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AN ENGINEERING FEASIBILITY STUDY FOR ONE-WAY TIME TRANSFER USING THE GOES SATELLITE RANGING SYSTEM

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AN ENGINEERING FEASIBILITY STUDY FOR ONE-WAY TIME TRANSFER USING THE GOES SATELLITE RANGING SYSTEM

J. B. Milton and W. F. Hamilton

The Time and Frequency Division of the National Bureau of Standards has conducted an engineering study to determine the feasibility of using the GOES satellite ranging system for precise (0.1 microsecond, one-sigma) time transfer to a receiving-only timing site. The GOES satellite ranging system, termed a trilateration system, will accurately locate this satellite within some coordinate structure. The sources of time transfer errors have been studied in some detail. These errors can be caused by satellite location errors, ground station location errors, unknown delays caused by the troposphere, the ionosphere, and the various equipments. Simplified designs for an automatic and a manually operated timing site are presented. Some technical problems found in the associated equipment are discussed. The study indicates that a secondary, or slave site, clock could be synchronized to within 0.1 microsecond, one-sigma, of some master clock utilizing a one-way, or receiving-only system.

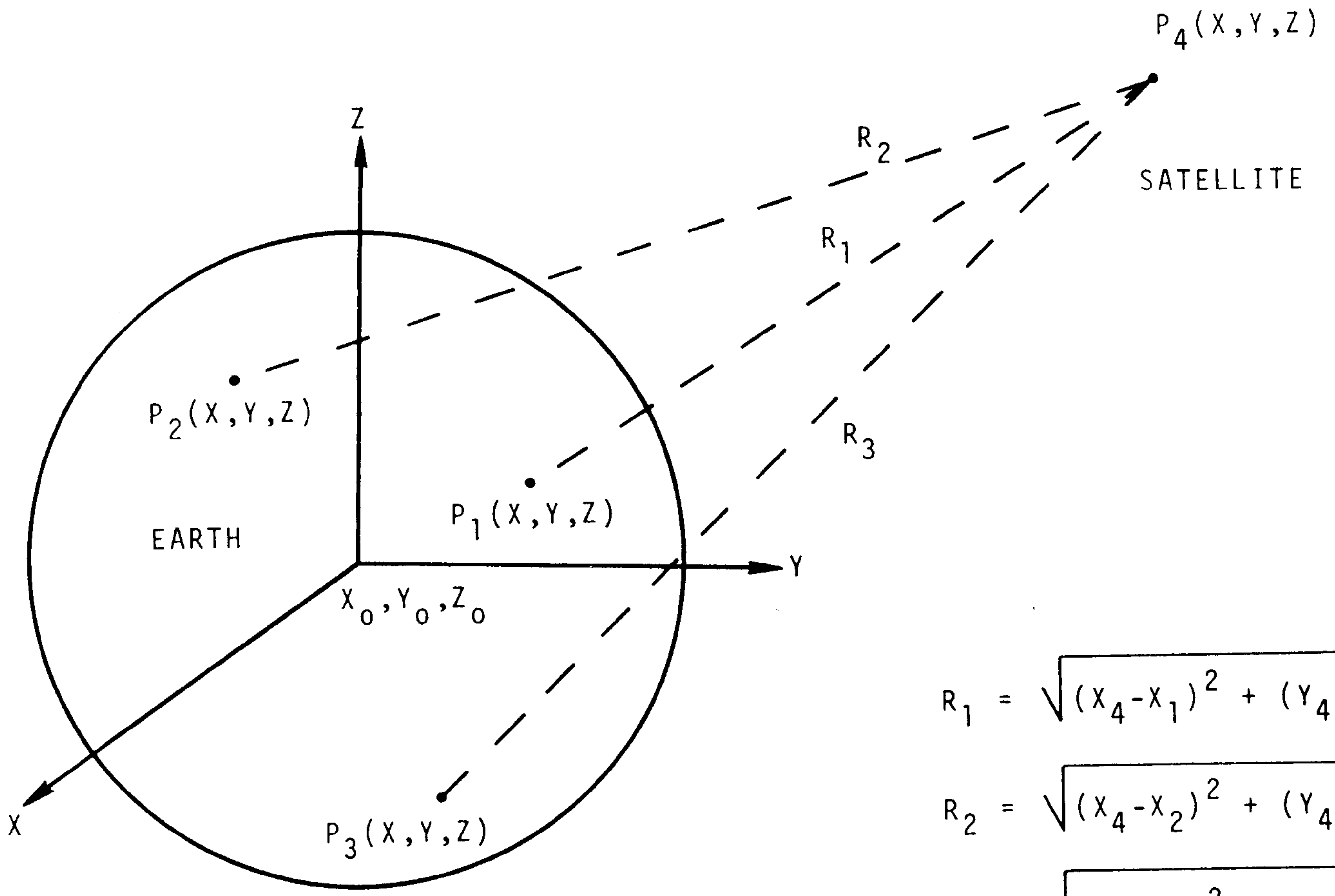
Key words: Clock synchronization; one-way time transfer; satellite timing; synchronous satellite.

1. INTRODUCTION

Sometime in early 1974, NASA plans to place the first of a series of new environmental satellites in synchronous orbit. These satellites will be called Synchronous Meteorological Satellites (SMS). When NOAA, the operating agency, begins using these satellites, they will be redesignated as Geostationary Operational Environmental Satellites (GOES). Part of the mission for GOES will be to take pictures of storm patterns, frontal systems and the like. In order to accurately locate these pictures with respect to earth longitude and latitude precise information on the location of the satellite must be obtained.

Toward this end, a new ranging system for these satellites has been developed for NOAA that has a theoretical precision of about one meter and an accuracy limited basically by the real time knowledge of the effects of the ionosphere and the troposphere [1]. This ranging system, termed trilateration, uses only time delay data obtained from three widely separated ground stations. No azimuth measurements are necessary. The primary tracking station, referred to as the Control and Data Acquisition Station (CDA), is located at Wallops Station, Virginia. The two unmanned secondary stations, called Turn-Around Ranging Stations (TARS) will be located at Santiago, Chile and either Honolulu, Hawaii, or Ascension Island, in the mid-Atlantic Ocean. This system of three locations will provide three slant ranges to the satellite. The location of the satellite is then determined geometrically (see fig. 1).

Another major mission of the GOES satellite will be to gather environmental data from many sensors located in rivers, tidal areas, and other strategic locations. The sensor data will be returned to the CDA via the GOES satellite. The ground equipment that will perform this function is referred to as a Data Collection Platform Radio Set (DCPRS) [2]. Some sensor data will be transmitted on satellite command, and some data will be transmitted at a prearranged time. The former is called an interrogated platform, the latter a self-timed platform. The interrogating signal is sent from the satellite to the platforms in the interrogation channel, 468.825 MHz. Time-of-day information, and other special data, will also be transmitted to users via this channel. The GOES frequency plan will be found in Appendix A.



$$R_1 = \sqrt{(X_4-X_1)^2 + (Y_4-Y_1)^2 + (Z_4-Z_1)^2}$$

$$R_2 = \sqrt{(X_4-X_2)^2 + (Y_4-Y_2)^2 + (Z_4-Z_2)^2}$$

$$R_3 = \sqrt{(X_4-X_3)^2 + (Y_4-Y_3)^2 + (Z_4-Z_3)^2}$$

GEOCENTRIC COORDINATE SYSTEM
USED FOR TRILATERATION RANGING

Figure 1.

Time transfer via satellite has been performed in the past using two-way and one-way systems [3]-[7]. In a two-way system, a timing signal is sent from a reference clock to a secondary clock via the satellite, and then, depending upon the method used, some timing signal is sent from the secondary clock back to the reference clock. These timing signals usually take the form of some type of modulation on a carrier signal. Electronic time "ticks" have been used as well as continuous tone modulation. The timing signal from the secondary clock to the reference clock can be either a signal generated by the secondary clock system or an actual retransmission of the timing signal received from the reference clock. Regardless of the method used, the desired result of the timing signal transfer procedure is to obtain sufficient data to accurately calculate the propagation delay time from the reference clock to the secondary clock. Once this delay is obtained, the secondary clock corrections are easily made. Notice that no reference has been made to satellite location. In a one-way system the reference clock signal is sent to a secondary clock site, but no return transmission is made. In this method, there is insufficient data to make an accurate determination of signal delay. The delay has to be computed by making assumptions as to satellite location, tropospheric effects and ionospheric effects. A two-way time transfer system has yielded precise ($\leq$ 1 microsecond, 1 sigma) time transfer while a one-way system has yielded medium precision ($\geq$ 10 microseconds, 1 sigma) time transfer. During the early precise time transfer experiments, a two-way system was necessary because adequate information on the satellite position was not available. A disadvantage of a two-way system is that a full transmitting and receiving facility is required at the secondary clock site. Also, only one secondary timing site may be serviced at any one time.

With the advent of the accurate trilateration ranging system for GOES, precise one-way timing systems become feasible. The basic requirements are accurate knowledge of transmitting location, receiving location, and the tropospheric and ionospheric conditions.

The Time and Frequency Division has performed a study to determine the practicality of precise (0.1 microsecond, 1 sigma) one-way time transfer systems. Specific attention has been paid to the errors caused by variations in the propagation medium and errors due to noise on the various radio links. Errors caused by faulty information concerning the locations of the CDA and TARS stations and the various receiving facilities that might be involved in the system are also discussed. Representative errors from these and other sources will be listed. Details of the trilateration method and the theory of one-way timing systems will be given. Technical factors involved in a one-way timing system are tabulated and discussed. The general logistics of a manned and unmanned receiving site is gone into in some detail. The GOES link analyses will be found in Appendix B.

2. SATELLITE RANGING TECHNIQUES

In order to determine the orbit of any satellite, certain parameters must be obtained. These parameters, called orbital elements, describe the position and velocity of the satellite at some specific time. These elements are determined by computer after examining a quantity of data. These data consist of measurements of signal delay and rate of change of signal delay, from one or more satellite tracking stations.

2.1. PRESENTLY USED SIDETONE RANGING TECHNIQUES

The Goddard Range and Range Rate System (GRRR) [8] uses a series of tones, called sidetones, to modulate a microwave carrier. After transmission to the satellite, the carrier with sidebands is returned to the tracking station through the satellite ranging transponder. After demodulation, the phase and rate of change of phase of the returning sidetone is continuously measured with respect to the phase of the same sidetone transmitted to the satellite. These phase data are converted to range and range-rate data. If this information is available in sufficient quantity an accurate determination of the orbital elements may be made.

