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ATS-F/GEOS-C SATELLITE TO SATELLITE TRACKING DATA PROCESSING CONSIDERATIONS

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ABSTRACT

The satellite to satellite tracking data unique processing considerations are presented. The strategy to be employed in the application of data processing routines to the ATS-F/GEOS-C satellite to satellite tracking (SST) experiment is described. When these considerations are included, studies, analysis and simulations predict an orbital position uncertainty of less than 15 meters and a velocity uncertainty of less than 1.5 millimeters per second.

CONTENTS

ILLUSTRATIONS

CONTENTS (continued)

Page

TABLES

INTRODUCTION

The Satellite to Satellite Tracking experiment to be performed during the GEOS-C/ATS-F mission is primarily designed to produce data which can be utilized to derive coefficients for the harmonic expansion of the gravity field and in a related effort to aid in the GEOS-C program for Geoid shape determination using the altimeter data.[1] Both of these goals or objectives require highly accurate orbits over long arcs.[2] Since GEOS-C will be visible from ATS-F for over one half an orbit these long data spans are realistic.

The geometry for this satellite to satellite tracking experiment is shown in Figure 1.

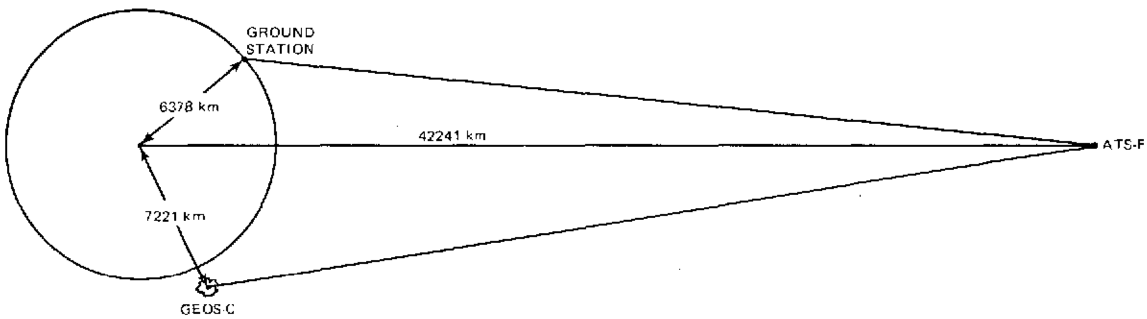

Figure 1. GEOS-C/ATS-F/GS Geometry

The ATS-F satellite will be in synchronous orbit over 94° West longitude during the early portion of the GEOS-C mission. Later ATS-F will be drifted to 34° East longitude. It is planned to track GEOS from ATS-F from both positions.

The nominal GEOS-C orbit will be:[1]

Height = 843 km
Eccentricity = 0.004
Inclination = 115°

The portion of the GEOS orbit visible from ATS-F will vary with time as the two satellites revolve in their respective orbital planes.

SPACECRAFT SYSTEMS

The transponders in the two spacecrafts and the associated antennas establish the tracking capability of this experiment.

ATS-F System

The ATS-F spacecraft[3] will employ a 9 meter (36 dB gain, 1.4° beamwidth) parabolic antenna programmed to follow the line of sight to the GEOS-C spacecraft. The communication transponder aboard the ATS-F will coherently translate the ground to ATS-F uplink frequency of approximately 6 GHz to 2 GHz for the ATS-F to GEOS forward link. On the return link the ATS-F transponder translates the GEOS-C to ATS-F return link from 2.25 GHz to 4 GHz. The 4 GHz signal is the ATS-F to ground station link frequency. These frequency translations are termed "pseudocoherent" in that the forward link translation is accomplished employing a phase locked oscillator that is coherent with the forward link signal at the time of translation, and the return link translation is accomplished employing the same phase locked oscillator however the oscillator is not coherent with the return link signal. The ATS-F translation oscillator is always phase locked to the ground source during satellite to satellite tracking operations.

GEOS-C System

The GEOS-C tracking transponder is a phase locked frequency multiplication device with a 240/221 transmit to receive ratio. The GEOS-C is fitted with four switchable antenna on the slant panels for receiving and transmitting to ATS-F. A fifth S-band antenna is mounted on the earth viewing side of GEOS-C. When commanded to this antenna the transponder may be interrogated directly from the ground.

The tracking data recorded at the Ground Station is in the form of time delays and doppler frequency count times corresponding to the round trip range and the round trip range rate (Doppler).

