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TIME AND FREQUENCY DISSEMINATION USING SATELLITE TRANSMISSIONS

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The need for accurate time and frequency calibration at remote locations, traceable to national standards, is increasing. The accuracy required by the user can widely vary. Several methods of time and frequency dissemination are in use and some are in experimental stage. The use of artificial earth satellites in navigation systems offer the ability of disseminating time and frequency. The capabilities of the currently available navigational satellites and the potential of the proposed satellites are reviewed. In particular, the possibilities of the NAVSTAR Global Positioning System are described.

INTRODUCTION

SATELLITES have been used for a number of years for transfer of time and frequency between primary standards and users of precise time (Easton *et al.*, 1976). Radio beacon transmission from satellites in the VHF, UHF or microwave region offer several advantages over the conventional radio dissemination methods. The major disadvantage of using conventional ionospherically reflected HF radio transmission is the uncertainty in computing or predicting the propagation path delay. The refractive index of the intervening ionosphere and troposphere, for most satellite-to-earth radio paths at the frequencies used in satellite systems, is near the free-space value and the atmospheric effects constitute only a small fraction of the total path. Further, the propagation delay can be calculated to a high degree of accuracy. Multipath effects are negligible for all but the high accuracy systems using reception at low elevation angles.

The users of time are usually classified into three categories based on their required accuracy:

1. Low accuracy — 1 second to 1 millisecond
2. Intermediate accuracy — 1 millisecond to 50 microseconds
3. High accuracy — 50 microseconds to 1 nanosecond

The time accuracy requirements of some typical users in these categories and the capabilities of representative time dissemination techniques and services are shown in Fig. 1 (Jesperson *et al.*, 1972).

CHOICE OF SATELLITE SYSTEM CONFIGURATIONS

In time and frequency dissemination *via* satellites, there are several configurations to consider. One can use a geostationary satellite or a low orbiting satellite. A geostationary satellite offers the advantage that continuous coverage can be

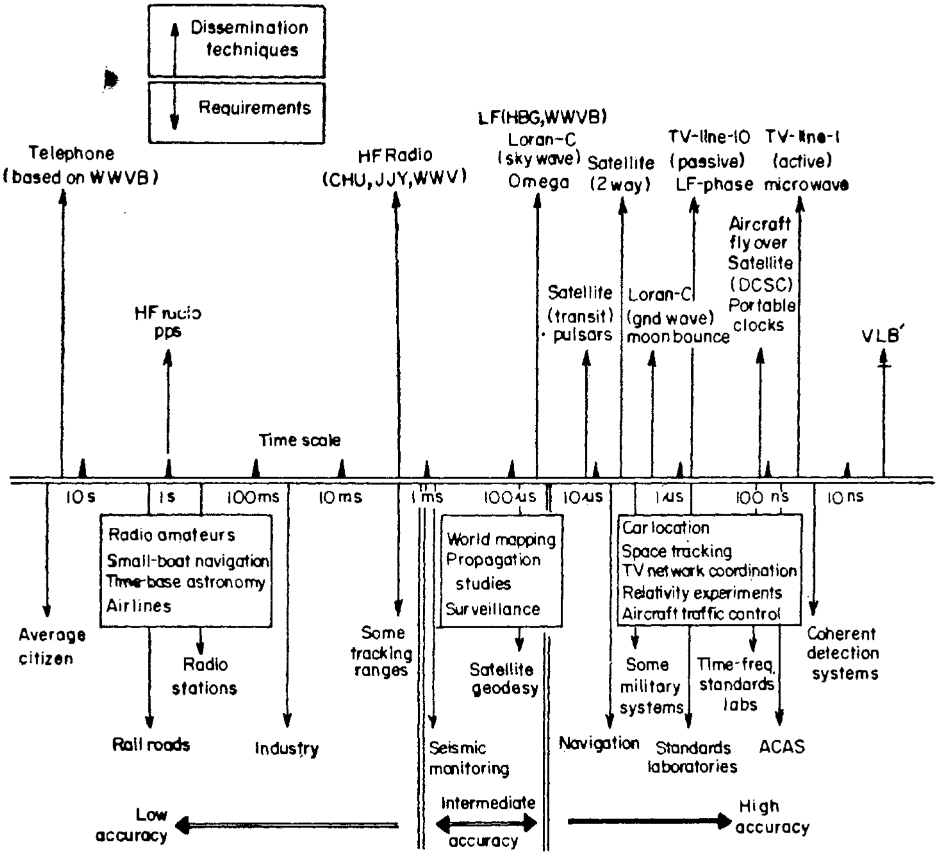

FIG. 1. Time accuracy requirements of different users and capabilities of dissemination techniques.