2.2. TRILATERATION SIDETONE RANGING

In a trilateration system, the computation of the orbital elements is somewhat simplified. There are always three tracking stations involved. Each station measures the phase of a sidetone such that three slant ranges may be computed. The three slant ranges may be geometrically resolved into a satellite range-to-earth center. This purely geometrical solution implies simultaneous slant range measurements, i.e., there will be a time, t_o, associated with the range calculation. Now if a new range is computed from new slant range data at time t_1, sufficient information is available to compute the orbital elements. The drawback to this system is that for accurate determination of range, the three tracking locations should be widely separated. These large separations make the task of synchronizing the tracking stations' clocks, (and therefore the slant range data) much more difficult.

In the GOES tracking system, there is no time synchronization problem. The master station (CDA) transmits the sidetone to the satellite. The satellite transmits the sidetone back to the CDA and simultaneously to each TARS station. The TARS stations return the sidetone transmission on their own individual carrier frequencies, via the satellite, to the CDA. This phase information is sufficient to allow a range determination to be made at the CDA station. Synchronization is no problem since all transmissions occur simultaneously.

2.3. THEORY OF SIDETONE RANGING

Because of the ambiguity associated with the determination of range based upon the phase measurements of a continuous tone, a multiple tone system is employed. While there are no constraints on the actual frequency of the tones, there are requirements on the relationships of the tones to each other and requirements on the high and low tones. The highest frequency tone determines the resolution and accuracy of the ranging system while the lower tones resolve the ambiguity of the range measurement. The number and relationship of the intermediate tones is determined basically by the link signal-to-noise ratio. The GOES ranging system's lowest tone has a frequency of about 35.4 Hz. The period is exact at 28,224 microseconds.

To begin with, the range to the satellite must be estimated to better than 1/2 wavelength of the lowest tone. The wavelength, λ, according to $C = \lambda/\tau$, is approximately 8,467 km. C is the velocity of light and τ is the period of the tone. The estimate of synchronous altitude must therefore be accurate to about ± 2,100 km. If a synchronous satellite has a reasonably circular orbit and low inclination, the satellite altitude is about 36,000 km. Dividing the round trip distance of 72,000 km, by the wavelength of the 35.4 Hz tone, yields a total of 8.5 wavelengths round trip delay for that tone. The actual proceedure is to measure the phase difference, expressed as a time interval, between the transmitted 35.4 Hz tone and the received 35.4 Hz tone from the satellite. The measurement is of the fractional or residual wavelength only. If the original estimate of round trip delay was accurate, it would be clear that 8 wavelengths should be added to the residual, rather than 7 or 9. If there were no noise in the system, the range measurement could stop there, but of course, this is not the case. Therefore, there is an error estimate attached to the phase measurement that translates to a range error, ΔR. In the case of GOES, this is about 30 km for this lowest tone. From Skolnik [9]:

$$\Delta R = C/\left(2\pi f \sqrt{2S/N}\right) \tag{1}$$

where f is the sidetone frequency, S/N is the signal-to-noise power ratio and C is the free space velocity of light.

The requirement that determines the first tone frequency above 35.4 is that 1/2 its wavelength be greater than the ΔR of the 35.4 Hz. If this requirement is met for each higher tone in turn, then progressive measurements may be made that will allow unambiguous range determination using the highest frequency tone. The range error, ΔR, is inversely proportional to the tone frequency, and so the range accuracy requirements and the signal-to-noise ratio determine the highest tone frequency. Table 1 lists the GOES ranging system tones and their respective range errors due to systematic bias and random noise. These are computed values [1].

3. ONE-WAY TIME TRANSFER METHOD

There are, of course, restrictions on the use of the GOES satellites. The GOES satellites are part of a future, world-wide group of environmental satellites that will be operational rather than experimental in nature. Consequently, except for a few strictly agreed upon and minimal services that can be performed by NOAA, all other use of these satellites by other agencies must be strictly passive. That is, any transmissions from the satellite may be received and utilized, but no transmission to the satellite will be allowed that is not in accordance with the GOES mission. This discussion will take place within the framework of these restrictions.

As can be seen from the GOES frequency plan (Appendix A), the S-band circuits in the satellite are used primarily for services other than ranging. Consequently, it may not be possible to schedule the time signal as desired. Hopefully, once the satellite is fully operational, a schedule of ranging times would be made available to time transfer users. In any case, the time transfer should take place during the 200 kHz tone transmission. The lower frequency tones could be utilized for time transfer, but their use presents certain problems. These tones are for ambiguity resolution only, and it doesn't matter to the ranging system that none have frequencies that are multiples of 1 Hz. To a user wishing to transfer time, however, the use of these tones will greatly increase the system complexity and bookkeeping requirements.

The data available at the CDA, after the ranging sequence, consists of a series of phase difference measurements (expressed as a time interval), along with a time-of-day label for each measurement. For the 200 kHz tone sequence, a measurement consists of a one second average of the phase difference values between the transmitted and the received tone. The average phase difference value is, of course, some interval between

Table 1.

PEAK RANGE (TIME ERRORS) DUE TO NOISE IN THE GOES RANGING SYSTEM

TONE / NOISE TYPE	35.4 Hz	283.4 Hz	3.968 kHz	27.77 kHz	200 kHz
SYSTEMATIC	3×10^{-9} S	3×10^{-9} S	3×10^{-9} S	3×10^{-9} S	3.8×10^{-9} S
RANDOM	1×10^{-4} S	1.3×10^{-5} S	9.0×10^{-7} S	1.0×10^{-7} S	2.2×10^{-9} S
TOTAL	1.0×10^{-4} S	1.3×10^{-5} S	1.0×10^{-7} S	1.0×10^{-7} S	6×10^{-9} S

0 and 5 microseconds, the period of the 200 kHz tone. The complete 200 kHz tone sequence consists of sixty such average phase values from each of the three range links: TARS I, TARS II and the CDA.

After the ranging sequence is completed all the phase data thus accumulated is transferred via telephone line, to the NOAA computer at Suitland, Maryland. This computer determines the range, the satellite coordinates, range-rate, and the time of ranging. The time of ranging and satellite coordinates are, via telephone line, returned to the CDA for transmission to the receive-only sites via the 468 MHz interrogation channel time code, (see fig. 2).

At the receive-only site the time recovery procedure would be as follows. Let the subscripts c, s and r refer to the CDA, satellite and receive-only site, respectively. The satellite coordinates X_s, Y_s, Z_s, are received from the 468 MHz transmission. The coordinates X_r, Y_r, Z_r, have been obtained previously from maps or surveys. The distance between the satellite and the receiving site is simply

$$R_{(s-r)} = \left[(X_s-X_r)^2 + (Y_s-Y_r)^2 + (Z_s-Z_r)^2\right]^{1/2} \qquad (2)$$

(see fig. (3).

Also, the coordinates of the CDA, X_c, Y_c, Z_c, must have been obtained by the receiving site. The distance between the satellite and the CDA, $R_{(c-x)}$, is computed as was $R_{(s-r)}$.

The propagation time, t, of an electromagnetic wave in a vacuum, over a distance R, is t=R/C where C is the velocity of light. Then the total delay time from the CDA through the satellite to the receiving site will be

$$t_{(c-r)} = t_{(c-s)} + t_{(s-r)} = \frac{R_{(c-s)}}{C} + \frac{R_{(s-r)}}{C} \qquad (3)$$

where the two distances were previously computed.

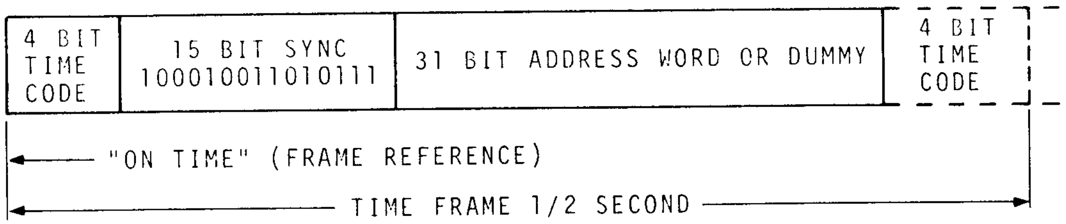
The theoretical propagation delay must be corrected for the following:

1. The difference between the CDA master clock pulse and the phase of the 200 kHz range tone at the range tone generator, if any.
2. The time delay from the range tone generator to the CDA transmitting antenna.
3. The propagation delay in the timing signal due to the troposphere and the ionosphere.
4. The equipment time delay in the receiving system.
5. The delay through the satellite transponder.

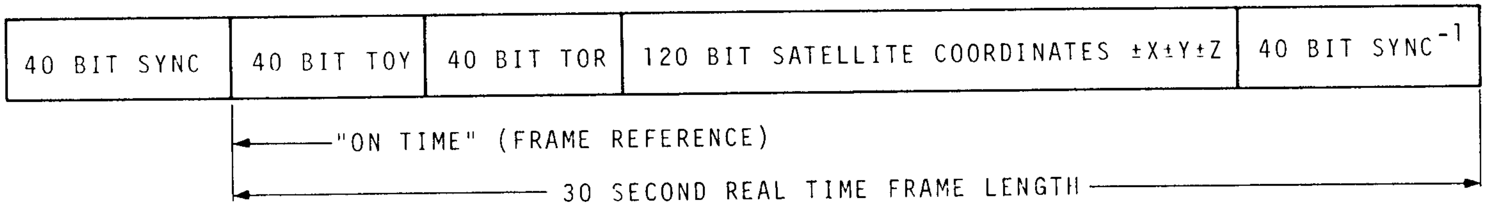
The receive site operator compares his received phase data with a value computed from summation of all the delays. Any difference can be attributed to receive site clock error. This sequence presupposes that the receive-only site clock tick was within 1/2 period of the 200 kHz tone, (2.5 microseconds), of the CDA master clock. See figure 4 for simple diagrams of receiving site systems.

