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Interim Technical Report

ANALYSIS OF A SYNTHETIC APERTURE RADIATING INTERFEROMETER NAVIGATION SATELLITE CONCEPT

by Perry I. Klein

May 1969

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Prepared for

National Aeronautics and Space Administration
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Moore School Report No.: 69-03

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ABSTRACT

This report describes and analyzes a synthetic aperture interferometer method of using satellites to provide navigating aircraft and ships with angular position information. The satellites transmit in the 1540 to 1660 MHz aeronautical mobile band already allocated for navigation satellite use, and the system is designed to keep the user's navigation equipment as simple as possible. A navigation satellite experiment based on the synthetic aperture interferometer concept is recommended both as a means of demonstrating the concept and to learn more about propagation phenomena at these frequencies.

It is found that the synthetic aperture interferometer navigation satellite concept is a very difficult one to implement successfully in an operational system because of the need to know the motion of the satellite and the user with extremely high accuracy. Moreover, very high-accuracy frequency standards are required both at the satellite and the user vehicle. Nevertheless, the concept is attractive because it offers the advantages of the already operational Navy Navigation Satellite System, without requiring many satellites for continuous coverage or long periods of time for a position fix.

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1.0 INTRODUCTION

There is currently a need for a general-purpose, world-wide navigation system capable of providing accurate position fixes, continuously and automatically, under all weather conditions. The system is most urgently needed for the North Atlantic region, but must be expandable for global coverage, and should not be overloaded by a large number of users. Any navigation system must be reliable, dependable, and provide position information in a form acceptable to the user. System obsolescence potential should be low, and the investment required by the user for navigation equipment should be as small as possible.

Potential users of a navigation system include commercial, private, scientific, and military aircraft and ships having a wide range of navigation requirements. The system should be capable of providing fully equipped users with position fixes having accuracies on the order of a nautical mile (1.85 km) or better. For users not requiring maximum navigation accuracy, navigation with less expensive user equipment, (with consequent trade-offs in position-determining capability and accuracy) is highly desirable. Oceanographic ships generally require the highest accuracy, but usually can afford to take more time to determine their positions. At the other extreme, supersonic aircraft require rapid and frequent position fixes since errors accumulate quickly at high traveling speeds.

In addition to these requirements, the Ad Hoc Joint Navigation Satellite Committee has concluded that an urgent need exists to provide North Atlantic air traffic controllers with adequate communications, and that an independent means of determining aircraft position is desirable for traffic surveillance purposes.[1] The Committee further recognized that a communications link could also provide additional functions such as the relaying of meteorological information, warnings of excessive radiation for high-altitude supersonic transports, and transmission of distress messages.

It has become widely recognized that earth satellites are potentially capable of meeting these requirements for a global navigation and traffic control system. Several studies have already considered various navigation satellite concepts based on Doppler, range-range, range-difference, and angle-measurement techniques. The synthetic aperture radiating interferometer navigation satellite concept to be developed in the following sections of this report has not previously been reported upon in any great detail.

Section 2 introduces and analyzes the synthetic aperture radiating interferometer concept and Section 3 contains an error analysis. The fourth section recommends a navigation satellite experiment based on the concept, and the last section summarizes the results, implications and conclusions of this research.

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[1] Final Report of the Ad Hoc Joint Navigation Satellite Committee, May 1966.

2.0 NAVIGATION SATELLITE CONCEPT ANALYSIS

2.1 General Description

The synthetic aperture radiating satellite interferometer concept utilizes the motion of a satellite to sweep out (i.e., "synthesize") an effective interferometer baseline. The satellite is placed in inclined-synchronous or subsynchronous orbit so that there is satellite motion with respect to the user. The navigating user measures the change in phase of a CW signal radiated from the satellite over a known interval of time and uses this information to determine his angular position with respect to the interferometer baseline synthesized by the satellite. The user's operation is entirely passive, i.e., the user need not transmit a signal in order to navigate. During the measurement interval, the coordinates of the satellite are calculated by ground reference stations, and this information is transmitted in real-time to the user by means of a modulated subcarrier radiated from the satellite. A digital computer, which constitutes a part of the user's equipment, determines the direction cosines and spacing of the effective satellite interferometer and then calculates the user's position with respect to the interferometer.

The synthetic aperture radiating interferometer concept is analogous to the integrated-Doppler cycle counting method used in the Navy Navigation Satellite System, but offers the advantages that fewer satellites are needed for continuous coverage, and a much shorter period of time is required to obtain a position fix.

2.2 Signal Analysis

Assume a navigation satellite radiates a continuous-wave (CW) signal

$$s(t) = A_o \cos(\omega_o t + \gamma) \tag{1}$$

where A_o is the amplitude of the radiated carrier,

ω_o is the carrier frequency, and

γ is some arbitrary carrier phase.

The signal and additive noise received by the navigating user is

$$s_R(t) + n_R(t) = A_1 \cos[\omega_o t + \gamma - \phi(t)] + n_c(t) \cos[\omega_o t + \gamma - \phi(t)]$$

$$- n_s(t) \sin[\omega_o t + \gamma - \phi(t)] \tag{2}$$

where A_1 is the amplitude of the received signal,

$n_c(t)$ is the in-phase component of the noise,

$n_s(t)$ is the quadrature component of the noise, and

$\phi(t)$ is the propagation phase delay given by

$$\phi(t) = 2\pi \frac{r(t)}{\lambda_o} \text{ radians} \tag{3}$$

where $r(t)$ is the distance from the satellite to the navigating user, and

λ_o is the wavelength of the signal radiated from the satellite.

