVE PHASE OF PN
CODES, λ.(ALL VALUES RELATIVE TO A TOTAL RECEIVED
VECTOR OF UNITY AMPLITUDE, α = 27° AND DITHER = ± τ/2.)

normalized by the ratio $\frac{.75}{.897}$. This gives a PN tracking gain of $\frac{.172}{T}$ volts per microsecond for a PN modulation angle of 27°.

4.2.2 Estimate of Accuracy

The PN tracking bandwidths required for one μsec dynamic timing error for typical received signal strengths are presented in Figure 9 for three possible modulation rates. In comparing Figure 7 with Figure 9, it can be seen that the band-widths tabulated in Figure 9 for the 416 kHz modulation rate are too wide for reliable acquisition and are therefore not practical. The maximum bandwidth for PN tracking is the acquisition bandwidth and for the 416 kHz modulation rate this gives an rms time recovery accuracy of .4 microseconds. Actually, once PN acquisition and satellite message synchronization have been achieved, the PN tracking bandwidth can be made much narrower so as to further reduce dynamic noise errors. The limit on how narrow the bandwidth can be made depends on the degree to which ionospheric refraction affects the PN sidebands.

The static errors consist of first, the receiver delay in the preselect filter which, for a bandwidth of 1 MHz, will be about 1 μsec, and second, voltage and current offsets in the tracking loop electronics. Worst case offsets on the order of 10 mv can be achieved relatively easily today. This gives rise to calibrateable offset timing errors of about .2 μsec, 1 μsec, and 2 μsec for modulation rates of 416 kHz, 52 kHz, and 26 kHz respectively. It is not unreasonable to expect that by careful design or by use of components with lower offset these errors could be reduced by one half.

TOTAL RECEIVED SIGNAL POWER

PN MODULATION RATE	−120 dbm	−130 dbm	−140 dbm
416 kHz	182 Hz	18.2 Hz	1.82 Hz
52 kHz	2.84 Hz	.284 Hz	.0284 Hz
26 kHz	.71 Hz	.071 Hz	.0071 Hz

Figure 9

Equivalent (RF) noise power bandwidth of
PN tracking loop required for 1 μsec rms
time recovery. Loop design BW equals one
quarter entered values. (for $\alpha = 27°$,
AGC correlation voltage = .75v, noise
figure = 10 db)

$$BW = \frac{CNR}{9.5\ \tau^2}$$

5.0 SUMMARY

The purpose of this memorandum has been to propose the incorporation of a pseudorandom time-signal modulation capability in the S/N-17 satellite. The proposed technique would take about 1 db of power away from the normal, narrowband satellite signal and spread this power into a wideband, spread-spectral signal. This widebanding would be achieved by the incorporation of a continuous pseudorandom phase modulation on the presently transmitted satellite signal. The overall signal received on the ground would consist of a normal, narrowband component and a spread-spectral component containing the fine-grain timing information. Present day receivers will acquire and track the normal, narrowband signal component with a net 1 db reduction of received carrier power. Those equipments containing the additional circuitry will be able to acquire and track the pseudorandom time-signal modulation.

The proposed receiving system has been designed so that with only an initial "factory" calibration of the equipment, absolute time epoch can be recovered in the field to an accuracy of from .5 to 3 microseconds depending on the selected modulation rate. Occasional "field" calibration of the receiver will readily allow recovery of time epoch to better than 1 microsecond.

Of the three PN modulation rates discussed, it would seem that the most desirable from the standpoint of accuracy versus acquisition time is the 52 kHz rate. A

conservative estimate of receiver performance would indicate a 1.5 μsec time epoch recovery accuracy with only "factory" calibration. Either by infrequent calibration, or by more careful design, or by an advance in the quality of "low offset" components, an accuracy of better than one microsecond is certainly achievable. Note particularly that the accuracy limitation of this approach is not imposed by bandwidth or integrating time restrictions, but by uncalibrated receiver system time delays and/or biases. Such static errors are substantially less for this PN time modulation system than for any other time recovery scheme now being considered.

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APPLIED PHYSICS LABORATORY
SILVER SPRING, MARYLAND

APPENDIX D

S3E-69-015
Z152
January 17, 1969

TO: L. J. Rueger

FROM: E. F. Osborne

SUBJECT: Frequency and Time Standards.

ENCLOSURE: (1) Compensation of a Reference Frequency by
Incremental Phase Adjustment.

   A report is attached which describes and recommends
the addition of sequential increments of phase to the output
signal of a reference oscillator of either the crystal or atomic
types for the purpose of generating and maintaining small off-
sets from a prescribed channel frequency or for the alternate
purpose of normalizing and maintaining calibration of the TIME
scale of a clock system relative to a STANDARD REFERENCE.