PREPROCESSING CONSTRAINTS

Each raw satellite to satellite tracking data record consists of two basic time measurements. These are usually referred to as range and range rate. The actual "range" measurement is a measure of the two way signal propagation time including systematic or instrument delays of a specific event, such as the zero crossing of a range tone. The actual "range rate" measurement is a measure of the time required to accumulate a known number of doppler plus bias frequency cycles (N-count). Since the Application Technology Satellite (ATS) ground station employs the N-count system the processing is designed for N-count doppler.

Actual tracking geometry (Figure 1) shows that the observed "range" (time delay) is a function of the positions of the two satellites and the ground station. It is not possible to separate any individual satellite to satellite or satellite to ground propagation time. The processing approach is to treat the observation "as is" and let the orbit determination program synthesize a propagation time based upon a priori or ephemeris derived information. The same is true of the doppler count time and it is also treated "as is" in the processing. The data processor is configured to allow independent time tagging of the two observables.

PREPROCESSING FUNCTIONS

The preprocessing performs the following functions:

(a) Read and correct data format
(b) Provide proper time tag
(c) Apply known corrections
(d) Edit, smooth, and compact data
(e) Format output data.

The preprocessor approach to each of those is explained in the following sections.

A. Input

The function accomplished here is to read in the raw data in the ATSR data format and convert it to the binary Unified Data Format.

B. Time Tagging

The time tag associated with the raw data is the ground clock time for the transmission of a positive going zero crossing of a range tone. This same time is associated with the doppler since the doppler count period starts also at this zero crossing time. The time tagging algorithm associated with Satellite to Satellite tracking must take into account all the motions of the two spacecrafts and the ground station. This time tagging algorithm is reflected in the observational equations. The observational equation is simply an expression relating the observed measurement to a computed measurement. The computed measurement is a function of the two satellite positions at the time the signal arrives at each satellite, the ground station position (coordinates) and other system parameters. The geometry is illustrated in Figure 2 where

$x_1(T)$ = ATS position vector
$x_2(T)$ = GEOS-C position vector
x_s = Ground Station position vector.