Figure 1 shows the geometry of the synthetic aperture interferometer navigation satellite. At time t_1 the signal radiated from the satellite is

$$s(t_1) = A_o \cos(\omega_o t_1 + \gamma) \tag{4}$$

while the received signal-plus-noise is

$$s_R(t_1) + n_R(t_1) = A_1 \cos[\omega_o t_1 + \gamma - \phi(t_1)] + n_c(t_1) \cos[\omega_o t_1 + \gamma - \phi(t_1)]$$

$$- n_s(t_1) \sin[\omega_o t_1 + \gamma - \phi(t_1)] \tag{5}$$

where

$$\phi(t_1) = 2\pi \frac{r(t_1)}{\lambda_o} \tag{6}$$

At a later time $(t_1 + \tau)$, the satellite will have moved a distance $D(\tau)$ with respect to the earth, as shown in Fig. 1, and the signal radiated from the satellite will be

$$s(t_1 + \tau) = A_o \cos[\omega_o(t_1 + \tau) + \gamma] \tag{7}$$

while the received signal-plus-noise will be

$$s_R(t_1 + \tau) + n_R(t_1 + \tau) = A_1 \cos[\omega_o(t_1 + \tau) + \gamma - \phi(t_1 + \tau)]$$

$$+ n_c(t_1 + \tau) \cos[\omega_o(t_1 + \tau) + \gamma - \phi(t_1 + \tau)]$$

$$- n_s(t_1 + \tau) \sin[\omega_o(t_1 + \tau) + \gamma - \phi(t_1 + \tau)] \tag{8}$$

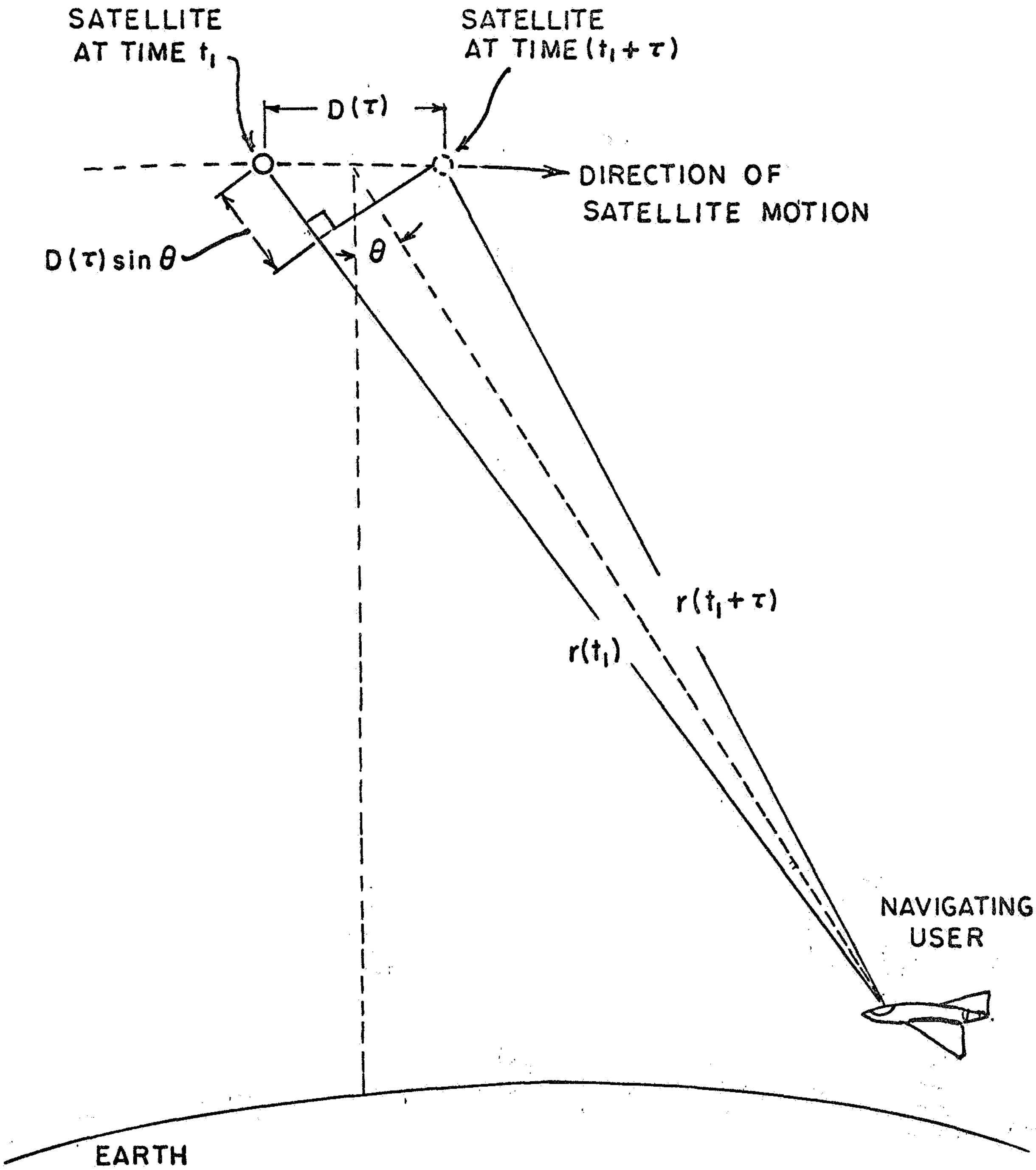

FIGURE I - SYNTHETIC APERTURE RADIATING INTERFEROMETER NAVIGATION SATELLITE GEOMETRY.

where

$$\phi(t_1 + \tau) = 2\pi \frac{r(t_1 + \tau)}{\lambda_o} \qquad (9)$$

From the geometry of Fig. 1, the direction (θ) of the navigating user with respect to the baseline synthesized by the satellite is given by

$$D(\tau) \sin \theta = r(t_1 + \tau) - r(t_1) \qquad (10)$$

or, substituting (6) for $r(t_1)$ and (9) for $r(t_1 + \tau)$,

$$\sin \theta = \frac{\lambda_o}{2\pi D(\tau)} [\phi(t_1 + \tau) - \phi(t_1)] \qquad (11)$$