   The system is digital and all-electronic and may
be designed for adjustment in the time scale with resolution
in the nanosecond region. It is recommended that the concept
be reviewed and considered for future applications in space-
craft and in ground stations.

COMPENSATION OF A REFERENCE FREQUENCY BY INCREMENTAL

PHASE ADJUSTMENT

INTRODUCTION

Secondary frequency standards are subject to drift in the output signal due to long term aging and to systematic and random variations of the controlling environmental factors. For many applications it is desired to stabilize and control the frequency of oscillation to a unique specified value within a small allowable tolerance, removing in effect all of the predictable variations that may occur in a finite sampling or observation interval. This report is written to describe the application and theoretical principles of an "Incremental Phase Adjustment" method of compensation which appears to have properties and advantages of interest for satellite and ground receiver service in the fields of navigation, world-wide timing, and communications.

Several approaches to the compensation of oscillator drift have been and are being developed. One group of systems, of which reference 6 is typical, operates directly to vary a parameter of the basic oscillator circuits thereby adjusting its frequency of oscillation. Another approach, exemplified by reference 5, preserves the reference oscillator parameters but adjusts the system output frequency by interposing a selectable or variable synthesizer between the reference source and the system output terminals.

In a recorded development of NBS (reference 2) synchronization of two independent time scales with calibrations each 12 hours was achieved with a demonstrated accuracy within 70 nanoseconds (rms) using an electromechanical resolver for continuous phase compensation. In England (reference 1) a differentially driven quadrant potentiometer was used with a rubidium standard to calibrate clock epochs to the offset required for UT2, using the phase adjustment concept. At APL (references 3 and 4) Bateman has demonstrated the use of solid state all electronic logic circuits and incremental phase adjustment techniques for offsetting frequency in the simulation of refraction and doppler shifts.

The "Incremental Phase Compensated Oscillator" is a digitally controlled all electronic concept of the synthesizer type. It uses a single quality reference oscillator followed by a controlled incremental phase shifter and a frequency selective transmission filter arranged as illustrated in Figure 1. The incremental phase controller has a total phase range of 360° divided into an integral number of steps which may be selected in sequential order to either advance or
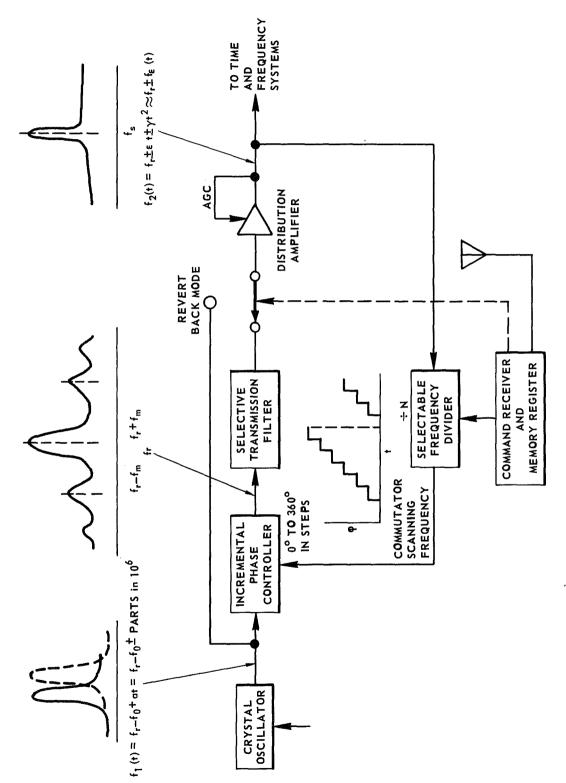
Fig. 1   FREQUENCY ADJUSTMENT BY SEQUENTIAL PHASE ADDITION

retard the rotating carrier vector. Due to the inherent
phase ambiguity of periodic waves the progressive addition of
phase over the limited range of 0 to 360° will produce a shift
in frequency of the output signal. Phase shifting in quan-
titized steps rather than in a smooth continuous function re-
sults in a small residual phase modulation which may be re-
moved from the output signal by standard frequency selective
amplitude filtering techniques.

However, for effective filtering it is necessary
that a small bias always exist between the oscillator frequency
(f_1 in Fig. 1) and the output signal frequency (f_2).

For purposes of illustration consider the following
requirements as typical of a satellite application for
accurate TIME epoch generation:

a. Nominal crystal oscillator reference source.

Output frequency - 5 $(1 -80 \times 10^{-6})$ MHz.