The ambiguity resolution at the receive-only site could take various forms depending upon the circumstances. One time honored method is to carry a portable

COMPOSITE INTERROGATION CHANNEL FORMAT



TIME CODE FORMAT



TIME-OF-YEAR (TOY) DATA:

TENS OF SECONDS (0 OR 30), MINUTES, HOURS, DAYS, UT CORRECTION (±0 TO .9 SECOND BY 0.1 SECOND)

TIME-OF-RANGING (TOR) DATA:

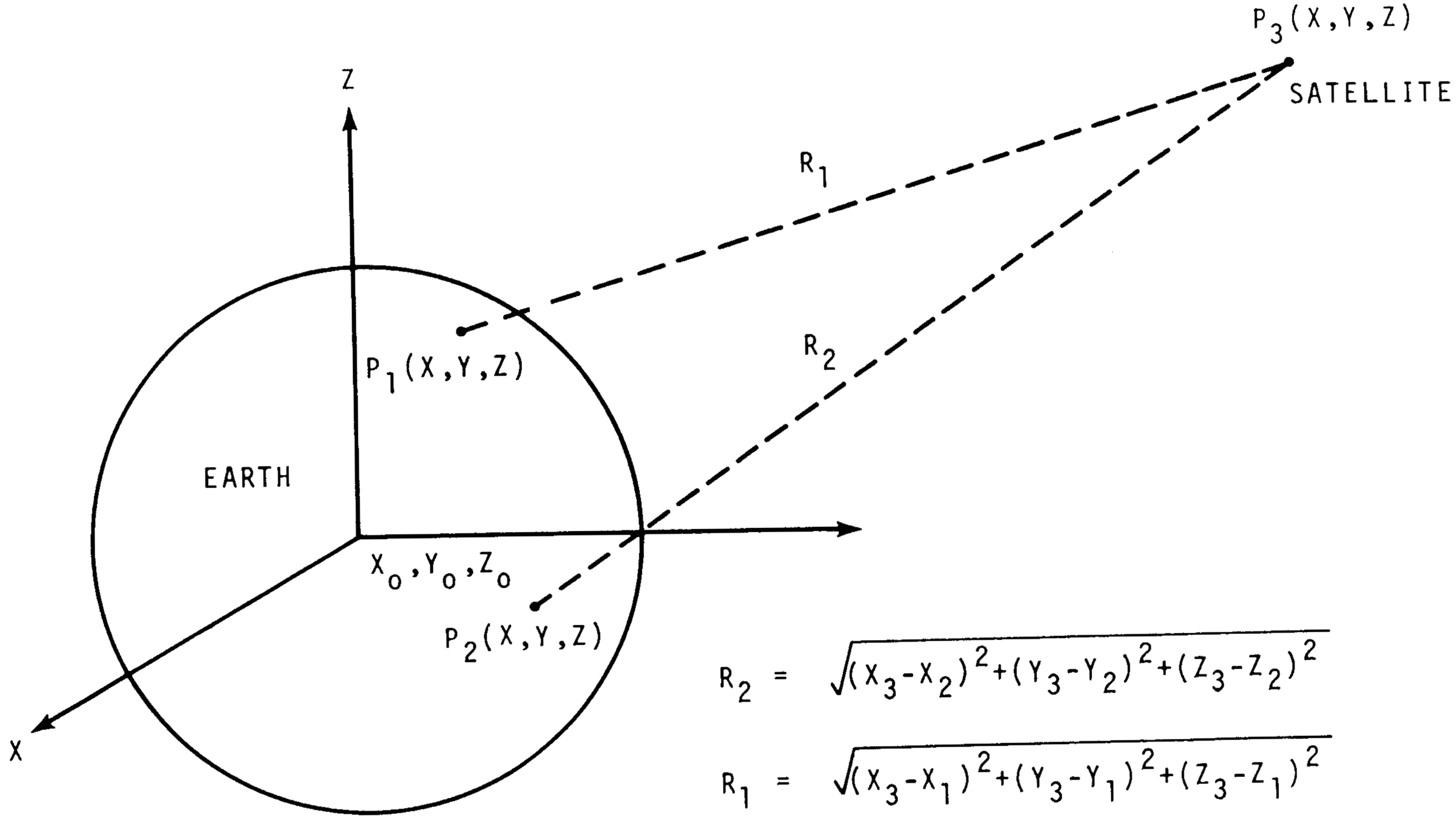
TENTHS OF SECONDS, SECONDS, MINUTES, HOURS, DAYS. RESOLUTION = 0.1 SECOND

SATELLITE COORDINATES:

± X(10^8 METERS), ± Y(10^8 METERS) ± Z(10^8 METERS), RESOLUTION = 1 METER

INTERROGATION CHANNEL FORMAT

Figure 2.

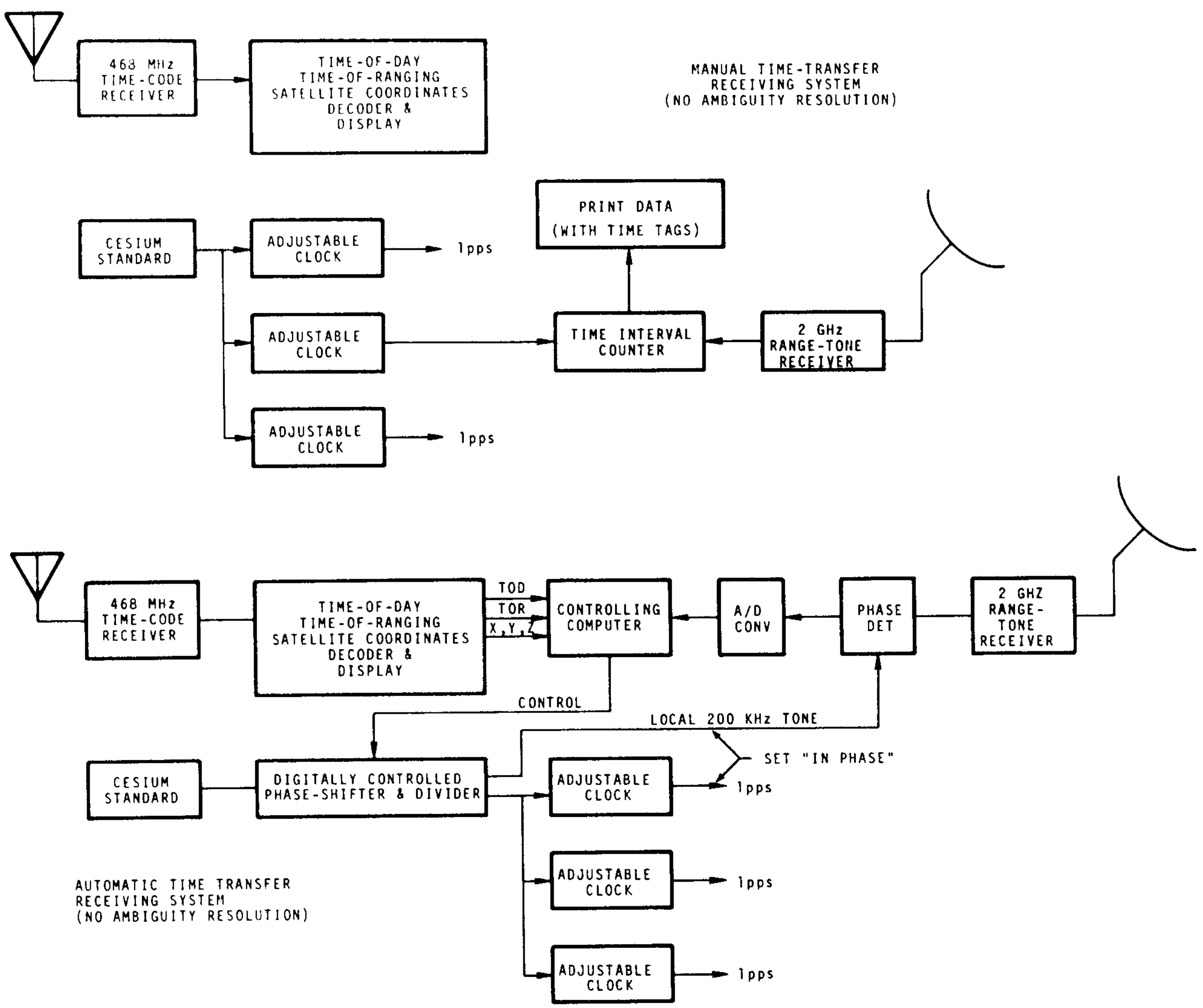


$$R_2 = \sqrt{(X_3-X_2)^2+(Y_3-Y_2)^2+(Z_3-Z_2)^2}$$

$$R_1 = \sqrt{(X_3-X_1)^2+(Y_3-Y_1)^2+(Z_3-Z_1)^2}$$

ONE-WAY TIME TRANSFER GEOMETRY

Figure 3.



TIME TRANSFER RECEIVING SYSTEMS

Figure 4.

cesium clock from the CDA to the receiving site. If the receiving site were within good ground-wave distance of a LORAN-C station, the LORAN signal might be used.

4. GEODETIC CONSIDERATIONS FOR SATELLITE TRILATERATION TIMING

The problems associated with determining ground station locations have two implications for the trilateration timing scheme of this report. Because of the method of solution for the satellite's position, the location of the TARS stations and of the CDA must be known very accurately. The location of the time recovery sites need only be known to an accuracy commensurate with the accuracy of timing desired at that particular site.

4.1. CDA AND TARS SITE LOCATION

The location of the CDA and TARS sites must be known to the highest possible accuracy. Knowledge of the location of these sites to a large degree determines the accuracy of the calculated satellite position and thus can greatly effect the overall accuracy of the proposed timing system. Two methods capable of delivering the desired accuracy are described below - triangulation surveys and doppler receiver surveys. Other surveying methods also may need to be considered, however, these two appear to be the most probable solutions to the location problems for the three trilateration stations.

Triangulation is a method of surveying which primarily involves the measurement of the angles in a triangulation network as illustrated in figure 5. In this figure A and B are known locations and AB is a known distance. The angles to be measured are shown by the arrows and the positions to be determined are indicated by the dots inside the small circles. Ultimately the location of position C is calculated.