Block diagrams of two possible types of navigation receivers are given in Fig. 2. In both cases, superheterodyne receivers are used with coherent detectors and narrowband post-detection integrating filters. A high-stability reference oscillator is required, and this oscillator must be synchronous with the satellite carrier frequency ω_o. The stability requirements and method of assuring oscillator synchronization are the subject of a later section. The two receivers differ in the method of measurement. The receiver represented in Fig. 2(a) counts cycles and fractions of a cycle (i.e., phase) during an accurately known interval of time. This time interval is obtained by dividing-down the known reference oscillator frequency and using the resulting clock pulses to control

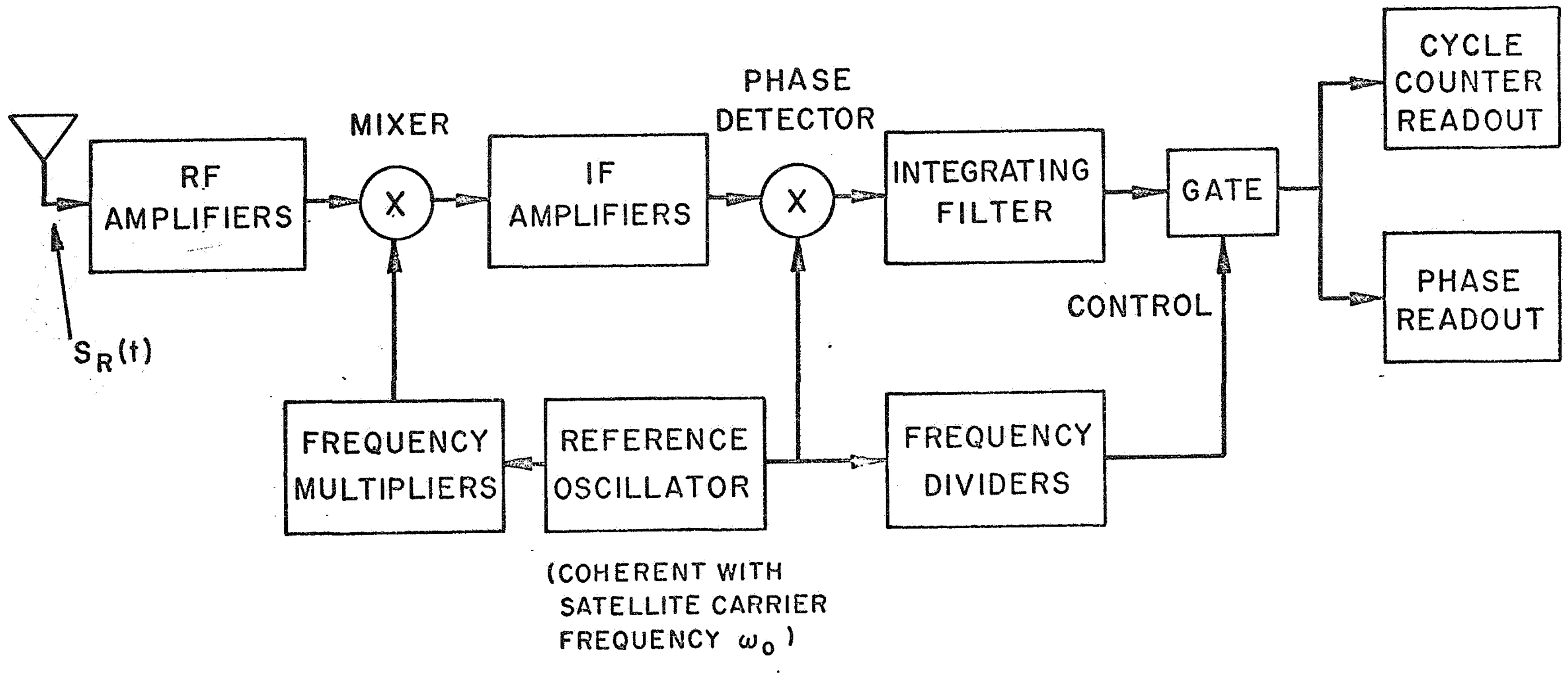

FIGURE 2(a) - USER'S NAVIGATION RECEIVING EQUIPMENT WITH CYCLE-COUNTING CIRCUITS (SIMPLIFIED BLOCK DIAGRAM)