Drift in 5 years $\pm$ 2 parts in 10^6

Average daily drift < 1 part in 10^9

Calibration - coarse adjustment to -80 $\pm$ 1 PPM.

b. Compensated mode.

Tuning method - sequential phase scanning.

Output frequency - 5 $(1 -84.48 \times 10^{-6})$ MHz.

Output tolerances* - < 5 parts 10^{12} for Crystal
with averaging times greater than 0.2 sec.

Time Epoch Settability Resolution -

< 10 nanoseconds

Spectral purity - residual phase modulation and
harmonics down at least 60 dB
relative to output carrier com-
ponent.

*Note: for a Rb standard the tolerance is < 5 parts 10^{13} with
averaging times greater than 100 sec.

ANALYSIS OF FEASIBILITY AND PERFORMANCE

The general theory of "Incremental Phase Compensation"

begins with definitions of the frequency, which is,

$$f(t) = \frac{d}{dt} \phi(t) \tag{1}$$

and the accumulative phase of the electric wave, which is

$$\phi(t) = 2\pi \int^{T} f(t)dt \quad \text{(in radians)} \tag{2}$$

Assume for a crystal oscillator that its frequency of oscillation can be expressed by a time series:

$$f_1(t) = f_r \pm f_o \pm at \pm bt^2 + \ldots\ldots \tag{3}$$

where f_r = specified frequency at the output terminal

f_o = offset or bias frequency at each calibration epoch which permits practical finite settability resolution and crystal procurement.

a = drift or aging rate of crystal effecting frequency of oscillation.

b = rate of change of drift or acceleration of the frequency of oscillation.

Now in any time period between calibration epochs we assume (a) the coefficients of the series are constant, (b) rapid convergence of the series so that the higher order components of the time series, equation (3) are negligible, and (c) the polarities of each coefficient are typical of crystal standards when operating in normal terrestrial environments so that

$$f_1(t) \approx f_r - f_o + at \tag{4}$$

The output of the oscillator is a vector quantity

$$v(t) = V e^{j\phi(t)} \tag{5}$$

where the accumulative phase in the interval is

$$\phi_1(t) = \left[2\pi \left(f_r - f_o + \frac{at}{2} \right) t \right]_0^T \tag{6}$$

The accumulated phase-time function of equation 6 can be compared to the numerically specified output of the system.

$$\phi_2(t) = \left[2\pi\, f_r\, t\right]_0^T \qquad (7)$$

to determine the amount of phase compensation required as a function of time which is

$$\phi_c(t) = -2\pi \left[(-f_0 + \frac{at}{2})t\right]_0^T \quad \text{radians} \qquad (8)$$

or

$$\phi_c(t) = -360 \left[(-f_0 + \frac{at}{2})\, t\right]_0^T \quad \text{degrees} \qquad (9)$$

But at any time, t, the required phase compensation may also be expressed as

$$\phi_c(t) = -360\, n(t) - \theta(t) \qquad (10)$$

where n(t) is limited to integral values 0,1,2,3,...N, and $\theta(t)$ is limited to values less than 2π radians. If the time, t_0, represents a system calibration and reset epoch then n(t) is merely the accumulative number of times that the phase controller has been commutated and $\theta(t)$ is the current phase position within the bounds of 0 to 360 degrees.

In a phase adjusted frequency shifter the signal output from the controller is

$$v(t) = A \cos\left[2\pi\, (f_r - f_0 + at)\, t + \phi_c(t)\right] \qquad (11)$$

If a logic controlled incremental phase shifter is used the output can be expressed as

$$v(t) = A \cos\left[2\pi\, (f_r - f_0 + at)\, t + \Delta_\theta t \cdot g(t)\right] \qquad (12)$$

Where Δ_θ = magnitude of phase increment equal to $2\pi/M$ radians
g(t) = a variable switching function as predicted for each interval between system calibration epochs based on oscillator offset and extrapolated drift rate.

Assuming an ideal prediction for incremental phase adjustment:

$$\Delta_\theta t \cdot g(t) = 2\pi\, (f_0 - at)\, t + \frac{\delta\theta}{2}(t) \sum_{n=-\infty}^{\infty} C_n\, e^{jn\omega(t)t} \qquad (13)$$

so that the phase controller output becomes:

$$v(t) = A\cos \left[2\pi f_r t + \frac{\delta\phi(t)}{2} \sum_{n=-\infty}^{\infty} C_n e^{jn\omega(t)t} \right] \quad (14)$$

This describes a signal at precisely the desired carrier frequency but one having residual low level symmetrical sidebands due to the quantification employed in the phase adjustment.