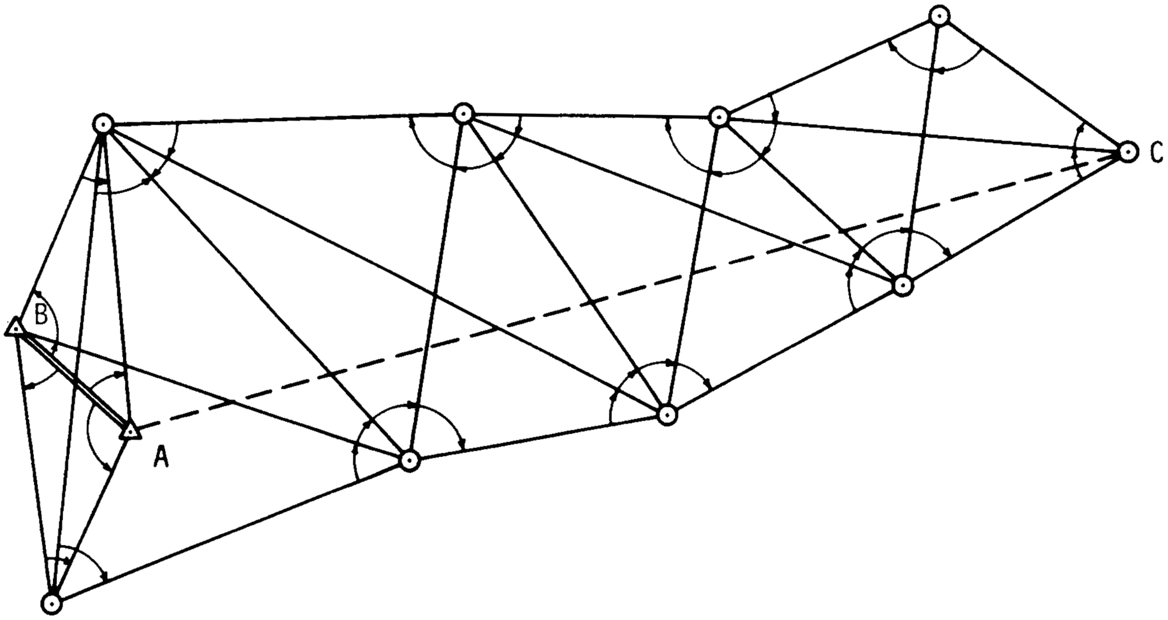
Criteria exist to statistically determine the accuracy of a position determined in such a manner. These criteria include the probable error in the measurement of each angle, the number of angles measured and the size of those angles, the length of the sides of the triangles, and the closure of the angles within each triangle and the whole figure. On the basis of such criteria, a survey is assigned an order which denotes the accuracy of that survey and of the locations determined by that survey. A first order triangulation is the most rigorous and would be acceptable for determining the location of the CDA and TARS sites.

A process of adjustment is used to make the overall accuracy of a given survey as high as possible. This involves adjustment of the locations determined, such that certain statistical properties are improved. The result, however, is that the determined locations are mathematically dependent, thus increasing the probability of systematic bias.

The coordinate system for a triangulation survey is determined by the reference spheroid. This spheroid is chosen such that for a given survey area, the surface of the spheroid closely approximates the surface of the earth in that area. The center of the spheroid, the geometric center of the earth, the center of mass of the earth, are distinct points which coincide only by chance.

The accuracy of a first order triangulation of intercontinental extent is estimated to be one part in one million [10].

An alternative method of locating the positions of the CDA and TARS is based upon data from a special radio receiver. This instrument measures the Doppler



KNOWN DATA:
LENGTH OF BASE LINE AB.
LATITUDE AND LONGITUDE OF POINTS A AND B.
AZIMUTH OF LINE AB.

MEASURED DATA:
ANGLES TO NEW CONTROL POINTS.

COMPUTED DATA:
LATITUDE AND LONGITUDE OF POINT C, AND OTHER NEW POINTS.
LENGTH AND AZIMUTH OF LINE AC.
LENGTH AND AZIMUTH OF ALL OTHER LINES.

A SIMPLE TRIANGULATION NETWORK

Figure 5.

shift of the signals transmitted from the TRANSIT [11] satellites. The orbits of these satellites are determined by measurements made at special tracking sites. From the satellite orbits and the Doppler measurements the position of the satellite receiver may be calculated.

This method of position determination yields a location that is essentially independent of other survey points, the dependency is only upon a limited number of tracking locations from which the satellite position was determined. This mathematical independence means that systematic errors will not accumulate, but that biases may exist.

The accuracy of this method is estimated to be one meter, one sigma, in each coordinate relative to the calculated orbit of the satellite.

The coordinate system for locations based on the satellite receiver has its origin at the center of mass of the earth. This is because the satellite travels in an orbit around the center of mass of the earth and the position fix is relative to this orbit. The accuracy of the receiver location relative to the center of mass is estimated to be 10 meters, one sigma, in each coordinate.

The timing implications of the inaccuracies of the satellite receiver and triangulation surveys will be delineated in section 5.3. of this report.

4.2. RECEIVING SITE LOCATION

The position location accuracy requirements for the receiving site are much less stringent than for the CDA and TARS sites. The requirement is a location accuracy which will support the timing needs of the site. Within the continental United States this translates roughly to an allowable location error of a few hundredths of a degree to support tenth microsecond timing. For instance, if the satellite were due south of Washington, D. C., a receiver located at Washington, D. C., would need to be located accurately to three hundredths of a degree if tenth microsecond timing were required. Any of the surveying methods commonly in use will provide this accuracy. In fact, for most sites it is probably sufficient to determine the site location from a high quality 15 minute or 7.5 minute quadrangle map.

In order to compute the delay between the satellite and the receiving site it is necessary to ensure that the satellite's location is given in the same coordinate system as the site's location.

5. ADVERSE EFFECTS UPON THE TIME TRANSFER

5.1. PROPAGATION EFFECTS

The Troposphere

An electromagnetic wave or ray propagating through the troposphere will experience a bending and a slowing due to the fact that the refractive index of the medium is other than unity [12]. The index of refraction, n, is generally an inconvenient number with which to work; therefore, the refractivity, N, is used for convenience in the various equations. The refractivity is defined as $(n-1) \times 10^6$ and is in the range of about 200 to 400 at the earth's surface. For the troposphere, N is dependent upon water vapor content of the air, the absolute temperature, and the barometric pressure. A widely used equation for N for the troposphere can be written as

$$N = \frac{77.6}{T}\left[P + \frac{4810\ e}{T}\right] \tag{4}$$

where T is the absolute temperature in K, P is the total pressure, and e is the partial pressure of water vapor, both in millibars [13, 14].

Figure 6 shows the path length change for two extreme values of N as a function of antenna elevation angle. Elevation angles of above 15° should be used unless some accurate measure of N is available on a real time basis. Equation 4 or an equivalent form could be used in these calculations.

Since the parameters that determine N are altitude dependent, N, for the troposphere, varies in some fashion from its sea level value to essentially 0 to about 60 km [13]. As radio rays pass through the atmosphere from a satellite to the earth, these rays are continuously bent due to the gradient of N. This bending again is most severe at low antenna angles. Unless very large antennas with very small beam angles are used, the bending can usually be ignored. The path length change and ray bending in the troposphere are essentially independent of frequencies below about 30 GHz.

The Ionosphere

The slowing and bending of radio waves passing through the ionosphere is due to the electron content of that region. The change in group path length, $\Delta \ell$, due to the ionosphere is given by

$$\Delta \ell = \frac{b}{\omega^2} \int_0^s N_e \, d\ell, \tag{5}$$

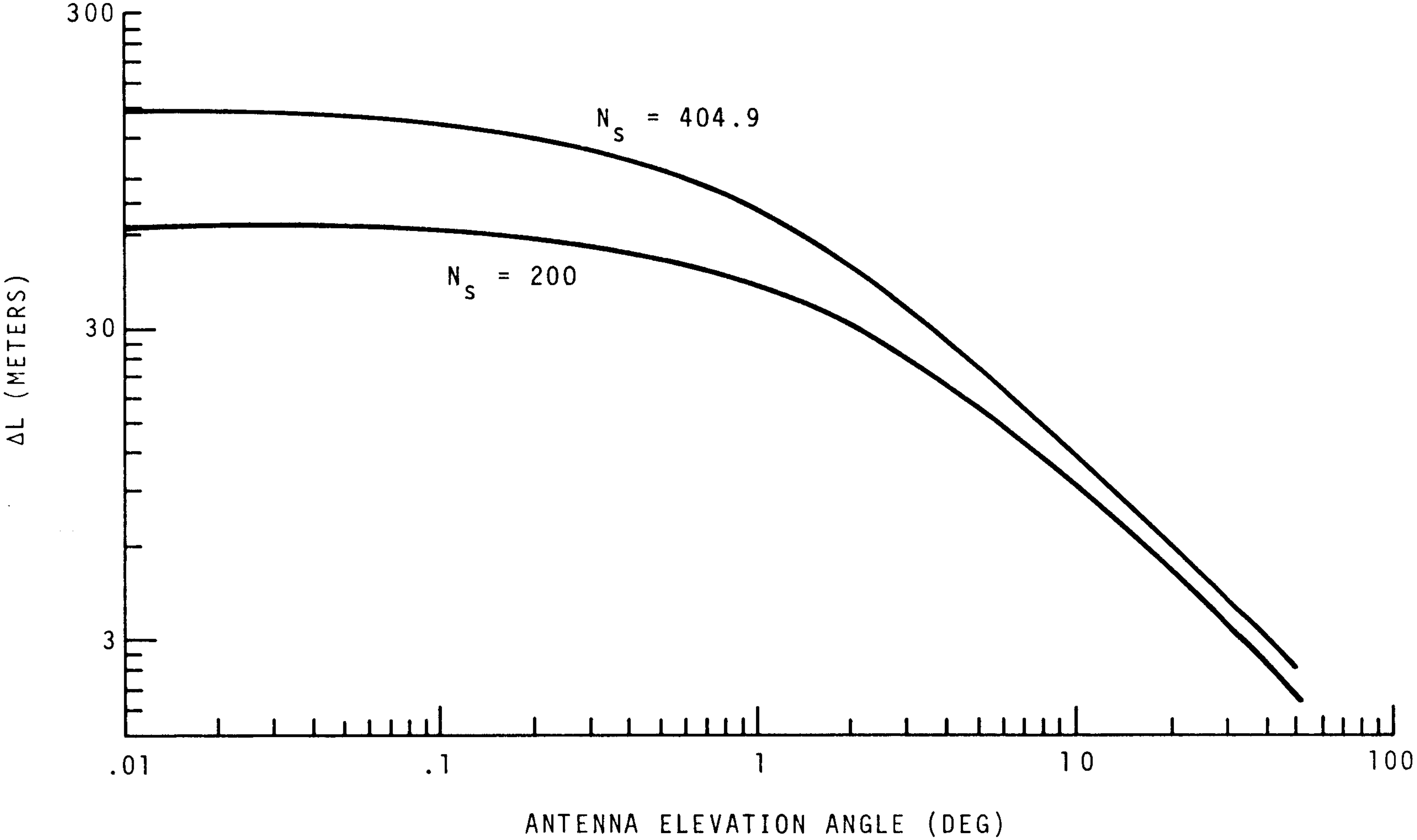
where N_e is the electron density, b is a function of the charge and mass of an electron as well as the permeativity of free space and has a value of 1.63×10^3 (mks) [15]. The integration is along the ray path to the satellite. It might be noted that this path length change, unlike that caused by the troposphere, is inversely proportional to the square of the angular frequency, ω. Path length changes for 90° antenna angles are of the order of 1 meter at 2 GHz. This will increase to about 25 meters at 0° antenna elevation. These values are for typical total electron content and can vary an order of magnitude in either direction. Figure 7 shows the path change with respect to antenna angle, for one representative value for total electron content, N_T, expressed as time.