provided over a third of the globe excepting at the poles. On the other hand, a high-inclination low-orbiting satellite provides worldwide coverage but only for a limited duration at each location during each pass. While three geostationary satellites provide complete global coverage, several low orbiting satellites would be required for providing substantial but intermittent worldwide coverage.

A satellite can be used as retransmitter of a time signal emanating from a clock located at a ground station or as an emitter of time signals from an on-board clock. Operation of an on-board clock requires clock maintenance and periodic adjustment. On the other hand, a satellite used as a retransmitter permits the clock to be maintained on the ground and allows a general purpose communications satellite to be used on a time-shared basis, but requires a transponder.

Again it is possible to have a one-way or a two-way transmission. The advantages of such transmission are summarised as follows:

One-way transmission	*Two-way transmission*
1. Widespread service area	1. Ease of confinement to limited areas on earth
2. Good timing accuracy	2. Demonstrated timing accuracies of the order of nanoseconds
3. Simple methods for time recovery	3. May be the only practical way to effect time transfers to certain remote areas with submicrosecond accuracy.

TIME/FREQUENCY DISSEMINATION USING NAVIGATION SATELLITES

Time and frequency play a key role in modern navigation. Therefore, navigation satellites usually have an on-board clock of high stability as part of the navigation system. Thus, navigation satellites while providing reliable and accurate navigation aids, offer, at the same time, the ability of disseminating time and frequency to a high degree of accuracy.

At present, the operational navigational satellites are the 'low-orbiting type' to make full use of the Doppler technique. The only operational system is the US Navigational Satellite System (NNSS) with six low altitude satellites, the details of which are given in Table I.

TABLE I

Characteristics of operating transit (NNSS) satellites

Scientific Name	Launch (Date)	Period (min)	Perigee (km)	Apogee (km)	Inclination (deg.)	Eccentricity
1973–81 A	25.10.73	106	896	1152	90.1	0.0004
1970–67 A	27.8.70	106.98	949.7	1218.2	90.04	0.018
1968–12 A	2.3.68	106.93	1024.7	1138.4	89.99	0.0076
1967–92 A	25.9.67	106.75	1036.0	1110.6	89.23	0.0050
1967–48 A	18.5.67	106.96	1066.8	1099.0	89.63	0.0022
1967–34 A	14.4.67	106.48	1046.9	1074.3	90.20	0.0018

The NNSS navigation system makes use of the Doppler shift on two carrier frequencies, viz., 150 MHz and 400 MHz. The observed Doppler shift is dependent on the relative position of the observer with respect to the position of the satellite and hence on his position on earth. The navigation message contained in the satellite's memory system is transmitted to the ground as phase modulation on the transmitted carrier frequencies. This navigation message is continuously and repetitively transmitted, and is carefully timed to last exactly two minutes, beginning and ending at the instant of even minute. The clock pulses are derived from a highly stable oscillator (1 part in 10^9). Because the message readout is so precisely controlled, the beginning and the end of each two-minute message serves as an accurate even-minute time mark.

TABLE II
Characteristics of TIMATION satellites

Satellite Name	Launch Date	Orbit height	Inclination deg.
TIMATION I	31 May 1967	Circular 570 km	70
TIMATION II	30 Sept. 1969	Circular 580 km	70
TIMATION III	14 July 1975	Circular 13600 km	125

TIMATION or Time Navigation System, is time based technique which permits a passive measurement of the range of the satellite to a navigator. Two low-altitude satellites and a third medium altitude have been launched (Table II).