The deviation ($\delta\theta$) and the modulating frequencies ($n\omega$) in equation 14 can be considered constant for periods much longer than the interval of a single commutation of the phase controller so that the residual phase modulation spectrum is amenable to estimation by standard Fourier techniques. The incremental phase compensation is illustrated in Figure 2.

At the beginning of life when the offset (less drift), f_o -at, is 4.48 PPM the fundamental modulating frequency (f_{ml}), for a correction of a 5 MHz oscillator frequency while assuming 18° phase increments, is approximately
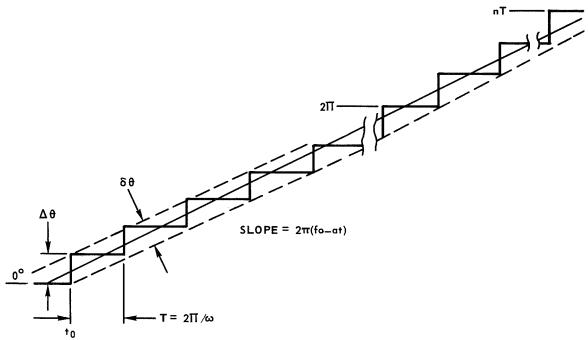
$$f_{ml} \bigg|_{SOL} \approx \frac{360}{18} \times 5 \times 10^6 \times \frac{4.48}{10^6} = 448 \text{ Hz} \quad (15)$$

At the system end of life if the accumulated drift is 2 PPM in a sense opposite to the frequency offset then
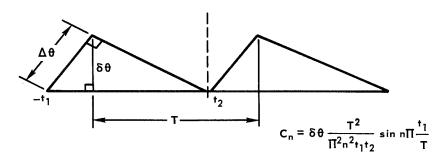
$$f_{ml} \bigg|_{EOL} \approx \frac{360}{18} \times 5 \times 10^6 \times \frac{2.48}{10^6} = 248 \text{ Hz} \quad (16)$$

Since the peak-to-peak deviation $\delta\theta$ of the incremental modulation is always less than the incremental step $\Delta\theta$ = 20 degrees, the maximum energy level of any sideband frequency can be expected to be down about 25 dB or more relative to the corrected carrier. (For small deviations halving the size of the phase step reduces the 1st order Sideband Power by 6db.)

If the frequency adjusted output of the incremental phase controller is to be used in any system requiring synthesis with large multiplying factors for the generation of an RF carrier it is clear that the residual PM sideband energy must be attenuated with a frequency selective transmission filter. A thorough analysis of the specific application is

SLOPE $= 2\pi(f_o - at)$

$T = 2\pi/\omega$

(a) INCREMENTAL ADJUSTMENT OF FREQUENCY

$$C_n = \delta\theta \, \frac{T^2}{\pi^2 n^2 t_1 t_2} \sin n\pi \frac{t_1}{T}$$

(b) RESIDUAL PHASE MODULATING WAVEFORM

Fig. 2   PHASE VERSUS TIME FUNCTIONS

needed when stating the exact characteristics of the filter,
however a relative attenuation of the sideband frequencies
from 200 to 500 Hz in the order of 60 dB is feasible for many
applications.

PHASE CONTROLLER MECHANIZATION

There are several configurations that may be used
to achieve a reliable solid state (or at least all electronic)
mechanization of an incremental phase controller for frequency
compensation. Examples are given in Figures 3, 4, and 5. The
four quadrant incremental phase controller is most compatible
with integrated circuit design. The LC components of the delay
line approach and the transformer-capacitor devices in the RC
network are less desirable from an integrated circuit point of
view, however, these are appropriate mechanizations in applica-
tions where space and weight are not controlling.

The delay line approach is described more fully by
Bateman (Reference 3 and 4), however, the use of paraphase
amplifiers is suggested as a means of reducing the number of
LC components. The sequential commutator design will employ
transistor switching generally as described by Bateman.

In the incremental phase compensation approach to the
generation of accurate TIMING epochs, note that exceedingly
small admustments can be made, yet relatively low frequency
components are adequate. For example in a 0.1 μsec. Time re-
covery system, the 20 phase steps at 5 MHz as suggested above
presents a potential control capability to 0.01 μsec. In
comparison, in a clock divider pulse deletion technique (the
method currently employed in the Navigation Satellite and
many other systems), the capability to adjust time in incre-
ments as small as 0.01 μsec. will require operation at a 100
MHz frequency level.

PRELIMINARY TEST PROPOSAL

In advance of testing of a complete system as illus-
trated by Figure 1, preliminary tests are suggested using the
equipment arrangement in Figure 6, for the purpose of obtaining
and analysing data on the residual (spectral) level of phase
modulation with and without filter smoothing, as a function of
the commutating rate of the incremental phase changes. The
spectral lines should be correlated with the commutating rate,
the number of phase steps in 2_π, and with the linearity or dis-
persion in the size of each phase step.