There will be certain times of the year or day, and certain times of the sunspot cycle where the correction to the group delay caused by the ionosphere must be adjusted. The total electron content may be written as

$$N_T = A_i \left[1 + (B_i/A_i)\ (R_z - 40) \right] \times 10^{17}, \tag{6}$$

where A_i and B_i are variables that depend upon the number of days elapsed from the beginning of the year, and R_z is the Zurich sunspot number [16]. When the total electron content has been determined from eq (6), $\Delta \ell$, the change in group path length, may be computed using the following equation rather than eq (5).

$$\Delta \ell = \frac{b}{\omega^2} \left(Q N_T f_L f_t \right) \text{ meters} \tag{7}$$



RANGE CHANGE DUE TO TROPOSPHERIC EFFECTS

Figure 6.

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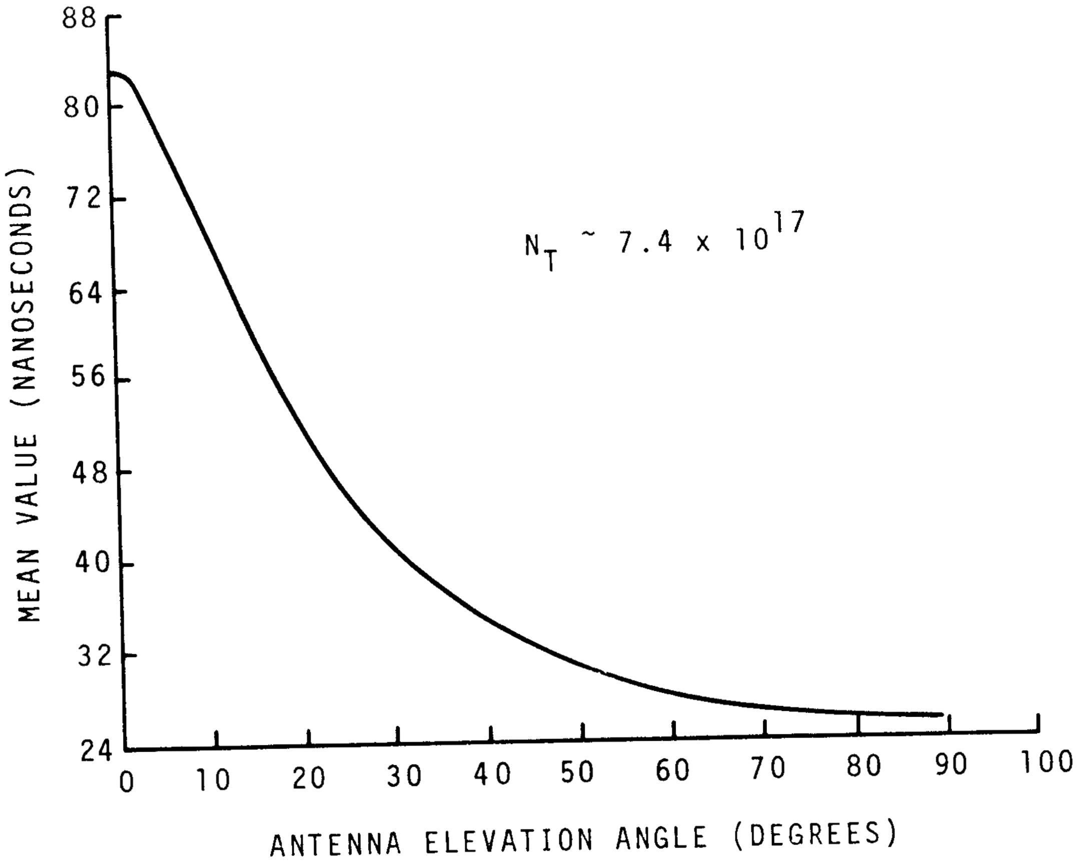

RANGE (TIME) CHANGE DUE TO IONOSPHERIC EFFECTS

Figure 7.

where b and ω are defined as in eq (5), Q is the obliquity factor, f_L is a latitude compensating factor and f_t is a time-of-day compensating factor [16, 17].

5.2. SATELLITE MOTION

Any geostationary satellite is in constant, although minor, motion with respect to any point on the earth's surface. Figure 8* shows the curves of satellite distance, velocity and acceleration versus elapsed time from the ascending node with respect to the CDA station at Wallops Island, Virginia. The maximum relative velocity is about 27 meters/second. Ranging and time transfer should take place within no more than about 10 milliseconds of each other to keep the error due to satellite range rate to an acceptable minimum. Actually, for the system under study the difference in time between ranging and time transfer will be on the order of 1 millisecond.

5.3. SATELLITE LOCATION ERRORS

In order to evaluate the magnitude of timing errors caused by inaccurate knowledge of ground station locations, it is first necessary to estimate the values of the errors in ground position. The doppler receiver locations are known with an estimated one-sigma position error of less than 17 meters (root sum square of the 10 meter error in each coordinate). To calculate the errors for the first order trilateration, one must know the distance between each of the trilateration stations. This may be estimated as 8000 km (Wallops-Hawaii, 8030 km; Wallops-Santiago, 7960 km; Wallops-Ascension, 8070 km; Hawaii-Santiago, 9080 km; Santiago-Ascension, 6370 km). The maximum error in this distance is between one part in 10^5 and one part in 10^6 as specified for intercontinental surveys; i.e., between 8 and 80 meters [10]. The 17 meter error for the doppler receiver is probably a workable figure for both types of surveying.

The assumed one sigma error of 17 meters will cause a proportionate error in the position of the satellite which may be caluclated from the trilateration formula [18]. For the particular ground stations of GOES trilateration and the assumed satellite position, the maximum displacement of the satellite due to ground station position errors is approximately 400 meters. It should be emphasized that whatever the error is in satellite position, it will not vary significantly and the net effect will be to introduce a constant bias to the calculated delays.

The amount of bias introduced in this manner is, of course, a function of receiving site as well as of the error in satellite position. In order to evaluate the timing potential of this system within the specified area of interest, 66 sites were chosen to comprehensively cover the longitudinal and latitudinal extend of the continental United States. The range between the satellite and each of these ground stations was determined from two satellite locations: (1) the assumed "true" location and (2) the "erroneous" satellite location caused by errors in knowledge of the location of the three trilateration stations. The erroneous satellite location was the one of maximum (400 m) displacement in the satellite's position. The difference between these two range calculations is shown in table 2 to the nearest meter. The 64 meter maximum range error implies an absolute time synchronization of 0.2 microsecond one sigma, within this limited geographic area. The average range error was approximately 40

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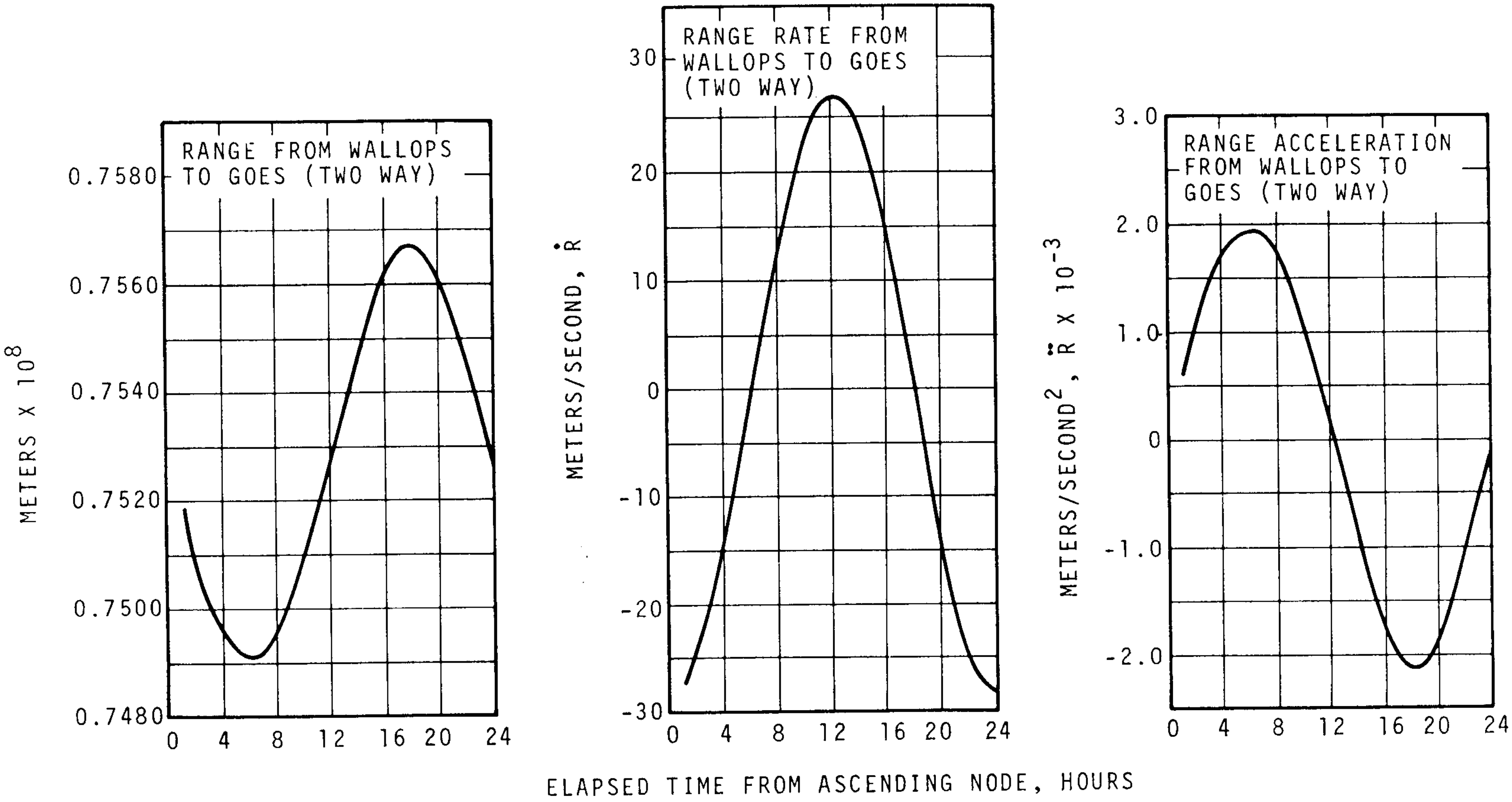
*The initial position of the first GOES satellite (GOES-A) will probably be 100° west longitude. The range values shown in figure 8 for 95° will change by about 1.5% due to this 5° shift is satellite longitude.