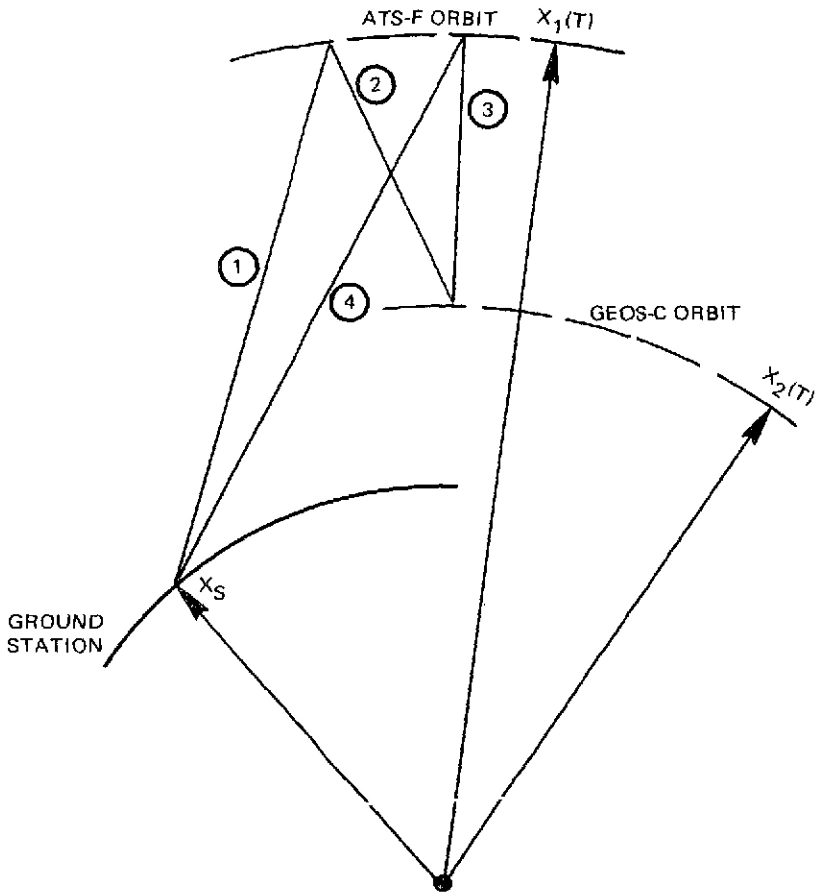

Figure 2. Position Vectors

The range tone is transmitted from the ground station at time (t) and reaches ATS-F at $(t + T_1)$. Thus T_1 represent the propagation time from the ground station to ATS-F. After a transponder delay of TD_1, the signal is transmitted to GEOS-C arriving at $t + T_1 + TD_1 + T_2$. Where T_2 is the propagation time from ATS-F to GEOS-C. If the GEOS-C transponder delay is TD_2, the signal arrives back at ATS-F at $t + T_1 + TD_1 + T_2 + TD_2 + T_3$. Since the ATS-F transponder may not be exactly reciprocal the time delay TD_3 is assigned for the return link delay. The signal then arrives back at the ground station at $t + T_1 + TD_1 + T_2 + TD_2 + T_3 + TD_3 + T_4$. One more time delay (T_R) is defined as the propagation delay caused by transmission path anomalies such as the troposphere. These time delays may be interpreted in terms of the various position vectors of Figure 2 as:

$$
\begin{aligned}
T_1 &= [X_1(t + T_1) - X_s]/c + T_R \\
T_2 &= [X_2(t + T_1 + TD_1 + T_2) - X_1(t + T_1 + TD_1)]/c \\
T_3 &= [X_1(t + T_1 + TD_1 + T_2 + TD_2 + T_3) - X_2(t + T_1 + TD_1 + T_2 + TD_2)]/c \\
T_4 &= [X_1(t + T_1 + TD_1 + T_2 + TD_2 + T_3 + TD_3) - X_s]/c + T_R
\end{aligned} \tag{1}
$$

The solution of this system of nonlinear equation may be obtained by means of the Newton-Ralphson iterative method for the solution of nonlinear equations. Models for the propagation path anomalies must also be included to evaluate T_R.

Data Corrections

The orbit dependent variation in the transponder delays TD_1, TD_2, TD_3 are functions of the deviation of the signal frequency from its nominal value. Such variations in carrier frequency are due to the relative motion between transmitter and receiver (Doppler shift). These variations can be expressed as function of the time derivative of the propagation time delay. The accepted expression for average doppler is:

$$f_d = -\frac{2\dot{r} f_t}{c} \tag{2}$$

Since the Doppler shift is a linear function of the transmission frequency, f_t may be defined to be the sum of two frequencies; an f_1 which propagates from the ground to ATS-F to GEOS-C and return and an f_2 which propagates from the ground to ATS-F and return. The values assigned to f_1 and f_2 and the proper frequency formulations are explained in the "Doppler Processing" section of this report. The Doppler expressed in terms of f_1, f_2 and the propagation paths of Figure 2 (r_1 and r_2) is

$$f_d = -\frac{2}{c}[f_1(\dot{r}_1 + \dot{r}_2) + f_2(\dot{r}_1)] \tag{3}$$

If we now define the time derivative of the propagation delay as $\dot{T}_i = \dot{r}_i/c$ then

$$f_d = -2[f_1(\dot{T}_1 + \dot{T}_2) + f_2(\dot{T}_1)] \tag{4}$$

Since the ATS-F is in geosynchronous orbit most of the observed Doppler is from the ATS-F/GEOS-C link. For evaluation of the variations of the various transponder delays due to the Doppler, the Ground to ATS-F Doppler will be assumed to be zero. However since, as stated before, it is impossible to separate the various contributions equation 4 for one way Doppler is approximated as;

$$f_d = f_1 [\dot{T}_1 + \dot{T}_2] \tag{5}$$

As previously stated the ATSR system employs "N-count" Doppler. The system determines the time, (T), required to accumulate a fixed number of Doppler plus bias frequency cycles (N). That is

$$T = \frac{N}{f_b + f_d}$$

which when combined with equation 5 gives:

$$T = \frac{N}{f_b + f_1(\dot{T}_1 + \dot{T}_2)} \tag{6}$$

which gives an approximate doppler count of

$$T = \frac{N}{f_b + \frac{2\dot{R}}{c} f_1} \tag{7}$$

and

$$\dot{R} = \frac{c}{2 f_1} (N - T f_b) \tag{8}$$

This expression for $\dot{R}$ is sufficiently accurate for the determination of delay variation in the ATS-F transponder due to Doppler frequency offset. It is to be noted that the dynamic loop lag of the GEOS-C transponder must also be in the modeling TD_2. The transponder delay variations can be given by the expressions:

$$TD_1 = \sum_{k=0}^{4} d_k \cdot \dot{T}^k$$

$$TD_2 = \sum_{k=0}^{4} e_k \cdot (\dot{T}_1 + \dot{T}_2)^k + \sum \frac{1}{k_a} \ (\ddot{T}_1 + \ddot{T}_2) \qquad (9)$$

$$TD_3 = \sum_{k=0}^{4} d_k \cdot (\dot{T}_1 + \dot{T}_2 + \dot{T}_3)^k$$

where d_k and e_k are a set of polynomial coefficients associated with the ATS-F and the GEOS-C transponder and K_a represents the GEOS-C phase lock loop acceleration gain constant. The time derivatives ($\dot{T}_i$) may be evaluated from the following expressions:

$$\begin{aligned}
\dot{T}_1 &= [X_1(t + T_1) - X_s] \cdot \dot{X}_1(t + T_1)/c^2 T_1 \\
\dot{T}_2 &= [X_2(t_q + T_1) - X_1(t_q)] \cdot [\dot{X}_2(t_q + T_1) - \dot{X}_1(t_q)]/c^2 T_2 \\
\dot{T}_3 &= [X_1(t_r + T_2) - X_2(t_r)] \cdot [\dot{X}_1(t_r + T_2) - \dot{X}_2(t_r)]/c^2 T_3 \\
\dot{T}_4 &= [X_1(t_s) - X_s] \cdot X_2(t_s)/c^2 T_4
\end{aligned} \qquad (10)$$

where

$$\begin{aligned}
t_q &= t + T_1 + TD_1 \\
t_r &= t_q + TD_2 \\
t_s &= t_r + T_3 + TD_3
\end{aligned}$$

Thus the range observation, expressed in time delays is:

$$\tau = T_1 + TD_1 + T_2 + TD_2 + T_3 + TD_3 + T_4 \qquad (11)$$

The lag error is a function of the range acceleration and the loop gain constant. The loop gain constant is of course a loop design parameter and is therefore readily available. However the range acceleration must somehow be developed either from the data or the orbit. The proposed method of obtaining the range acceleration is outlined in the following section.

The data corrections derived from the station and instrument calibrations must also be applied to the observational data. These corrections include: the station survey corrections in East, North and Vertical components, instrument bias, timing bias and the previously mentioned refraction bias. These corrections are modeled in the NAP-3 and are applied to the appropriate measurements by the program. The value of τ is transmitted in the ATSR data format[4] as Words 2 and 5 in nanoseconds.

SMOOTHING AND EDITING

The routine employed for data smoothing is a portion of the Navigation Analysis Program (NAP).[7] The data are fitted to a polynomial function of time. The number of data points to be included in the fitting as well as the order of the polynomial (up to 6th order in t) may be selected as user inputs. The user may also select the criteria for the rejection of statistically inconsistant data points.

Once this polynomial fitting is accomplished the range acceleration may be derived directly since the acceleration is the slope of the fitted curve. As indicated in the previous section of this paper the range acceleration is required to evaluate the dynamic loop lag in the GEOS-C transponder. In utilizing this capability the user must select:

(1) the order of the polynomial
(2) rejection criteria for statistically inconsistant data points
(3) the number of data points to be smoothed

With this acceleration model the transponder delay variation for the GEOS-C can be evaluated.

DOPPLER PROCESSING

The Doppler or time delay rate measurement analysis is similar but more involved. The propagation time delay is not effected by carrier frequency translations and multiplications. However, since the Doppler is proportional to the carrier frequency the various carrier frequency adjustments must be considered. The frequency of the carrier may be traced with the aid of Figure 3. The signals appearing at the various points in the diagram are listed in Table 1. The constants involved are given in Table 2. The signal at x (Table 1) is the input to the phase locked ATSR receiver for doppler extraction. The extracted doppler is then,

$$f_d = \left(\frac{n}{m}\right)\left(\frac{1}{a+b}\right)\left[a(K_2+K_3)+b(K_2-K_1)+c(K_1+K_3)\right]\left[\alpha_1\alpha_2\beta_1\beta_2-1\right] f_r$$
$$+\left(\frac{1}{a+b}\right)\left[(d-e)(K_1+K_3)\right]\left[\alpha_1\alpha_2-1\right] f_r \tag{12}$$