When the complete system is eventually placed in an
orbiting satellite tests should be made using a hydrogen maser
clock as a reference to determine the precisions to which time

PHASE LINEAR 4 QUADRANT
INCREMENTAL
"POTENTIOMETER"
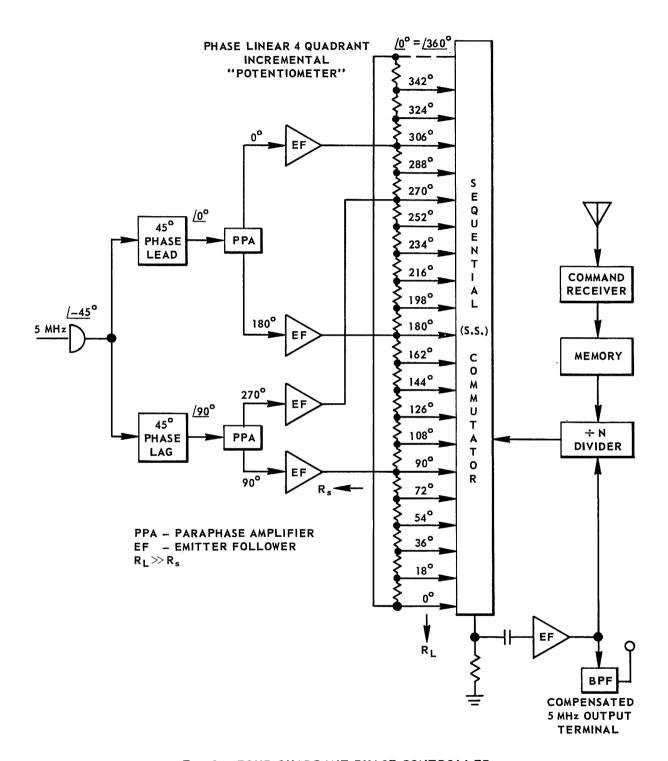
Fig. 3   FOUR QUADRANT PHASE CONTROLLER

PPA – PARAPHASE AMPLIFIER
EF   – EMITTER FOLLOWER
$R_L \gg R_s$
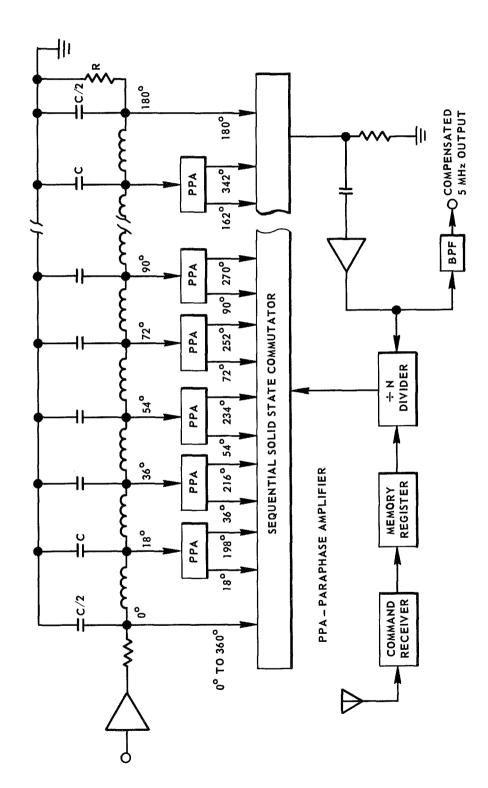
Fig. 4 DELAY LINE PHASE CONTROLLER

PPA – PARAPHASE AMPLIFIER

- 165 -

COMMUTATED SOLID
STATE SWITCHES

$$\frac{V_2}{V_1}(s) = \frac{1-kCRs}{1+kCRs}$$

Fig. 5   RC PHASE CONTROLLER

HP 5100B/5110B

LABORATORY
REFERENCE
SIGNAL

5 MHz

LOW FREQUENCY
FUNCTION
GENERATOR

HP 202A

10–25 Hz

INCREMENTAL
PHASE
CONTROLLER

BPF

MIXER

HP MODELS
10514 A/B
OR
10534 A/B

20 Hz TO 50 kHz
7 Hz SAMPLING
BANDWIDTH

WAVE
ANALYZER

HP 302A
OR EQUIVALENT

Fig. 6   LABORATORY TEST CIRCUIT FOR RESIDUAL MODULATION ANALYSIS

calibrations of the satellite can be made and also the degradation in accuracy of timing vs. the interval between calibration epochs.