In the TIMATION technique of passive ranging, the range to the satellite is computed by measuring the time it takes a radio signal to travel from the satellite to the navigation receiving equipment. The TIMATION satellite transmits the following modulation sequence on its 400–MHz carrier : 100Hz, 300Hz, 1KHz, 3KHz, 10KHz, 30KHz and 100KHz signal continuously. The time delay is obtained by a sequenced phase comparison between the satellite and navigation's clocks. The higher modulation frequencies give progressively higher resolution. The use of 100 KHz allows a resolution of 0.1 us.

NAVSTAR GLOBAL POSITIONING SYSTEM

The NAVSTAR satellites of the Global Positioning System (GPS) is a satellite-based navigation system and will soon provide worldwide access to precise timing signals (Smith & Criss, 1976) which will enable a properly equipped user to calibrate a local time source relative to a primary standard or compare two clocks, to a precision within fractions of a microsecond. The NTS–1 spacecraft is the third satellite in a series of advanced research and technology satellites, previously known as TIMATION satellites, built and operated by the U. S. Navy Research Laboratory. The primary objectives of these missions were advanced clock development, satellite navigation and orbit determination; but a natural by-product of such work is the precise transfer of time using remote receiver sites. The first fully operational satellite of the GPS system, the Navigation Technology Satellite–II (NTS–II) was launched in June, 1977. The Navigation Development Satellite (NDS) of the GPS has been launched in 1978 to form a test constellation with the operational NTS–II satellite which was launched into a near circular orbit at an approximate altitude of 20,000 km and at an inclination of 63° with a period of 12 sidereal hours. The GPS system eventually calls for the development of a constellation of 24 navigation satellites in circular, sub-synchronous 12 hr orbits to provide global navigational coverage. Each of these satellites will be in view for an average of six hours per day anywhere in the world. At least one satellite is in view about 18 out of 24 hours each day.

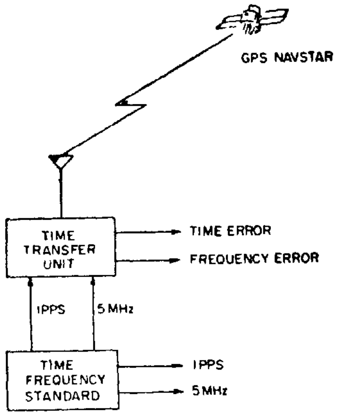

FIG. 2. GPS Time Transfer Geometry for single receiver location.

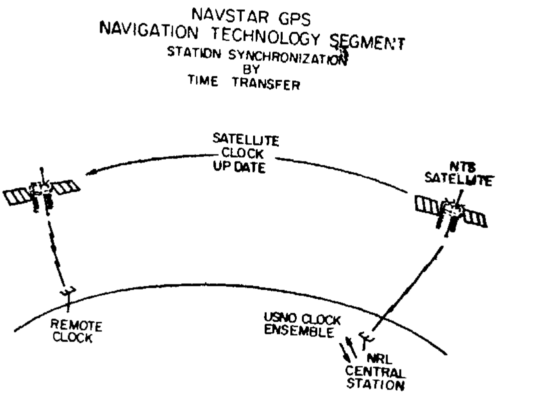

FIG. 3. GPS Time Comparison Geometry for two ground stations.

The basic time transfer with a single receiving location is shown in Fig. 2. The receiver accepts stable reference time (1 pps) and frequency (5 MHz) signals from a local time standard or a clock to be calibrated, and the signal at 1575 MHz from any GPS NAVSTAR satellite. Ephemeris data from the NAVSTAR satellite is detected and processed to determine the position of the satellite and hence to estimate the time of arrival of the satellite signal epoch. The actual time of arrival is recorded and compared with the expected value after correction for ionospheric, tropospheric, and relativistic errors.

A typical ground station configuration for comparing two ground station clocks is depicted in Fig. 3. Range observations are made at two or more sites by processing the signals transmitted from the spacecraft. These observations are then combined to obtain the difference between the two ground clocks, after allowing for the drift of the satellite oscillator for the time difference of the observations.