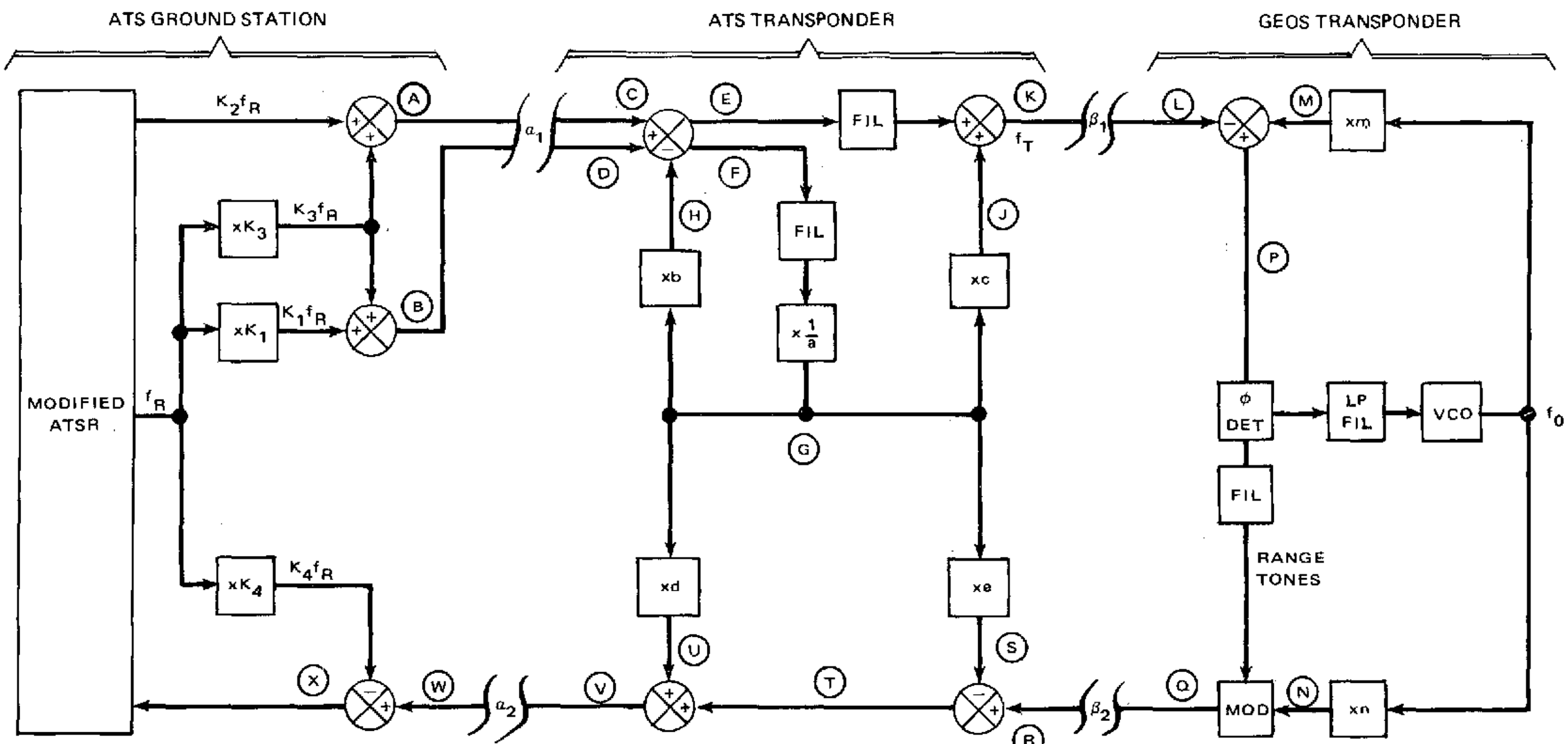

Figure 3. System Diagram

TABLE 1

A $(K_2 + K_3)\ f_r$

B $(K_1 + K_3)\ f_r$

C $\alpha_1 (K_2 + K_3)\ f_r$

D $\alpha_1 (K_1 + K_3)\ f_r$

E $\left[\alpha_1 (K_2 + K_3) - \frac{b\alpha_1 (K_1 + K_3)}{a + b}\right] f_r = \frac{\alpha_1}{a + b}\ [a(K_2 + K_3) + b(K_2 - K_1)]\ f_r$

F $\left[\alpha_1 (K_1 + K_3) - \frac{b\alpha_1 (K_1 + K_3)}{a + b}\right] f_r = \frac{\alpha_1}{a + b}\ [a(K_1 + K_3)]\ f_r$