CONCLUSIONS

This report has described the principle features of the phase adjustment method of compensation of secondary frequency standards and has shown the method to be both feasible and practical for accurate **TIME AND FREQUENCY** applications. The sequentially scanned incremental phase adjustment method can provide a bias offset in frequency and can be programmed to compensate for the drift of the secondary standard over a predictable interval. The control can be achieved with digital logic. Mechanization is feasible at low frequencies (typically 5 MHz) with the vast majority of the components in integrated circuit packaging. The mechanization at 5 MHz, with 20 phase steps of 18 degrees each per cycle permits adjustments and calibrations of **TIME** epochs with a resolution of 10 nanoseconds.
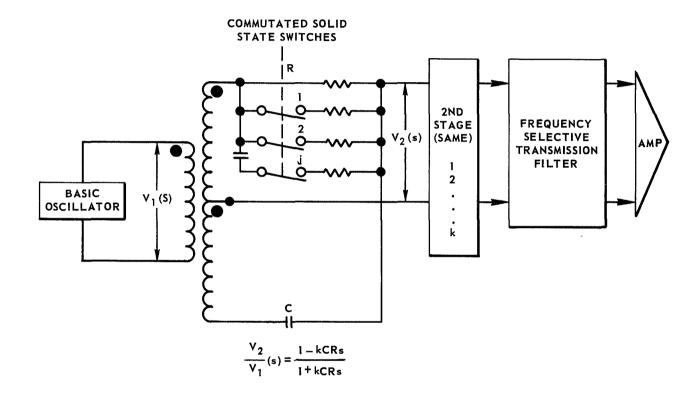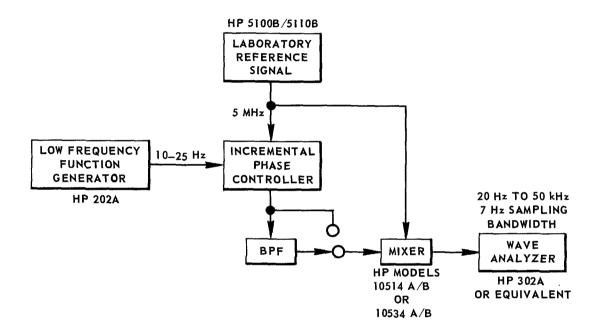
Among the advantages which may be cited in favor of the incremental phase adjustment concept are the following.

1. It is programmable and controllable with digital logic concepts and components.

2. Only one oscillator is required in the system.

3. The parameters and environment of the source oscillator are independent and unaffected by the compensation.

4. The resolution for **TIME** epoch adjustment can be in the nanosecond region with circuitry operating in the 5 MHz region.

5. The residual phase modulation energy is small and can be designed to fall in frequency bands sufficiently far removed from the compensated output carrier that passive transmission filters may be used for further attenuation.

6. The possibilities of mechanization of the compensating system using solid state integrated packaging is excellent.

7. Design tradeoffs, between (a) the total offset frequency, (b) the size and number of incremental phase positions per cycle of compensation, and (c) the frequency at which the compensation is applied, may be manipulated to adjust the resolution of the control, and also the energy and spectral distribution of the residual phase modulation energy (before filtering).

8. The incremental phase adjustment provides, in a single system, the capability for (a) direct or delayed tuning of a secondary standard from its arbitrary frequency of oscillation to a specified offset of relatively large numerical value, with acceptable errors in the presence of systematic drifts; (b) normalizing a **TIME** scale to conventional time units (seconds, minutes, etc.) in a combined **TIME AND FREQUENCY** System where the frequency of oscillation does not have an integral relationship to the time unit or marker repetition rate; and (c) calibrating the **TIME MARKER EPOCHS** as generated to a recognized **STANDARD REFERENCE OF TIME.**

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APPENDIX E

GEOS TIME AND FREQUENCY PARAMETERS

Part I - List of RF Channel Allocations (GEOS B):

A. Satellite Active Radio Transmissions

    1. Coherent Doppler Channels:

        a. 972 MHz - 50 PPM, transmitter power - 0.5 watts carrier signal only.

        b. 324 MHz - 50 PPM, transmitter power - 0.5 watts carrier plus PM time marker at 1 PPM.

        c. 162 MHz - 50 PPM, transmitter power - 0.25 watts carrier plus PM time marker at 1 PPM.

        Note: Each carrier and time marker waveform are derived from the on board precision secondary frequency standard. Oscillator drift is uncompensated relative to carriers but is normalized by pulse deletion techniques under memory command relative to timing waveforms. The time normalizer can accomodate a deviation of ±19 PPM from the nominal offset of -50 PPM covering a range of offsets from -31 PPM to -69 PPM.