The time transfer technique used is illustrated in Fig. 4 which shows a typical satellite, user and received time epochs relative to system (GPS) time. GPS satellites transmit continuous navigation signals with readily identifiable epochs every 6 seconds. The satellite transmission is determined by an atomic standard which will differ by some amount 'A' from system time. An estimate of A is contained in the navigation data and is available to the time transfer receiver (TTR). The satellite epoch arrives at the TTR and is detected at some later time and is measured by reference to the local station time reference C. The transit time (A + B + C) can be estimated from satellite ephemeris and ionospheric error available in navigation data, and from known user location and equipment bias calibrations. The station time error is taken as the difference between expected and measured time of arrival.

The heart of the system is a receiver which determines the range of the satellite in terms of the time required for its transmitted signal to reach the receiver by side-tone ranging. Side-tone ranging involves phase comparisons

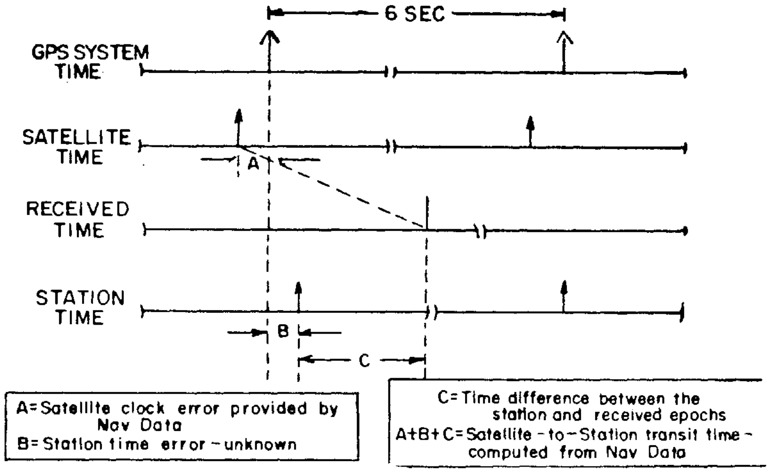

FIG. 4. Basic time transfer technique using GPS.

between the satellite transmitted tones and receiver generated tones of the same frequency. Both sets of tones are derived from very stable frequency sources so that the phase differences represent mostly the propagation delay with some error due to small frequency drift in the sources, ionospheric refraction, and propagation delay in the receiver. The last one is significantly constant for each tone and can be calibrated out. The other errors have to be dealt with in the data processing performed subsequently.

The signals transmitted from the spacecraft consist of a carrier at 335.355 MHz, a reference tone at 335.325 MHz and ten sequentially occurring tones from 335.324900 MHz through 328.92500 MHz. These signals may contain a doppler shift proportional to frequency. The tones synthesized in the receiver are compared with those of the satellite to get phase information. Usually several samples are taken for each tone and a least squares fit is used to the data points. The data is then used to derive the range.

The phase differences thus determined represent the propagation delay and clock error between the satellite clock and the receiver clock. These phases are interpreted in terms of observed range to the satellite in milliseconds. The phases of the lower tones are used to get a rough range and those of the higher tones are used to resolve range to nanosecond accuracy. The range resolution is given by (Raymond *et al.*, 1977).

$$R_i = \frac{Q_i + \text{INTEGER } R_{i-1}^{f_i + 1/2 - Q_i}}{f_i},$$

where Q_i is the phase of ith tone,

f_i is the frequency of the ith tone and

R_i is the range in seconds whose accuracy is based on the phase of the ith tone.

Usually the phase of each tone is measured to an accuracy of 1 per cent. The accuracy of the final range is 1 per cent of the 6.4 MHz tone period or 1.56 nsec.

In order to achieve maximum accuracy for time transfer it is required to have minimum uncertainty in the following parameters:

1. Satellite Clock.
2. Ground Station Clock.
3. Radial location of the satellite.
4. Ground station antenna position.
5. Transmission path.

In any case, the quantitative value of the uncertainties for all the above parameters should be available to determine the accuracy of the time trasfer.

The major sources of error are summarized in Table III. These errors are associated with a single measurement and can be improved upon from smoothing over multiple samples or combining measurements from multiple satellites.

TABLE III

Sources of error

TTR	Error Budget
Satellite Ephemeris	10 ns
Satellite Clock Drift	10 ns
Ionosphere/Troposphere Refraction error	30 ns
User location/calibration	15 ns
Receiver noise	20 ns
RMS error	41 ns

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