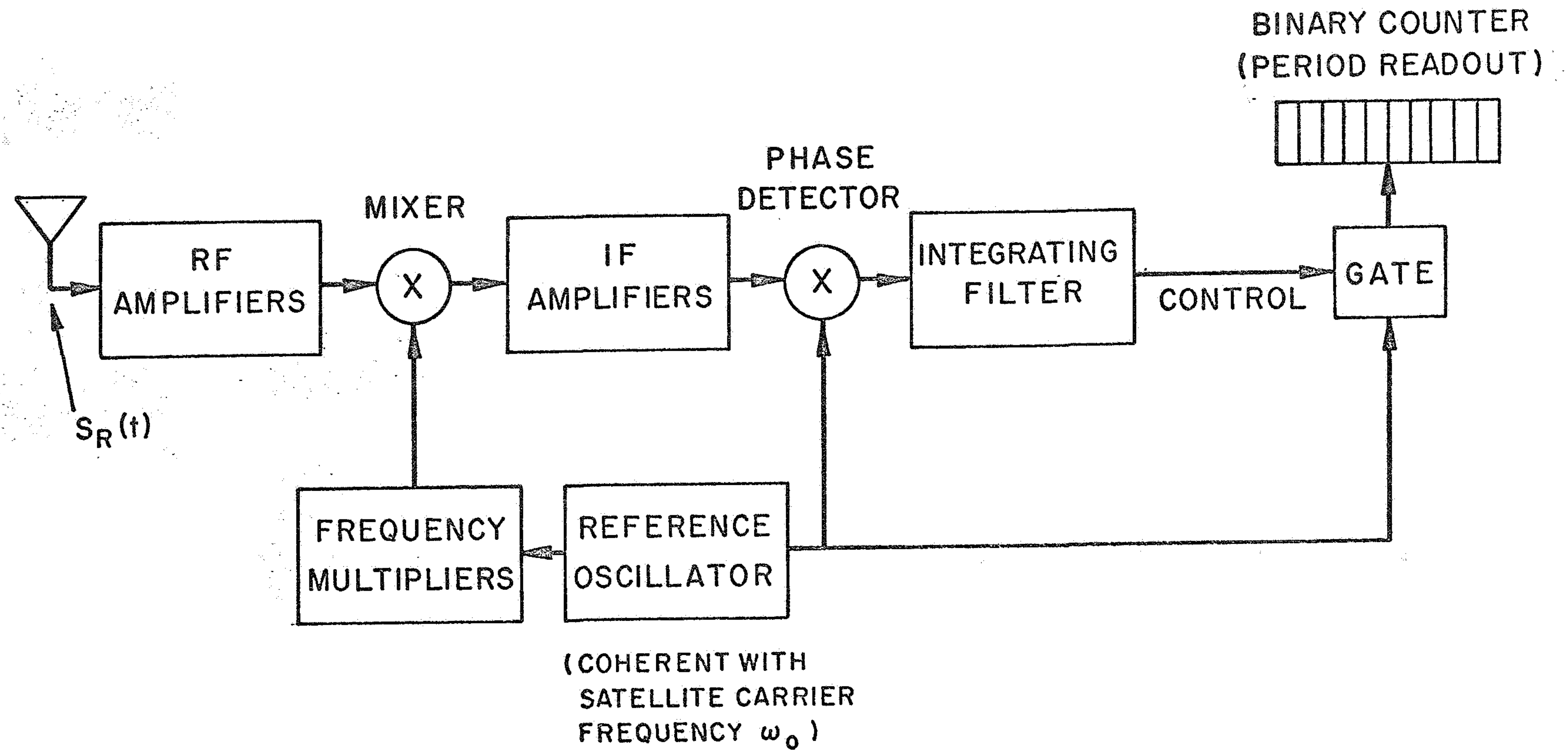

FIGURE 2(b) - USER'S NAVIGATION RECEIVING EQUIPMENT WITH PERIOD-COUNTING CIRCUITS (SIMPLIFIED BLOCK DIAGRAM) a gate to the cycle counter and phase readouts. The receiver shown in Fig. 2(b), on the other hand, counts the period of one cycle of change in carrier phase, i.e., the value of τ for which

$$[\phi(t_1 + \tau) - \phi(t_1)] = 2\pi \text{ radians} \tag{12}$$

In this case, (11) becomes

$$\sin \theta = \frac{\lambda_o}{D(\tau)} \tag{13}$$

The function $[\frac{\lambda_o}{D(\tau)}]$, i.e., the rate at which the satellite synthesizes the interferometer baseline, is calculated by a central ground station and this information is part of the data sent to the user via the satellite in real-time.

2.3 Extension of the Concept to Two Perpendicular Interferometer Baselines

A single satellite synthesizes a single interferometer which provides the navigating user with only a single angle, actually an angular line of position. A second interferometer perpendicular to the first is needed to provide a second angular line of position that will intersect the first line at a point, thereby fixing the user's position. In the case of navigating aircraft, it is assumed that an altimeter is available to provide information on the aircraft's altitude.

The second perpendicular interferometer baseline can be obtained by means of a second satellite whose orbit is perpendicular to the first. In practice, one satellite could be in a circular near-synchronous equatorial orbit, while the other satellite would be in a circular near-synchronous polar orbit. For continuous, world-wide coverage, approximately three equally spaced satellites are required in each of the two perpendicular orbital planes. The user navigation equipment is switched alternately between two perpendicular satellites (radiating on slightly different frequencies) in order to obtain a complete position fix. Methods of calibrating the user's local reference oscillator to the different satellite transmitting frequencies are discussed later.

2.4 Data Links, Processing, and Traffic Control Provisions

Before the user's position can be determined in a geodetic frame of reference, it is necessary that the navigator be supplied information on the position of each satellite as a function of time. This may be accomplished by pulse-code modulating the data onto a phase-modulated subcarrier of the satellite transmitter. The subcarrier is located within a few kHz of the radiated CW carrier so that a single navigation receiver can receive the navigation signals and the data simultaneously. The position coordinates are given as altitude, longitude and latitude, each with a precision of 0.1 millimeter. It should be noted that the accuracy of these three parameters need not be this good; instead, it is the differences in these variables with time that must have this high degree of accuracy. The data are transmitted from the satellite at a one-second frame rate. The received data are entered into the user's computer which subtracts two adjacent frames to obtain the difference $\vec{D}(\tau)$, where $\tau = 1$ second. The magnitude of $\vec{D}(\tau)$ represents the length of the interferometer baseline synthesized by the satellite and is needed to solve (11) and (13). The components of $\vec{D}(\tau)$ describe the direction of motion of the satellite and hence the orientation of the interferometer.

The satellite motion $\vec{D}(\tau)$ is solved by ground reference stations whose positions are already known. These stations measure the change in phase of the signal received from the satellite. The phase-difference data are sent to a central computation center which uses this information to solve backwards for $\vec{D}(\tau)$, best-fitting the solution to the observed data. $\vec{D}(\tau)$ is then expressed in the form of the altitude, longitude and latitude of the satellite, and this information is telemetered to the user via the satellite data-link, as mentioned previously. The central computation center also provides adjustments of the satellite transmitter frequency by ground command.

It is envisioned that two classes of users would navigate with this system. First is the independent passive user which is equipped with a digital computer for performing its own calculations. Second is the traffic control system user which does not have a computer and depends upon a central traffic control center to perform the calculations. A method of telemetering the measurements to the central traffic control center has already been described in a previous report[2] and is straightforward.

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[2] P. I. Klein, Analysis of a Short-Baseline Radiating Interferometer Navigation Satellite Concept Incorporating Methods to Eliminate Systematic Navigation Error, Univ. of Pa., Moore School of E. E. Report No. 68-26, prepared for the NASA Space Applications Programs Office under Grant NGR-39-010-087, May 1968.