    2. Telemetry Channel:

        136.32 MHz $\pm$ .001% at 0.4 watts transmitter power carrier plus two FM subcarriers carrying telemetry data plus the time marker waveforms as a composite PM on the carrier.

        Note: The time marker waveform is the same as for the Doppler channels. The telemetry carrier and subcarriers are derived from independent nonsynchronous oscillators.

B. Satellite Radio Relay Transmissions

    1. UHF Transceiver.

        a. Receive at 421.0 MHz.

        b. Transmit at 224.5 MHz and 449 MHz.

        Note: This subsystem is for SECOR ranging.

2. S-Band Transceiver.

    a. Receive at 2270 MHz.

    b. Transmit at 1705 MHz.

    Note: This subsystem accomodates the NASA-GSFC
           Range and Range Rate measurements.

3. C-Band Transponder.

    a. Receive at 5690 MHz.

    b. Transmit at 5765 MHz.

    Note: This subsystem is for pulsed radar ranging
           and has a peak pulse output of 400 watts.

Part II - Satellite Synthesis Chains (GEOS B):

A. RF Carrier Frequencies (at the satellite transmitter)

    1. Coherent Doppler Channels (5 MHz common reference):

        a. $(5 \text{ MHz}-50 \text{ PPM}) \times \frac{3}{5} \times 6 \times 3 \times 3 \times 3 \times 2 = 972 \text{ MHz}-50 \text{ PPM}$.

        b. $(5 \text{ MHz}-50 \text{ PPM}) \times \frac{3}{5} \times 6 \times 3 \times 3 \times 2 = 324 \text{ MHz}-50 \text{ PPM}$.

        c. $(5 \text{ MHz}-50 \text{ PPM}) \times \frac{3}{5} \times 6 \times 3 \times 3 = 162 \text{ MHz}-50 \text{ PPM}$.

    Note: (1) Common point in synthesis chain is at 3 MHz.
           (2) PM is applied at 54 MHz (separately on the
                324 and 162 MHz channels) to deviate the RF
                output carrier $\pm 45^{\circ}$ during time marker burst.

    2. Telemetry Channel (8.52 MHz crystal oscillator):

        $(8.52 \text{ MHz} \pm .001\%) \times 2^{4} = 136.32 \text{ MHz} \pm .001\%$

    Note: (1) PM is applied at 8.52 MHz to deviate the final
                RF carrier ± 1.5 radians.
           (2) Subcarriers employ voltage controlled oscil-
                lators at 2.3 and 5.4 KHz with no synthesis.

B. Time Marker Waveforms

    1. Marker Characteristics:

        a. Periodic burst.

        b. Repetition rate - 1 per minute.

c.   Modulation frequency - 186.88 PPS.

d.   Format: 66 cycles of square wave at zero
     phase followed by 7 cycles of square wave
     at 180° phase.

e.   Fiducial Timing Mark - end of cycle following
     phase reversal, calibrated to 6.842 msec
     after the integer minute.

f.   Satellite Transmissions: 136 MHz Telemetry Channel
     (with time marker)   162 MHz Doppler Channel
                                324 MHz Doppler Channel.

2.   Clock Divider Chain:

$$\left\{\left[(5\ MHz-50\ PPM)\overset{N1}{\div}7-(Fast\ Delete)\right]\overset{N2}{\div}7-(Normal\ Delete)\right\}\overset{N3}{\div}$$

$$4485 \div 1365 = 1\ PPM$$

Note: (N1)   Source is the same precision secondary
              standard that is used for Doppler Channel
              carrier synthesis.

       (N2)   Fast delete Time normalization occurs at
              714,250 Hz nominal, representing 1.4μsec
              delay shift per each deletion. In normal
              operation a fixed deletion of 5 pulses
              occur each minute during Word 61, Bits 13
              through Bit 18. In addition vernier deletions
              are commanded from the satellite memory,
              a variable number of pulse deletions between
              zero and ten, which occur during even bits
              of word 60.

       (N3)   Normal delete Time normalization occurs at
              102 KHz, representing 9.8μsec delay shift
              per each deletion. In normal operation a
              fixed deletion of 117 pulses each minute
              are distributed during words 1 through 59,
              Bits 18 through 21.

       (N4)   The satellite memory comprises 1365 bits
              arranged in 65 words of 21 bits each.

       (N5)   Other clock outputs are provided at:

              186.88 Hz
              22.75 Hz
              0.25 Hz.

Part III – Source Documents for Parametric Data (included
above):

A. JHU/APL Block No. 7211 Design Data Sheets.

B. JHU/APL Technical Report TG-896, "A Delayed Command
System for a Near-Earth Satellite", by R. S. Cooperman,
dated April 1967.

