ON-BOARD DATA PROCESSING FOR APPLICATIONS SATELLITES

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ABSTRACT

With recent advances in microcomputer technology, on board data reduction for orbit determination is now feasible. On-board data processing would be advantageous for a class of satellite applications which involve a one way Doppler positioning system. Examples are the Nimbus-RAMS system, satellite aided search and rescue, and coastal surveillance in support of the newly imposed 200 mile fishing limit. Orbit determination requirements for these systems are typically in the region of 1 km.

This paper presents a proposal for on-board orbit determination which would rely entirely on reference beacons located within continental United States. The beacons would emit a one way Doppler signal in which is encoded coordinates of the beacon's location. An on-board computer would process the signal and update the satellite ephemeris. When a Doppler signal external to the system is received, the problem is inverted in the sense that the satellite ephemeris is considered as known and the coordinates of the Doppler signal source are estimated and transmitted to the ground. The feasibility of this concept is dependent on the possibility of developing algorithms which are at once compatible with limitations of on-board computers and accurate enough to maintain an adequate satellite ephemeris.

A conventional batch-processing filter is not ideal for this application because of its data storage requirements. Another problem associated with batch-processing of satellite tracking data is that errors in the models of satellite dynamics are such that in order to achieve acceptable accuracies the time span of the data must be limited. A recursive filter appears to be a more logical choice. But conventional recursive processing schemes such as the usual form of the Kalman filter, which do not explicitly account for dynamic modeling errors, encounter similar difficulties. In this case, the problem manifests itself through the computed covariance matrix of the estimate reducing towards zero. This in turn results in new measurement information being effectively ignored. Consequently, measurement residuals will increase, manifesting the well-known Kalman filter divergence phenomenon.

The filter used to generate the results of this paper is recursive from one pass of Doppler data to the next. However, each pass is processed in a conventional batch mode. A "state noise" covariance matrix is added to the computed covariance matrix of the estimate at each step in the recursion, thus preventing the eigen values of the matrix from approaching zero. The form of the state noise covariance matrix is chosen from a priori mathematical considerations and then modified by a multiplicative constant obtained from an examination of residuals. The resulting algorithm is sufficiently simple that it can be implemented on a small computing machine.

Numerical simulations were performed to test the validity of the procedure. Reference beacons were situated at Portsmouth, New Hampshire and San Francisco, California. Epoch elements for a typical TIROS-N orbit were utilized. Data was generated using a 13 x 13 degree reference field. A random number generator added white noise of standard deviation 1 m/sec. The data was reduced using a modified 4 x 4 degree field. Maximum observed position errors were less than 1 km. The same procedure was implemented for real data obtained from Nimbus reference beacons with comparable results.

ON-BOARD ORBIT DETERMINATION FOR APPLICATIONS SATELLITES

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Introduction

With recent advances in the technology of low power, low weight computers, on-board data reduction for orbit determination is now feasible [1,2]. On-board data processing would be advantageous for a class of satellite applications which involve a one-way Doppler positioning system. Examples are the NIMBUS-RAMS system [3], satellite aided search and rescue [4,5], and coastal surveillance in support of the newly imposed 200 mile fishing limit [6]. Orbit determination accuracy requirements for these systems are typically in the region of 1 km.

An examination of the NIMBUS-RAMS system provides insight into the possible usefulness of on-board orbit determination and data processing. Typically, 10 to 15 one-way Doppler measurements from each of up to 50 sources are recorded on the NIMBUS-6 and telemetered on command to a control station such as NASA-Fairbanks, Alaska. The data is then relayed to a central computer at the Goddard Space Flight Center. With the aid of ephemeris information obtained from independent tracking, the data is processed and the results transmitted to individual users. The delay time is several days. The need for faster response has been expressed by several members of the user community. Also, future applications of the satellite Doppler positioning concept (coastal surveillance, satellite aided search and rescue) will require near real time signal processing.

The need for rapid signal processing could be satisfied if tracking data were processed on-board a satellite. In that case ephemeris information based on fresh tracking data would be available at all times to the satellite's computer. Hence a Doppler signal received by the satellite could be processed by the on-board computer and the resulting position estimate transmitted to the ground. Very low telemetry data rates are adequate to transmit position information. With low data rates, the use of omnidirectional or low-gain, wide-beam-width antennas becomes possible and costs are reduced by simplifying the antenna array and antenna drive assembly. Low data rates also permit the use of a geostationary satellite system such as the Tracking and Data Relay Satellite System [7] to relay information to inexpensive receiver terminals. Another significant fact is that the number of Doppler signal sources monitored per satellite pass can be significantly increased as a consequence of the relatively low bit allocation required for each position determination.

This paper presents a proposal for on-board orbit determination which would rely entirely on reference beacons located within the Continental United States. The beacons would emit a signal in which is encoded coordinates of the beacon's location. An on-board computer would process the signal and update the satellite ephemeris. When a Doppler signal external to the system is received, the problem is inverted in the sense that the satellite ephemeris is considered as known and the coordinates of the Doppler signal source are estimated and transmitted to the ground. The feasibility of this concept is, of course, dependent on the possibility of developing algorithms which are at once compatible with the limitations of on-board computers and accurate enough to maintain an adequate satellite ephemeris. This paper recommends a filter which is recursive on a pass-by-pass basis and which has a fading memory to account for the degrading effect of gravity field error. The recursive filter requires the storage of only one pass of data at a time, and hence is suitable for on-board computers with limited storage capacity. The mathematical details are described in the succeeding sections. The paper also provides the results for simulated data and real data reductions as well as suggestions for further analysis and development of these concepts.