3.0 NAVIGATION SATELLITE ERROR ANALYSIS

Further analysis of the synthetic aperture radiating interferometer navigation satellite indicates that the primary contributions to navigation error, and to the feasibility of the concept itself, are those due to equipment error, uncertainties in the motion of both the satellite and the user, and propagation.

3.1 Equipment Error

3.1.1 Carrier-to-Noise Ratio Limitations on Accuracy

Suppose that the reference oscillator in the user's receiver (Fig. 2) generates a signal of the form $\sin(\omega_o{}'t + \beta)$. This signal is effectively multiplied by the received signal (2) in the receiver phase detector to produce the difference signal output

$$\begin{aligned} s_D(t) + n_D(t) = {} & A_2 \sin[(\omega_o{}' - \omega_o)t + \beta - \gamma + \phi(t)] \\ & + n_c(t) \sin[(\omega_o{}' - \omega_o)t + \beta - \gamma + \phi(t)] \\ & - n_s(t) \cos[(\omega_o{}' - \omega_o)t + \beta - \gamma + \phi(t)] \quad (14) \end{aligned}$$

where A_2 is the amplitude of the signal portion of the phase detector output.

If the gate to the phase counter readout is triggered by positive-going zero crossings of (14), then between time t_1 and $t_1 + \tau$

$$[(\omega_o' - \omega_o)(t_1 + \tau) + \beta - \gamma + \phi(t_1 + \tau) + \eta(t_1 + \tau)]$$

$$- [(\omega_o' - \omega_o)\, t_1 + \beta - \gamma + \phi(t_1) + \eta(t_1)] = 2\pi\, X \text{ radians} \qquad (15)$$

i.e.,

$$[(\omega_o' - \omega_o)\tau + \phi(t_1 + \tau) - \phi(t_1) + \eta(t_1 + \tau) - \eta(t_1)]$$

$$= 2\pi\, X \text{ radians} \qquad (16)$$

where $\eta(t_1)$ and $\eta(t_1 + \tau)$ are the quadrature components of the phase noise in the phase detector output at time t_1 and $t_1 + \tau$, respectively, and X is the number of cycles counted by the cycle counter and phase readouts.* These noise terms are obtained from the second term of (14), i.e., the quadrature noise term. From (14) it can be shown that the rms value of the phase noise is

$$< \eta^2(t) >^{1/2} = \sqrt{\frac{N}{2C}} \qquad (17)$$

where C is the received signal power and

N is the noise power in the post-detection filter noise bandwidth.

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* In the case of the receiver shown in Fig. 2(a), the full integral number of cycles is measured by the cycle counter readout, while the remaining fraction of a cycle is measured by the phase readout. In the case of the receiver in Fig. 2(b), the value of τ corresponding to a given integral value of X is displayed.

Assuming independence between the noise terms in (16), the noise adds in the root-sum-square sense, and the expected value of the phase readout is

$$< X > = \frac{1}{2\pi} \left[(\omega_o' - \omega_o)\tau + \phi(t_1 + \tau) - \phi(t_1) + \sqrt{\frac{N}{C}} \right] \tag{18}$$

Substituting (11) for $\phi(t_1 + \tau) - \phi(t_1)$, this becomes

$$< X > = (f_o' - f_o)\tau + \frac{D(\tau)}{\lambda_o} \sin \theta + \frac{1}{2\pi} \sqrt{\frac{N}{C}} \tag{19}$$

or solving for sin θ,

$$\sin \theta = \frac{\lambda_o}{D(\tau)} \left[< X > - (f_o' - f_o)\tau - \frac{1}{2\pi} \sqrt{\frac{N}{C}} \right] \tag{20}$$

In this equation, θ is the space angle from the interferometer to the user, and X is the number of cycles of phase shift measured by the cycle counter and phase readouts. The $(f_o' - f_o)\tau$ term represents an error in the angle measurement due to an offset in frequency between the user's reference oscillator frequency (f_o') and the satellite transmitter frequency (f_o). This source of error is discussed later. The $\frac{1}{2\pi}\sqrt{N/C}$ term represents the error in the angle measurement due to limitations in the carrier-to-noise ratio of the received signal. It is evident from (19) that increasing $D(\tau)/\lambda_o$ will increase the sensitivity of the cycle counter (reading X) to small changes in angular position θ. In addition, (20) shows that increasing $D(\tau)/\lambda_o$ reduces the error in angular position caused by the $(f_o' - f_o)\tau$ and $\frac{1}{2\pi}\sqrt{N/C}$ terms. Figure 3 shows the relationship between angular position measurement error and carrier-to-noise ratio, for several values of $D(\tau)/\lambda_o$.

Table 1 lists the power budget for a satellite at near-synchronous altitude transmitting at a frequency of 1600 MHz with a power of 50 watts and a gain of 18 dB (assuming a satellite antenna with a half-power beamwidth of 20 degrees for full earth coverage). An omnidirectional (0-dB) user receiving antenna is assumed, and the receiver effective noise temperature is assumed to be 1000°K. It is seen from Table 1 and Fig. 3 that if a 1-Hz post-detection filter bandwidth is used, the angular position measurement error due to the 43.5-dB carrier-to-noise ratio will range from 20 miles to 0.1 mile proportionately as the baseline of the interferometer is increased from 1 wavelength to 200 wavelengths. Thus it is desirable to use long synthesized interferometer baselines if high accuracy navigation is to be achieved.