G $\frac{\alpha_1 (K_1 + K_3)\ f_r}{a + b}$

K $\frac{c\alpha_1 (K_1 + K_3)\ f_r}{a + b} + \frac{\alpha_1}{a + b}\ [a(K_2 + K_3) + b(K_2 - K_1)]\ f_r =$

$\alpha_1 \left(\frac{1}{a + b}\right) [a(K_2 + K_3) + b(K_2 - K_1) + c(K_1 + K_3)]\ f_r = f_t$

L $\beta_1 f_t = \frac{\alpha_1 \beta_1}{a + b}\ [a(K_2 + K_3) + b(K_2 - K_1) + c(K_1 + K_3)]\ f_r$

N $\beta_1 \frac{n}{m} f_t$

R $\beta_1 \beta_2 \frac{n}{m} f_t$

T $\beta_1 \beta_2 \frac{n}{m} f_t - \frac{e}{a + b}\ \alpha_1 (K_1 + K_3)\ f_r$

V $\beta_1 \beta_2 \frac{n}{m} f_t - \frac{e}{a + b}\ (\alpha_1 (K_1 + K_3)\ f_r) + \frac{d}{a + b}\ (\alpha_1 (K_1 + K_3)\ f_r)$

W $\alpha_2 \beta_1 \beta_2 \frac{n}{m} f_t + d - e\ \alpha_1 (K_1 + K_3)\ f_r \alpha_2$

X $\alpha_2 \beta_1 \beta_2 \frac{n}{m} f_t + \left(\frac{d - e}{a + b}\right) \alpha_1 \alpha_2\ (K_1 + K_3)\ f_r - K_4\ f_r$

TABLE 2

$f_r = 5 \times 10^6$ Hz

$K_1 = 16.43$

$K_2 = 15.2525$

$K_3 = 1213.57$

$K_4 = 775.4$

$a = 6$

$b = 240$

$c = 77$

$d = 152$

$e = 84$

$m = 221$

$n = 240$

$$\left.\begin{array}{l} \alpha_1 = 1 - \dot{T}_1 \\[2ex] \alpha_2 = \dfrac{1}{1 + \dot{T}_2} \\[2ex] \beta_1 = 1 - \dot{T}_3 \\[2ex] \beta_2 = \dfrac{1}{1 + \dot{T}_4} \end{array}\right| \text{ reference 5}$$

In the implementation of the system a bias frequency is added to this Doppler frequency to prevent the count from going through zero. If the count goes through zero the direction of the range rate is lost. Inserting the constants of Table 2 in equation 12:

$$f_d = 2247\,[\alpha_1\alpha_2\beta_1\beta_2 - 1] + 1700\,[\alpha_1\alpha_2 - 1]\ \text{MHz} \quad (6)$$

In the system (ATSR) data output the Doppler data appears as the time required to accumulate a known number of bias (f_b) plus Doppler frequency cycles. The output is

$$T = \frac{N}{f_b + f_d}$$

where

f_b = bias frequency (500 KHz)

f_d = Doppler frequency (equation 6)

N = cycles counted (reference 4)

In the implementation of this experiment the values of the constants K_1, K_2, K_3 and K_4 cannot be realized exactly. Therefore a delta in the bias frequency must be introduced into the data system. The bias frequency is,

$$f_b = f_b' + \Delta f_b \tag{13}$$

where

f_b = correct doppler bias including frequency offsets

f_b' = nominal bias (500 KHz)

Δf_b = bias offset caused by transmitted and local oscillator offsets

and

$$\Delta f_b = \frac{n}{m}\Delta f_{RR} + \left[\left(\frac{n}{m}\right)\left(\frac{c - d}{a + b}\right) + \left(\frac{d - e}{a + b}\right)\right]\Delta f_{ATS} + \Delta f_{LO} \tag{14}$$

where

Δf_{RR} = frequency offset in the ranging carrier from ground to ATS-F

Δf_{ATS} = frequency offset in the ground to ATS-F beacon

Δf_{LO} = frequency offset in the first down converter in the ATSR receiver

These frequency offsets differ with different operating frequencies and also with the ground stations. As of this time there are no plans to include these as part of the data message. The computer program is designed to accept the Δf_b as an input variable.

For the selected frequencies in the ATS-F/GEOS-C experiment this Δf_b = +16.3102 and the zero Doppler count, T = .51190330 seconds.