C. JHU/APL Instruction Manual SDO-2207, "GEOS Time
Recovery System", dated October 1967.

APPENDIX F

IMPLEMENTATION OF WORLD-WIDE ACCURATE
TIMING WITH A GEOS SATELLITE

Part I - System Objectives.

A satellite system is desired for the generation, transmission and recovery of TIME reference signals that will permit world-wide calibration and synchronization of frequency standards and timing ·clocks with (1) moderate accuracy, i.e., 1 to 10 microseconds error, using inexpensive ground station equipment, and also (2) high accuracy, i.e., 0.1 to 1 microsecond error, using more sophisticated ground station equipment and procedures.

Part II - Candidate Approaches using a GEOS satellite.

    A.   Active Time Dissemination by Orbiting Radio Clock to Passive Users.

        1.   Doppler channels: carriers plus Time Marker PM at 972, 324 and 162 MHz.

    B.   Candidate Subsystems for the Potential Transfer of Time Between Active Users via Satellite Radio Relay.

        1.   UHF (SECOR Ranging) Transceiver.

        2.   S-Band (GSFC Range/Range Rate) Transceiver.

        3.   C-Band (Pulsed Radar Ranging) Transponder.

Part III - Anticipated GEOS-C Subsystems pertinent to Time Reference Signals.

The Preliminary technical plan for GEOS-C which is subject to modification with the direction and concurrence of NASA indicates that the following subsystems will be available and will support the technical achievement of an operational system for transmission and recovery of time references on a world-wide basis with high accuracy.

    A.   The Satellite Frequency Standard.

        1.   Rubidium reference mode.

        2.   Precision (non-slaved) crystal mode.

    B.   Satellite RF Subsystems.

        1.   Coherent carrier signal generation and transmission at each of the 162, 324, and 972 MHz doppler channels.

2. A wideband transceiver system at the unified S-Band (USB) frequencies for range and range rate measurements. The exact carrier and sidetone modulating frequencies are controlled by the using radio terminals (under GSFC direction).

3. An X-Band radar altimeter system (parameters to be established).

4. A telemetry channel for readout of satellite data near 136 MHz, the exact carrier frequency to be determined by NASA for compatibility with the MINI-TRACK and STADAN terminal receiver operation.

Part IV - Preliminary Suggestions for GEOS-C Time Subsystems.

A. To satisfy the objective of obtaining a coarse accuracy (1 to 10 μsec) Time Recovery System, retain but improve the time normalization accuracy of the present time marker modulation for transmission on the 136 MHz telemetry and 162 MHz doppler channels. The Time Mark Decoder presently incorporated in NASA terminals, which is a 'low cost' item, may be used without redesign. Consider also the feasibility and benefit of time marker repetition rates more frequent than 1 per minute.

B. To satisfy the objective of obtaining a high precision, high accuracy (0.1 to 1 μsec) Time Recovery System, design a new digital modulation waveform with precise time epochs for the continuous modulation of one or both of the 324 and 972 MHz coherent doppler carriers. The modulation format should be compatible with a class of decoders having coarse or high accuracy depending upon terminal (or station) complexity and decoder cost.

C. Consider the use of the Time Transfer techniques using the unified S-Band transceiver both for high precision time synchronization between active ground stations, and also for management and calibration of the on-board Satellite Clock TIME Dissemination System.

D. Among the primary system constraints are the basic limitations on available satellite prime power for sustaining the Rubidium standard, synthesizer and clock dividers and for the generation of RF power. The system is constrained to the radiation of three coherent carriers for doppler measurement of range rate at 972, 324, and 162 MHz (with nominal offset of 50 PPM).

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11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
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13. ABSTRACT

The application of artificial satellites in providing radio reference signals for the synchronization and calibration of local clock and timing systems has been studied. Space technologies in the specific areas of geodesy and navigation are applied with digital signaling techniques and atomic time and frequency standards. The result of the study predicts that a useful operational service can be provided on a global basis with a low-altitude polar satellite having an on-board atomic clock to most effectively satisfy user requirements at various levels of system accuracy. For fixed site users, system accuracies as good as 100 nanoseconds (rms) are realistic with sophisticated equipment and data processing.

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14.	KEY WORDS

Accuracy
Atomic Clock
Calibration
Compensation
Digital Signaling
Doppler
Encoding
Error Analysis
Geodesy
GEOS
Modulation
Navigation
NAVSAT
One-way Timing
Orbiting Clock
Propagation
Radio Systems
Receivers
Satellites
Stability
Standards
Synchronization
Systems Study
Time and Frequency
Time Transfer