3.1.2 Frequency Stability Requirements and Calibration Methods

The term $(f_o' - f_o)\tau$ in (20) represents an error in the angle measurement due to bias errors in the user's reference oscillator frequency (f_o') and the satellite transmitter frequency (f_o). Since $D(\tau)$, the interferometer baseline synthesized in an interval of time τ, is very nearly a linear function of τ, the error $(\delta\theta)$ due to frequency offset bias error is (from 20)

$$\delta\theta = -\frac{\lambda_o}{V\tau}(f_o' - f_o)\tau = -\frac{\lambda_o}{V}(f_o' - f_o) \qquad (21)$$

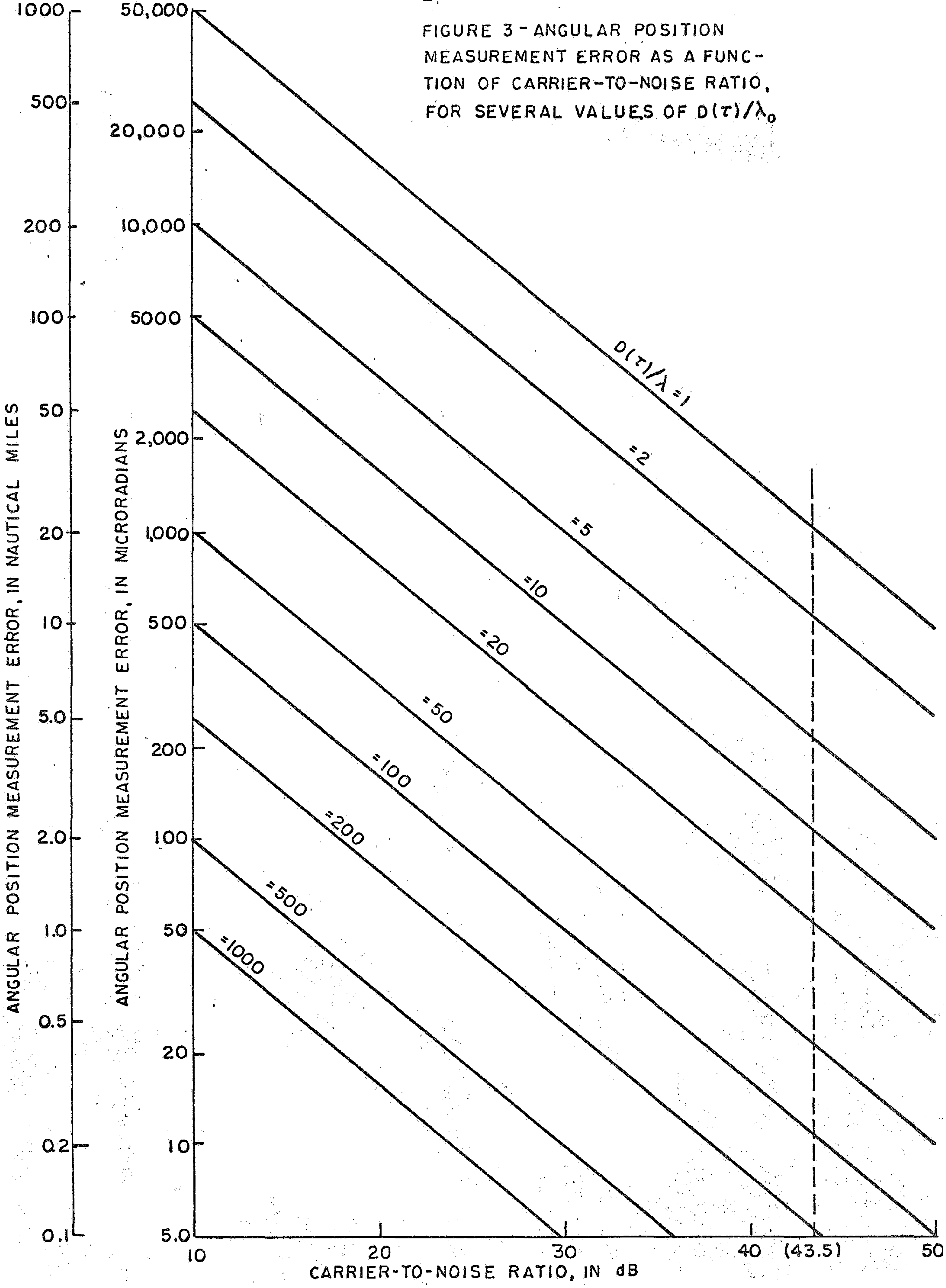

FIGURE 3 - ANGULAR POSITION MEASUREMENT ERROR AS A FUNCTION OF CARRIER-TO-NOISE RATIO, FOR SEVERAL VALUES OF $D(\tau)/\lambda_0$

Table 1

POWER BUDGET FOR A SYNTHETIC APERTURE RADIATING INTERFEROMETER NAVIGATION SATELLITE SYSTEM

Satellite transmitter power (50 watts)	17	dBW
Satellite antenna gain (20° beamwidth)	18	dB
Free space loss at 1600 MHz, from synchronous altitude to horizon	-190	dB
Navigation user receiving antenna gain (omnidirectional)	0	dB
User receiver noise power density kT (T = 1000°K)	-198.5	dBW/Hz
Received carrier-to-noise power density	43.5	dB-Hz

where V is the speed at which the satellite synthesizes the interferometer baseline.

Figure 4 shows the relationship between the angular position measurement error and the frequency offset, assuming a transmitting frequency of 1600 MHz. It is evident from the curves that the frequency accuracy and stability requirements are quite severe if position measurement errors are to be kept below one nautical mile. If the satellite is at near-synchronous altitude, V will be on the order of 100 wavelengths per second, and the accuracy and stability of the frequency standards at both the satellite and the user are required to be on the order of 1×10^{-12}, or better. Thus it appears that atomic frequency standards may be required, unless the frequency standards can be calibrated. One method to accomplish such a calibration is to make additional measurements of the user's angular position with respect to the satellite. This permits an oversolution for position from which it is possible to solve for any significant frequency offset in the user's reference oscillator. This same method of solving for bias in the reference oscillator is used in the Navy Navigation Satellite System. An accurate knowledge of the user's velocity is required before the frequency offset can be computed.