CONCLUSION

The test of any system is "How well can the desired mission be accomplished?" To answer this question, the orbit determination capability of the system was investigated employing the NAP-3 (ref. 7). This program was developed to accept and process various types of tracking data. As such is includes the algorithms required to process satellite to satellite range sum and range sum rate data. The NAP-3 actually considers the four paths separately and through an iterative solution resolves the final orbit for each of the two satellites. This capability has been exercised and evaluated using simulated data.[8]

Studies[9] involved in these simulations have indicated the necessity of solving not only for the two satellites but also the more dominant terms of the harmonic expansion of the geopotential. The question then becomes, "What is the smallest number of geopotential harmonic expansion coefficients to be considered to meet a position uncertainty criteria?" A position uncertainty of 25 meters was chosen for our analysis. A covariance analysis (ref. 10) was employed to answer this question. The object of this analysis is to satisfy the constraint of 25 meters total position uncertainty by adding the smallest possible number of coefficients to the adjusted parameter set which will accomplish the task. The procedure employed, as described in reference 11 is recursive where the $(N + 1)^{st}$ coefficient is adjusted by examining the results of adjusting N coefficients along with the GEOS-C and ATS-F states.

When gravity harmonics are included in the solution, position and velocity uncertainties of Figures 4 and 5 are acheived.