PREDICTED RANGE, RANGE RATE, AND RANGE ACCELERATION FROM CDA STATION, WALLOPS IS., VA. SATELLITE LONGITUDE 95°W, 2.5° INCLINED ORBIT

Figure 8.

Table 2.

RANGE ERRORS IN METERS DUE TO ERRORS IN LOCATION OF THE TRILATERATION STATIONS.

LATITUDE / LONGITUDE	25°	30°	35°	40°	45°	50°
75°	18	19	19	20	21	22
80°	23	23	23	24	24	25
85°	27	27	27	28	28	28
90°	32	32	32	32	32	32
95°	37	36	36	36	35	35
100°	42	41	40	40	39	38
105°	47	46	45	43	42	41
110°	51	50	49	47	46	45
115°	56	54	53	51	49	48
120°	60	58	57	55	53	51
125°	64	62	60	58	56	53

AVERAGE RANGE ERROR 440 METERS

STANDARD DEVIATION OF THE RANGE ERRORS - 12.8 METERS

meters with a standard deviation of 13 meters. This implies a relative time synchronization within the continental United States of approximately 40 nanoseconds one sigma, and an average offset from an arbitrary time scale of 120 nanoseconds. It should be once more emphasized that these figures represent outside maximum values for errors. The actual system may have significantly less positioning error and bias than have been estimated here.

5.4. EQUIPMENT DELAYS AND INSTABILITIES

Another source of error in time transfer is equipment delay instability. For the ranging system, great care has been taken to insure short-term stability of the TARS stations. The signal through the TARS is down-converted to 70 MHz and filtered with a bandwidth of 1 MHz. This filter is the only VHF narrowband device in the TARS and consequently much attention has been given to its design. Long-term drift of IF stages, amplifiers, and the like is in the order of 10% of one cycle at the particular operating frequency. At 70 MHz, this drift would be in the order of 2 nanoseconds. At the higher frequencies, the drift is even less.

The delay through the CDA equipment, both transmitting and receiving, is measured prior to each range measurement; therefore, it is automatically taken care of in the ranging program.

The delays in the receiving system for a time transfer station must be taken into account with the same care as was applied to the TARS stations. Also the transmitting delay at the CDA station must be monitored separately for time transfer. The delay at the CDA that is measured for the range calculation does not separate the receive delay from the transmit delay.

5.5. EFFECTS OF NOISE ON TIME TRANSFER

In section 2, the theoretical considerations of noise were presented for the sidetone system,

$$\Delta R = C/\left(2\pi f\sqrt{2S/N}\right) \tag{8}$$

where f is the frequency of a particular sidetone. Note how this range error is effected by the signal-to-noise power ratio (S/N). If the range error due to noise is unacceptable, averaging techniques may be applied to reduce that error provided the noise is uncorrelated. The range error may also be reduced by increasing S/N. This can be done by narrowing the effective bandwidth using a suitable filter. Both techniques may be applied using some caution. Equation 8 gives the range error, ΔR, for a single phase measurement. ΔR will be reduced by a factor M, if M is the number of independent phase measurements taken during the averaging process. The independence of the samples is of prime importance when considering an averaging process. The number of independent samples or measurements taken is related to the tone frequency, f, only if the effective bandwidth is greater than 2f. If the bandwidth is less than 2f, the maximum number of independent samples available is related to the bandwidth of the filter.

6. GENERAL LOGISTICS

The term general logistics is taken to include the details of specifying components and spares, of operational and maintenance personnel, and of overall annual costs. Environment, auxiliary power, and geographical location for the timing site will be mentioned.

6.1. SYSTEM ENVIRONMENTAL CONSIDERATIONS

Good phase stabilities in a timing system depends on a carefully controlled environment. In the GOES ranging system, the TARS station's electronics are housed in special foam insulated rooms whose heating and cooling systems maintain the ambient inside temperature at 21°C (70°F) in an outside temperature range of -57°C (-70°F) to 49°C (120°F). The phase shift stability through dividers, clocks, multipliers and other components of a timing system is no less critically dependent upon temperature.

Probably the most environmentally sensitive component in the timing system is the cesium standard. The phase stability of a standard of this type, or any other type, is also dependent to some extent upon line voltage regulation. All time and frequency equipment at the NBS high frequency radio stations is powered by regulated voltage supplies. When on occasion, a regulator has failed, the phase stability of the affected equipment was obviously decreased.

Figure 9 is a representative 24-hour sample of the phase intecomparisons of the three cesium standards at station WWV in Ft. Collins, Colorado. It should not be inferred from figure 9 that any three cesium standards at widely separated locations could be placed in service and achieve this degree of frequency synchronization without any expenditure of time and effort.

The absolute frequency output of a commercial cesium standard will be specified plus or minus some value, e.g., 5 MHz $\pm 10^{-11}$. The adjustments that must be made to bring the frequencies of a sample of units into synchronism are time consuming because as one works with frequency differences of between 1×10^{-12} and 1×10^{-13}, nothing much happens very fast. It might take days of measurements before a systematic frequency offset is even detected. Therefore, the initial effort required at each receiving site is considerably greater than the ongoing effort after frequency synchronization is achieved.

Also, it is not possible to synchronize all units at a central location and then deploy them. Some of the adjustments pertain to the particular site involved. This includes geographical location, the building and room housing the standard, presence of local mineral deposits, local electric lines, etc.

The clocks that are deployed at the receiving site rate special attention also. An electronic clock is nothing more than a set of dividers that are arranged in a fashion such that, for N input cycles, pulses, or electrical events, the clock delivers one output pulse. These output pulses are then added, and the sum displayed or recorded. It is important that no extraneous pulse is allowed to get into the system. Line voltage transients, surges, static electricity, lightning discharge, and poorly grounded circuits, are all potential problem areas. These problems can be minimized by operating all on-line equipment from batteries. This of course, adds to the maintenance problem, but for the timing system, it is essential. The microwave and UHF receiving systems are not as susceptible to this type of problem, but backup power systems should still be provided.

6.2. RECEIVING SITE EQUIPMENT COMPLEMENT

The equipment at a typical basic timing site might consist of:

1. A cesium standard.
2. A UHF receiving system that is tuned to the GOES interrogation channel, (see Appendix A).

FREQUENCY STANDARD INTERCOMPARISONS
FROM STATION WWV - 3 UNITS

1 µs

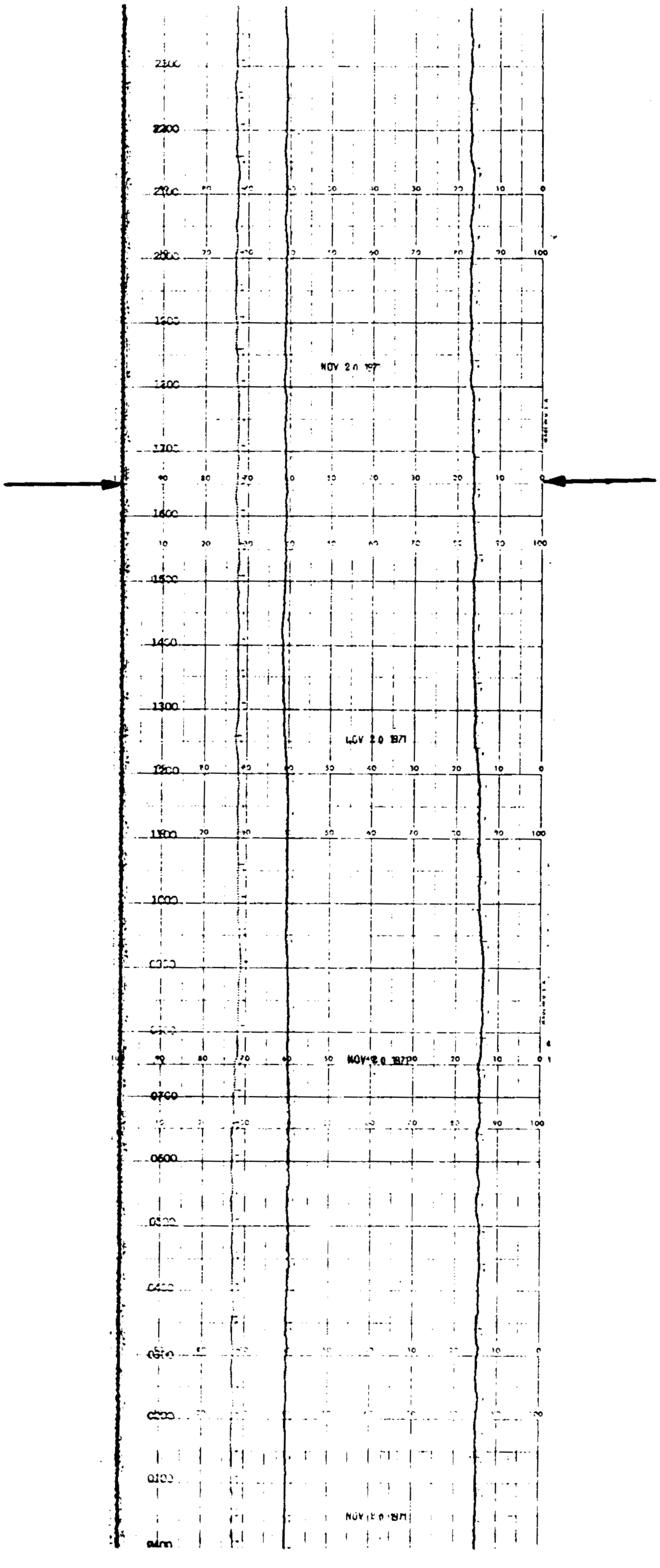


Figure 9.