Satellite oscillators having sufficient accuracy have already been flown. The U. S. Naval Research Laboratory's TIMATION satellite employs a special crystal oscillator reported to be accurate to 3 parts in 10^{12}. Adjustments to the satellite oscillator

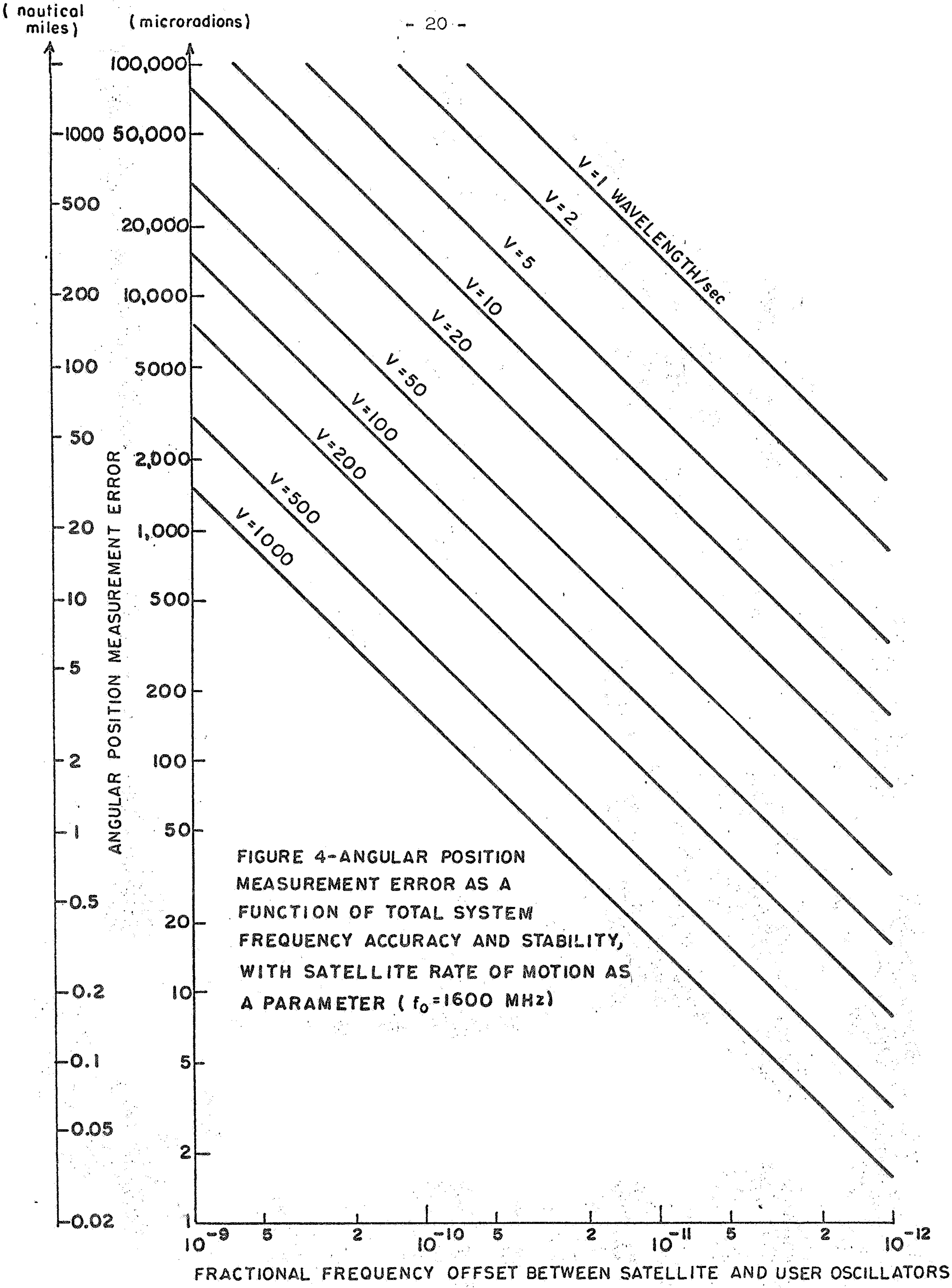

FIGURE 4-ANGULAR POSITION MEASUREMENT ERROR AS A FUNCTION OF TOTAL SYSTEM FREQUENCY ACCURACY AND STABILITY, WITH SATELLITE RATE OF MOTION AS A PARAMETER (f_0=1600 MHz)

frequency can be performed upon ground command through the use of ground reference stations at known locations on the earth. Observations by these stations can be used to solve backwards for the frequency of the satellite transmitter, so that the satellite oscillator frequency can be corrected accordingly. Atomic clocks having frequency stabilities on the order of parts in 10^{12} are available commercially, and stabilities of parts in 10^{13} to 10^{14} are available from atomic hydrogen masers.[3] These devices have not yet flown in spacecraft, however.

3.2 Error Due to Uncertainties in User, Satellite and Satellite Antenna Motion

The measurements of phase difference made by the navigating user corresponds to changes in the path length between the satellite and the user, and this information locates the user's angular position with respect to the satellite. The total path-length change $\delta\vec{r}(\tau)$ is actually made up of three component vectors:

$$\delta\vec{r}(\tau) = \vec{D}(\tau) + \vec{u}(\tau) + \vec{q}(\tau) \tag{22}$$

where $\delta\vec{r}(\tau) = \vec{r}(t + \tau) - \vec{r}(t)$ (23)

$\vec{D}(\tau)$ is the orbital velocity vector of the satellite,

$\vec{u}(\tau)$ is the velocity vector of the user, and

$\vec{q}(\tau)$ is a velocity vector corresponding to motion of the satellite antenna phase center about the center of the

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[3] A. O. McCoubrey, "A Survey of Atomic Frequency Standards," Proc. of the IEEE, Vol. 54, pp. 116-135, February 1966.

satellite.

The $\vec{D}(\tau)$ component is desired, while the $\vec{u}(\tau)$ and $\vec{q}(\tau)$ components represent errors due to uncertainties in the motion of the user and the satellite antenna. If Z is the amount of motion of the satellite antenna phase center about the center of the satellite, then the corresponding phase difference error is

$$\delta\phi = \frac{2\pi Z}{\lambda} \text{ radians} \tag{24}$$

and the angular position error is

$$\delta\theta = \frac{\lambda}{2\pi D}\,\delta\phi = \frac{Z}{D} \text{ radians} \tag{25}$$

Table 2 shows the expected angular position error for several values of antenna motion (Z) and synthesized baseline lengths (D). It is evident from the Table that very constant attitude control is required at the satellite in order to limit motion of the satellite antenna phase center about the center of the satellite. In addition, the faster the satellite sweeps out the interferometer baseline, the smaller will be the error for a given value of antenna motion.