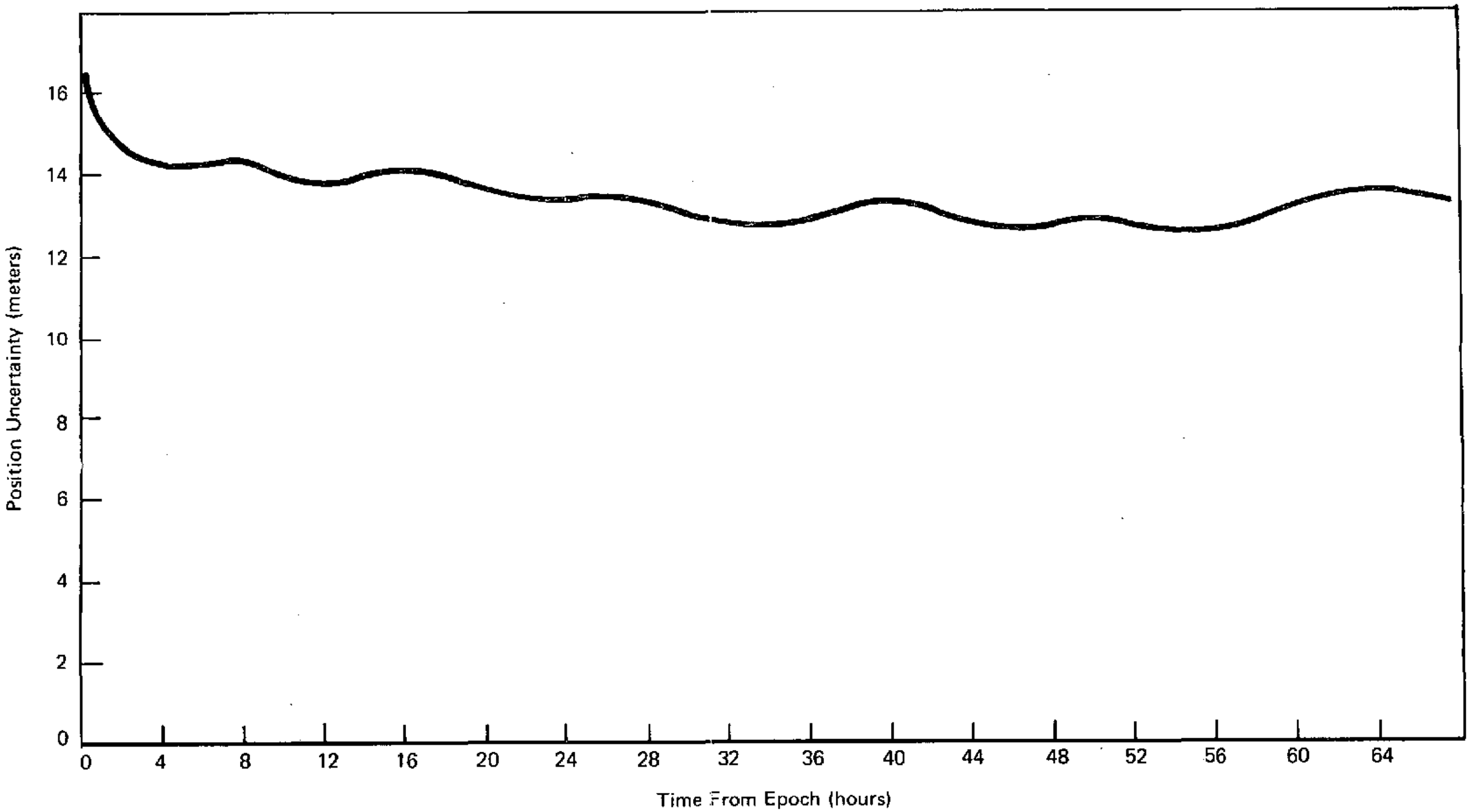

Figure 4. GEOS Position Uncertainty

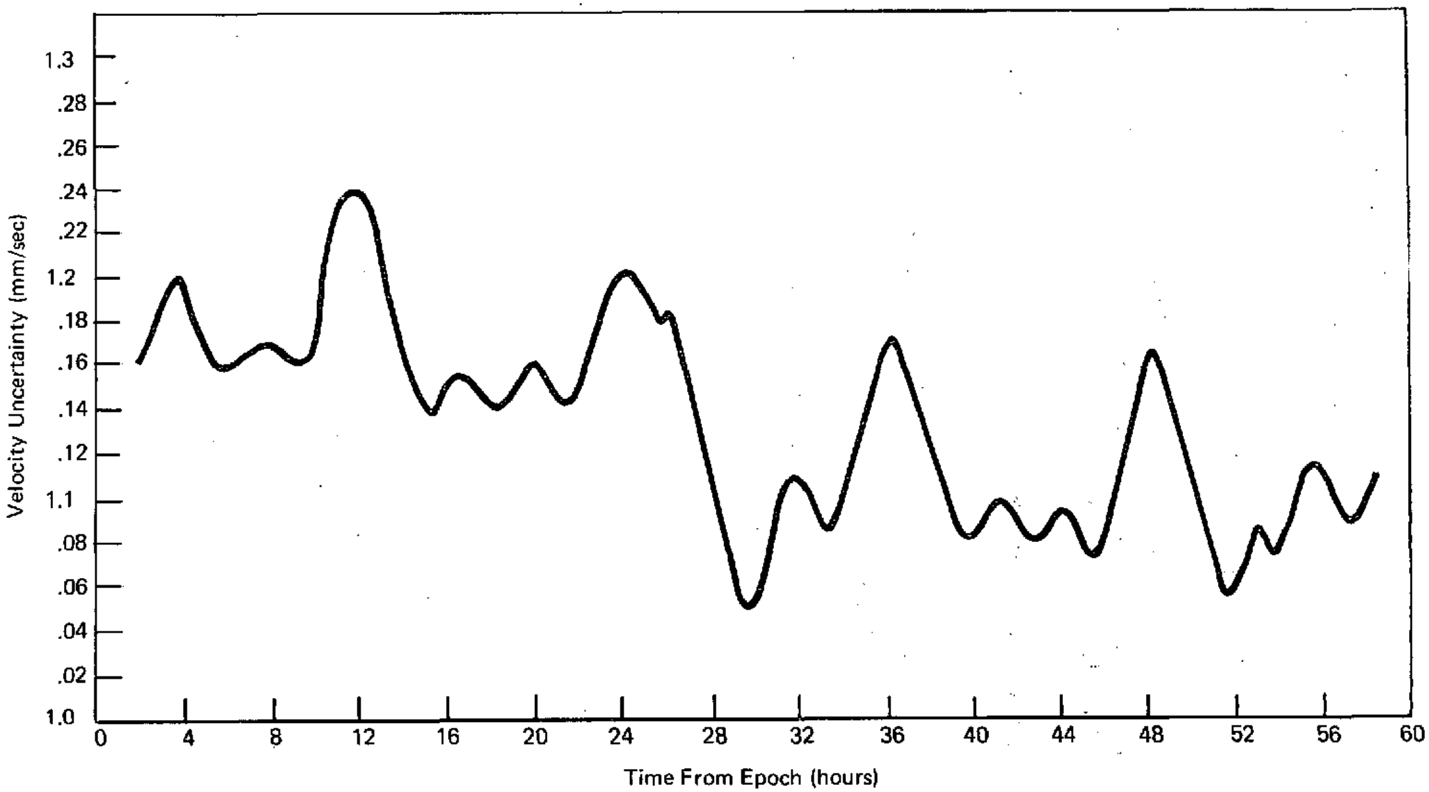

Figure 5. Velocity Uncertainty

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