3. A decoder used in conjunction with the UHF system to provide the ranging information.
4. The microwave system that receives the timing signals from the satellite via the ranging channel, (see Appendix A).
5. The time interval counter that makes the actual time difference measurement.
6. A set of local clocks.

To this basic list must be added the battery backup systems, shielded enclosures (if necessary), rack space, and spares. If the site is to be fully automatic, a small computer and a digitally controlled phase shifter must be added. The hardware interfacing and the software requirements make a fully automatic system exceedingly expensive, and added cost should be weighted very carefully against the cost of a manual operation.

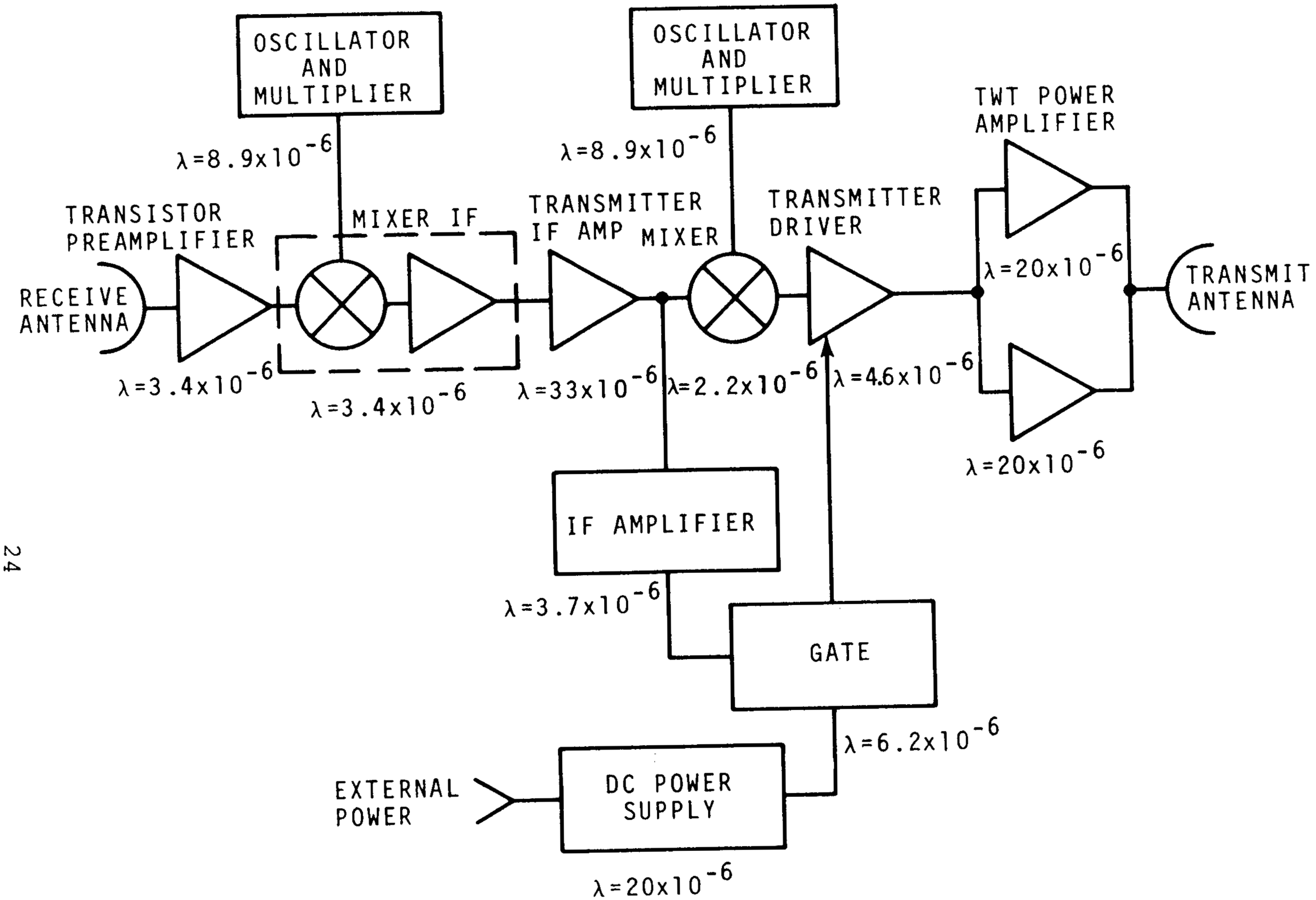
6.3. PERSONNEL REQUIREMENTS

In discussing personnel requirements, we refer to the experience gained by NBS in operating the various NBS field sites as well as in maintaining the NBS frequency standard and time scale. The control room at radio systion WWV contains a triply redundant set of timing systems. The time signal originates at a commercial cesium beam standard and progresses through sets of dividers and a manual phase shifter to the format generator. The format generator controls the broadcast format and generates the various tones, codes and time ticks. Also in the control room is all the measuring equipment required to monitor the three systems: phase detectors used for intercomparisons, chart recorders, time interval counters, and the like.

During the period April 1970 through December 1972, forty entries were made in the WWV maintenance logs. Many related to simple adjustment and some to replacements of peripheral equipment. But most of the items dealt with erratic clock behavior. This experience supports our contention that shielding the clock systems from outside disturbances is most important. We estimate the total time to make these adjustments, change components, and make repairs, to be twenty manhours for about 1,000 days, or a few minutes per day. In addition routine measurement adjustments consume about another twenty minutes per day. Therefore, after initial shake down, modern timing equipment is remarkably reliable, and normal maintenance personnel should be able to absorb the added duties.

6.4. COMPONENT RELIABILITY AND MEAN-TIME-BEFORE-FAILURE

There will be some significant maintenance tasks from time to time that have not yet been mentioned. Nickel-cadmium batteries should be cycled every few months and should be replaced every one to two years. The beam tubes in the cesium standards have a guaranteed life of three years and some models in laboratory environments exhibit mean time before failure (MTBF) of something in the order of 20,000 hours. The failure rate for the satellite position decoder and the mini-computer will probably be the highest of all components simply because of the complixity of these items. A conservative estimate of the MTBF for these units might be 5,000 to 10,000 hours. There is evidence that suggests that continuous operation should be discouraged. For example, the TARS units have a total system MTBF estimate of about 7,000 hours which is not very long until one considers that many of the TARS components are powered only during the ranging sequence. Figure 10 lists the failure rates for the various TARS components.



TARS COMPONENTS FAILURE RATES

Figure 10.

6.5. POWER REQUIREMENTS

The power requirement for the timing system and computer is about 900 watts. The computer consumes about 300 watts, the most power consuming component in the system. This power consumption, could dictate that the system operation include standby mode for some items that are used only a few minutes per day.

6.6. SPARES COMPLEMENT

The spares complement for each receiving site should be considered on an individual basis. For example, the overall spares complement of a Central Processing Unit would be determined by the failure rate of that component in that particular computer. We feel that MTBF information should be required from the manufacturer. If necessary, the failure rates can be computed from basic information on the number of components on each plug in card. The various cards in the UHF decoder, the time interval counter, and other units should be treated the same way. Failure of main frames on items like computer counters and decoders is somewhat more serious than card failures. This is because the main frame contains the power supply which is more time consuming to fix, takes more tools, and will take the entire machine out of service. One solution is to require modular power supplies; another is to have an entire main frame spare. All that would be required then would be to move the plug-in cards from one unit to another.

Probably the best solution would be to reqiure the total system designer to determine the failure rates of all the assemblies and sub-assemblies, main frames, and even components like power transformers. This should determine the kinds and numbers of spares to be procured for the total timing systems. The deployment of these spares should be determined on a geographical and logistical basis by the actual site locations.

7. SUMMARY OF TIMING BIASES

The Time and Frequency Division of NBS has completed a study to determine the feasibility of one-way time transfer utilizing the trilateration ranging system of the GOES satellites. The effects of noise in the channel, the propagation medium, the site locations, and the ranging system equipment were examined in some detail. The errors associated with these aspects are summarized below.

The Ranging System

The final design plan for the GOES ranging system lists the following range errors for the 200 kHz tone: total random errors, 2.2 nanoseconds (RMS); total systematic errors, 3.8 nanoseconds (RMS). The random and systematic error sources are such that they may be applied to an independent receiving site also. The range system systematic, random, and peak errors will be found in tables 3, 4, 1, respectively.

The Troposphere

With an antenna elevation angle of zero degrees (worst case), the predicted change in radio path length to the satellite due to tropospheric effects is in the order of 100 meters with a possible variation of ± 50 meters due to extremes in refractivity. But with the GOES satellites stationed at 65°W and 135°W, the range error due to the troposphere goes down considerably for all locations in the United States. For mid-Atlantic seaboard stations tracking the eastern satellite, the antenna elevation angles will be in the order of 40 to 50 degrees. For antenna elevation angles greater than 15° above the horizon, the radio path length change is predicted to be in the order of

10 meters. A value of 15° antenna elevation angle has been used when considering the error contributed to the total by the troposphere.

The Ionosphere

The predicted path length change due to the effects of the ionosphere can be calculated fairly accurately if the electron density or total electron content is known at the time and place of ranging. Lawrence et al., [15] have indicated that the path length change for zenith angles and a frequency of 2 GHz is in the order of one meter with a possible variation of an order of magnitude in either direction. Tables produced by Hughes Aircraft Co. [17] conducting studies on the atmospheric effects on the NAVSAT ranging signals indicate a range (time) change in the order of 82 nanoseconds with an RMS variation of 24 nanoseconds for an antenna elevation angle of zero degrees. The errors along the mid-Atlantic seaboard (angle ~45°) would be in the order of 33 nanoseconds with an RMS error of 9 nanoseconds. For stations operating at low antenna angles, these corrections along with additional references like sunspot number, should be applied.

Site Location

From our own studies of geodesy, and discussions with the geodetic squadron personnel of Warren AFB, Cheyenne, Wyoming, we have arrived at a value of 17 meters as a probable maximum satellite range error due to site location errors. Experiments have indicated that satellite doppler receiver data would locate an earth point with reference to some satellite orbit with an error of 1 meter in each coordinate. It has been estimated that this would allow determination of an earth point location with respect to the mass center of the earth to about 10 meters in each coordinate [19]. In this paper we have used a value of 30 meters as a safe estimate of the RMS range error to a receiving site caused by geodetic considerations.

Receiving Site Equipment

The random and systematic timing errors or biases, found in tables 3 and 4, that would apply to a receiving site have been entered into the bias summation. The receiving equipment as with the CDA and TARS equipments contributes to some fixed time delay. These delays must be measured and removed from the time transfer computations.