The effects of user motion can be looked upon in much the same way, i.e., unknown motion of the user antenna can cause errors in angular position by the same amounts as those indicated in Table 2. In the case of the moving user, unless the number of wavelengths swept out by the satellite is designed to be much larger than the number of wavelengths swept out by the user, the system

Table 2

ANGULAR POSITION ERROR DUE TO MOTION OF THE SATELLITE ANTENNA PHASE CENTER ABOUT THE CENTER OF THE SATELLITE

Note 1 Z in millimeters	Note 2 D in meters	$\delta\theta$ in microradians	Note 3 δX in n miles
0.1	2	50	1
0.1	4	25	0.5
0.1	10	10	0.2
0.1	20	5	0.1
0.1	40	2.5	0.05
0.1	100	1.0	0.02
0.1	200	0.5	0.01
1.0	2	500	10
1.0	4	250	5
1.0	10	100	2
1.0	20	50	1
1.0	40	25	0.5
1.0	100	10	0.2
1.0	200	5	0.1
10	2	5000	100
10	4	2500	50
10	10	1000	20
10	20	500	10
10	40	250	5
10	100	100	2
10	200	50	1

Note 1 Z is the amount of motion of the satellite antenna phase center about the center of the satellite.

Note 2 D is the length of the synthesized interferometer baseline.

Note 3 δX is position error at the subsatellite point from a near-synchronous satellite.

would actually be a ground-based interferometer (with the baseline swept out by the user) rather than a satellite-based interferometer.

3.3 Propagation Error

The effects of ionospheric refraction and dispersion and tropospheric phase fluctuations have already been analyzed in a previous report,[4] the results of which can be expected to apply here. The effects of multipath have also been analyzed in the previous report. Multipath is found to be a very significant source of error; however, multipath effects can be reduced considerably through the use of narrowband filtering which tends to average out multipath phase error.[5] The effects of multipath can also be reduced through the use of spread spectrum signals at the satellite in order to achieve ensemble averaging of the multipath error.[6]

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[4] Klein, Ibid, pp. 75-78.

[5] Ibid, pp. 78-84.

[6] "An Angle-Measurement Navigation Satellite Concepts Study," (Phase II) Proposal submitted to the NASA Space Applications Programs Office by the University of Pennsylvania, December 1968, pp. 32-34.

4.0 RECOMMENDATION OF A NAVIGATION SATELLITE EXPERIMENT

The synthetic aperture interferometer satellite concept is one that can be evaluated readily by means of a satellite experiment. There are several reasons why such an experiment is valuable:

1) A synthetic aperture interferometer is the easiest method of obtaining a satellite interferometer. Other interferometer concepts which require at least two coherent radiating sources separated in space, are much more difficult to realize with satellites.

2) Specialized satellites are not necessarily needed for a synthetic aperture interferometer satellite experiment. An existing or planned satellite that contains a high frequency-stability CW transmitter can be used for the experiment. TIMATION or Navy Navigation Satellites might possibly be used to demonstrate the concept.

3) A synthetic aperture interferometer satellite can provide a large amount of much-needed data on propagation of satellite signals. The use of a stable signal transmitted by a satellite and a coherent reference at the user receiver provides a very sensitive measurement of multipath and other spatially-sensitive propagation characteristics.

Several of the problems associated with the synthetic aperture concept can be eliminated through the use of a stationary user station with the satellite. A stationary user has no uncertainty in velocity, and hence a potential source of error is immediately eliminated. In addition, the effects of multipath propagation can be assessed by comparing results from a high-gain user antenna with those obtained from low-gain antennas. The directional characteristics of the high-gain antenna can be used to isolate and measure the properties of the direct and reflected multipath signal components. A medium or low-altitude satellite orbit can be used for the experiment in order to greatly reduce the frequency stability requirements of the satellite oscillator and the user reference oscillator, and at the same time reduce errors due to uncertainties in user velocity.

5.0 SUMMARY AND CONCLUSIONS

This report has introduced a concept of using the motion of a non-synchronous satellite to form the baseline of an interferometer. The interferometer is capable of providing a passive navigating user with angular position information. In effect, the length of the measurement interval determines the length of the synthetic aperture baseline. However, it is found that the longer the measurement interval, the more stringent are the frequency stability requirements of the satellite and user reference oscillators, and the need to know the exact amount of motion of the satellite and the user.

It can be concluded from the error analysis of Section 3 that lower orbit satellites are more desirable than near-synchronous ones for the synthetic aperture interferometer because of the shorter period of time required to synthesize a given interferometer baseline length. A lower orbit satellite relaxes the reference oscillator frequency stability requirements and at the same time introduces less error from uncertainty in the motion of the user.

While the synthetic aperture interferometer concept appears to be a questionable technique to implement as an operational navigation satellite system, the concept should provide the basis for an invaluable interferometer experiment. Such an experiment was discussed in the previous section.

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13. ABSTRACT

This report describes and analyzes a synthetic aperture interferometer method of using satellites to provide navigating aircraft and ships with angular position information. The satellites transmit in the 1540-1660 MHz aeronautical mobile band already allocated for navigation satellite use, and the system is designed to keep the user's navigation equipment as simple as possible. A navigation satellite experiment based on the synthetic aperture interferometer concept is recommended both as a means of demonstrating the concept and to learn more about propagation phenomena at these frequencies.

It is found that the synthetic aperture interferometer navigation satellite concept is a very difficult one to implement successfully in an operational system because of the need to know the motion of the satellite and the user with extremely high accuracy. Moreover, very high-accuracy frequency standards are required both at the satellite and user vehicle. Nevertheless, the concept is attravtive because it offers the advantage of the already operational Navy Navigation Satellite System, without requiring many satellites for continuous coverage or long periods of time for a position fix.

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