8. CONCLUSION

Table 5 lists the various sources of timing biases, their uncertainties, and the summation. The uncertainties of the various contributing factors are with respect to the representative antenna elevation angles that were previously mentioned. The root-sum-square (RSS) of all bias uncertainties indicates that a time synchronization between a receiving site and the CDA master clock could be achieved with an accuracy of ~ 0.3 microseconds (3 sigma).

Table 3.

TRILATERATION SYSTEM

SYSTEMATIC ERRORS FOR ALL SIDETONES - EXPRESSED AS TIME

TONE SOURCE	35.4 Hz	283.4 Hz	3.968 kHz	27.77 kHz	200 kHz	COMMENT
ERROR DUE TO PHASE INSTABILITY OF SATELLITE FILTER	1×10^{-9} S	1×10^{-9} S	1×10^{-9} S	1×10^{-0} S	1×10^{-9} S	
ERROR DUE TO PHASE INSTABILITY OF TARS FILTER	1×10^{-9} S	1×10^{-9} S	1×10^{-9} S	1×10^{-9} S	1×10^{-9} S	
ERROR DUE TO SPACECRAFT INTERMOD	-	-	-	-	-	
AM-TO-PM CONVERSION	-	-	-	-	0.8×10^{-9}S	
MOD/DEMOD NONLINEARITY	-	-	-	-		
CALIBRATION BIAS	1×10^{-9} S	1×10^{-9} S	1×10^{-9} S	1×10^{-9} S	1×10^{-9} S	TOTAL MEASUREMENT ERROR IN GOES, CDA AND TARS CALIBRATION
TOTAL	3×10^{-9} S	3×10^{-9} S	3×10^{-9} S	3×10^{-9} S	3.8×10^{-9}S	

Table 4.

TRILATERATION SYSTEM
RANDOM ERRORS FOR ALL TONES - EXPRESSED AS TIME

SOURCE \ TONE	35.4 Hz	283.4 Hz	3.968 kHz	27.77 kHz	200 kHz	COMMENTS
COUNTER CLOCK INSTABILITY	NEGLIGIBLE	NEGLIGIBLE	NEGLIGIBLE	NEGLIGIBLE	NEGLIGIBLE	
REFERENCE TONE OSCILLATOR STABILITY	2.5×10^{-10} S	2.5×10^{-10} S	2.5×10^{-10} S	2.5×10^{-10} S	2.5×10^{-10} S	
TIME INTERVAL COUNTER RESOLUTION	10^{-10} S	10^{-10} S	10^{-10} S	10^{-10} S	10^{-10} S	
RANDOM NOISE ON REFERENCE SIGNAL 50 db IN 100 Hz BW	1.9×10^{-6} S	2.4×10^{-7} S	1.7×10^{-8} S	2.5×10^{-8} S	1.7×10^{-10} S	200 KHz TONE COUNTED FOR 1 S; ALL OTHER TONES COUNTED FOR 1/4 S
RANDOM NOISE ON RECEIVING SIGNAL	1.0×10^{-4} S	1.3×10^{-5} S	9.0×10^{-7} S	1.0×10^{-7} S	2.1×10^{-9} S	200 KHz TONE COUNTED FOR 1 S; ALL OTHER TONES COUNTED FOR 1/4 S
LEVEL STABILITY	0.5×10^{-9} S	0.5×10^{-9} S	0.5×10^{-9} S	0.5×10^{-9} S	0.5×10^{-9} S	
MODULATOR DEMODULATOR	NIL	NIL	NIL	NIL	NIL	
TOTAL RSS ERROR	1.0×10^{-4} S	1.3×10^{-5} S	9×10^{-7} S	1.0×10^{-7} S	2.2×10^{-9} S	

Table 5.

SUMMATION OF TIMING BIASES AND SOURCES

BIAS SOURCE	ANTENNA ANGLE	PREDICTED TIME TRANSFER BIAS	RMS UNCERTAINTY OF TIME BIAS
TROPOSPHERE	15°	~ 30 ns	~ 5 ns
IONOSPHERE	0°	~ 80 ns	~ 25 ns
RANGING SYSTEM AND SATELLITE EQUIPMENT DELAYS	-	MUST BE CALIBRATED	~ 6 ns
RECEIVING STATION EQUIPMENT DELAYS	-	MUST BE CALIBRATED	~ 5 ns
RESOLUTION OF RECEIVING STATION TIME INTERVAL COUNTER	-	-	10 ns
SATELLITE LOCATION	-	0	100 ns
RSS TOTALS		THESE BIASES ARE MODELED OUT	~ 104 ns (1σ)

9. REFERENCES

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APPENDIX A

SMS/GOES FREQUENCY PLAN

Receiving:

401.7 MHz to 401.85 MHz

50 self-timed 3 kHz channels for Data Collection Platform Radio sets (DCPRS) reports.

401.85 MHz to 402.0 MHz

100 interrogated 1.5 kHz channels for DCPRS reports.

402.0 MHz to 402.1 MHz

Spare channels

2025.0 MHz to 2033.2 MHz

Ranging or stretched Visible or Infrared Spin-Scan Radiometer (VISSR), also WEFAX.

2034.2 MHz ± 30 kHz

Command from CDA

2034.9 MHz ± 5 kHz

DCPRS interrogation from CDA, also special time code in time sharing mode.

Transmitting:

468.825 MHz ± 5 kHz

DCPRS interrogation and special time code in time sharing mode.

1687.6 MHz to 1695.6 MHz

Wideband VISSR

1685.0 MHz to 1693.2 MHz

Ranging or stretched VISSR

1690.1 MHz ± 25 kHz

WEFAX

1694.0 MHz ± 100 kHz

Telemetry beacon

1694.5 MHz ± 200 kHz

DCPRS reports

Note: Wideband VISSR, stretched VISSR, ranging and WEFAX are time-shared function.

Appendix A continued.

LINK FREQUENCY PLAN
SMS/GOES
RANGING SYSTEM

CDA Link:		
Up link	2026.0 MHz	CDA to SMS/GOES
Down link	1684.0 MHz	SMS/GOES to CDA
TARS I Link:		
Up link	2026.0 MHz	CDA to SMS/GOES
Down link	1684.0 MHz	SMS/GOES to TARS I
Up link	2030.2 MHz	TARS I to SMS/GOES
Down link	1688.2 MHz	SMS/GOES to CDA
TARS II Link:		
Up link	2026.0 MHz	CDA to SMS/GOES
Down link	1684.0 MHz	SMS/GOES to TARS II
Up link	2032.2 MHz	TARS II to SMS/GOES
Down link	1690.2 MHz	SMS/GOES to CDA
Receive Site Link:		
Up link	2026.0 MHz	CDA to SMS/GOES
Down link	1684.0 MHz	SMS/GOES to Site

APPENDIX B

POWER BUDGET:

LINK 1 CDA TO SMS/GOES

Transmitter Power	(dBm)	48.00
Transmitter Antenna Gain	(dB)	48.00
Transmitter Line Loss	(dB)	-1.60
Transmitter Off Beam Center Loss	(dB)	-1.00
(Angle in Degrees)		0.25
Free Space Loss	(dB)	190.20
Polarization Loss		-0.20
Receiver Antenna Gain	(dB)	13.40
Receiver Off Beam Center Loss	(dB)	-1.40
(Angle in Degrees)		7.00
Receiver Line Loss	(dB)	-4.50
Receiver Input Power Level	(dBm)	89.50
System Noise Temperature	(dB-K)	32.12
Boltzman's Constant	(dBm/Hz-K)	-198.60
Receiver Input No	(dBm/Hz)	-166.48
Receiver Input C/No	(dB-Hz)	76.98
Overall C/No	(dB-Hz)	76.98
Receiver Bandwidth	(MHz)	12.00
Receiver Bandwidth	(dB)	70.79
Receiver Output C/N	(dB)	6.19
Limiter Improvement	(dB)	2.31
Transmitter Output C/N	(dB)	8.50

LINK 2 SMS/GOES TO CDA

Transmitter Power	(dBm)	43.00
Transponder Power Sharing Loss	(dB)	-0.57
Transmitter Line Loss	(dB)	-3.40
Transmitter Antenna Gain	(dB)	19.10
Transmitter Off Beam Center Loss	(dB)	-1.60
(Angle in Degrees)		7.00
Free Space Loss	(dB)	-188.60
Polarization Loss	(dB)	-0.2
Receiver Antenna Gain	(dB)	48.00
Receiver Off Beam Center Loss	(dB)	-0.70
(Angle in Degrees)		0.25
Receiver Line Loss	(dB)	-0.40
Receiver Input Power Level	(dBm)	-85.37
System Noise Temperature	(dB-K)	20.00
Boltzman's Constant	(dB/Hz-K)	-198.60
Receiver Input No	(dBm/Hz-)	-178.60
Receiver Input C/No	(dB-Hz)	93.23
Overall C/No	(dB-Hz)	79.12
Modulation Loss	(dB)	-2.20
S/N Output (600 Hz BW)	(dB)	49.10

Appendix B continued.

Two Way Range Timing Error (For One Second Averaging Time)	(S)	$.06 \times 10^{-9}$

LINK 3 SMS/GOES TO TYPICAL RECEIVING SITE

Transmitter Power	(dBm)	43.00
Transmitter Power Sharing Loss	(dB)	-0.57
Transmitter Line Loss	(dB)	-3.40
Transmitter Antenna Gain	(dB)	19.10
Transmitter Off Beam Center Loss	(dB)	-2.5
(Angle in Degrees)		9.00
Free Space Loss	(dB)	-188.60
Polarization Loss	(dB)	-0.20
Receiver Antenna Gain	(dB)	30.40
Receiver Off Beam Center Loss	(dB)	-2.40
(Angle in Degrees)		2.20
Receiver Line Loss	(dB)	-0.70
Receiver Input Power Level	(dBm)	-105.87
System Noise Temperature	(dB-K)	28.50
Boltzman's Constant	(dBm/K-Hz)	-198.60
Receiver Input No	(dBm/Hz)	-170.10
Receiver Input C/No	(dB-Hz)	64.23
Overall C/No	(dB-Hz)	64.10
Receiver Bandwidth	(MHz)	1.00
Receiver Bandwidth	(dB)	60.00
Receiver Output C/N	(dB)	4.10
Modulation Loss	(dB)	-2.20
S/N Output	(dB)	61.90
Two Way Range Timing Error (For One Second Averaging Time)	(S)	0.72×10^{-9}