A Recursive Filter for Satellite State Estimation

Let $\{Z(T_i)\}_{i\leq N}$ be a set of Doppler passes with each pass referenced to a time T_i which may be taken as the time for the first observation in the pass. Assume that observation set $\{Z(T_i)\}_{i\leq N}$ has been processed to yield a minimum variance estimate, $\delta\hat{X}(T_N)$, of the deviation, $\delta\tilde{X}(T_N)$, of the satellite state at time T_N from a nominal orbit. Data pass $Z(T_{N+1})$ is to be combined with $\delta\hat{X}(T_N)$ in a way which yields a sufficiently accurate estimate, $\delta\hat{X}(T_{N+1})$, of $\delta\tilde{X}(T_{N+1})$. Furthermore, the resulting algorithm is to be compatible with small computing machines.

Assume a linear state transition equation

$$\delta\tilde{X}(T_{N+1}) = \phi(T_{N+1}, T_N)\, \delta\tilde{X}(T_N) + \tau_{N+1} \qquad (1)$$

where $\phi(T_{N+1}, T_N)$ is a six-by-six state transition matrix and where τ_{N+1} is a six dimensional state noise random vector. Equation 1 is assumed to be referenced to a standard inertial coordinate set. Define

$$E(\delta\hat{X}(T_N)\ \delta\hat{X}^T(T_N)) = P_N \quad (2)$$

Before the data set, $\tilde{Z}(T_{N+1})$, is processed, the optimal estimate of $\delta\tilde{X}(T_{N+1})$ is obtained from Equation 1.

$$\delta\hat{X}^-(T_{N+1}) = \phi(T_{N+1},T_N)\ \delta\hat{X}(T_N) \quad (3)$$

Hence

$$E\left(\delta\hat{X}^-(T_{N+1})\ \delta\hat{X}^{-T}(T_{N+1})\right) = P_{N+1,0} = \phi(T_{N+1},T_N)\ P_N\phi^T(T_{N+1},T_N) = \Delta P_{N+1} \quad (4)$$

where

$$E(\tau_{N+1}\tau^T_{N+1}) = \Delta P_{N+1} \quad (5)$$

Define a linearized observation equation as

$$\delta\tilde{Z}(T_{N+1}) = A_{N+1}\delta\tilde{X}(T_{N+1}) \quad (6)$$

where $\delta\tilde{Z}(T_{N+1})$ represents a vector of deviations of the noiseless or correct representations of the data from nominal values. Since the data are corrupted by noise, we have

$$E\left(\left(\delta Z(T_{N+1})-\delta\tilde{Z}(T_{N+1})\right)\left(\delta Z(T_{N+1})-\delta\tilde{Z}(T_{N+1})\right)^T\right) = Q \quad (7)$$

Given Equations 1 through 7, a minimum variance estimate of $\delta\tilde{X}(T_{N+1})$ is

$$\delta\hat{X}(T_{N+1}) = (A^TQ^{-1}A+P^{-1}_{N+1,0})^{-1}(A^TQ^{-1}\delta Z(T_{N+1}) + P^{-1}_{N-1,0}\delta\hat{X}^-(T_{N+1})) \quad (8)$$

and

$$E\left((\delta\hat{X}(T_{N+1})-\delta\tilde{X}(T_{N+1}))(\delta\hat{X}(T_{N+1})-\delta\tilde{X}(T_{N+1}))^T\right) = P_{N+1} = (A^TQ^{-1}A+P^{-1}_{N+1,0})^{-1} \quad (9)$$

It remains to specify how the covariance matrix, ΔP_{N+1} of τ_{N+1}, is obtained. To generate the results of this paper, the following assumptions are imposed:

A. Components of τ_{N+1} are uncorrelated in the instantaneous along-track, cross-track, and radial coordinate set.
B. Along-track, cross-track, and radial components of τ_N for both position and velocity are in the ratio of 10:5:2.
C. The along-track position component of τ_{N+1} is a linear function of $T_{N+1}-T_N$.
D. The along-track velocity component of τ_{N+1} is three orders of magnitude less than the along-track position component of τ_{N+1}.

Under assumptions A through D, one can write

$$\tau_{N+1} = \psi(T_{N+1})D(T_{N+1}-T_N)x_{n+1} \quad (10)$$

where x_{n+1} is the along-track state noise per unit time, D is a diagonal matrix with diagonal elements $(1, .5, .2, 10^{-3}, .5(10)^{-3}, .2(10)^{-3})$, and $\psi(T_{N+1})$ is a rotation matrix which transforms satellite state from an along-track, cross-track and radial coordinate set at time T_N to a standard inertial coordinate set. From Equation 10 we have

$$\Delta P_{N+1} = \left(\sigma_x(T_{N+1}-T_N)\right)^2\psi(T_{N+1})DD^T\psi^T(T_{N+1}) \quad (11)$$

where σ_x is the standard deviation of x_{n+1}. The value of σ_x can be chosen based on a priori considerations or it can be chosen adaptively from previous residuals. Adaptive algorithms based on a maximum likelihood principal [8], or on a minimum variance principal [9] are available and can be implemented on small computers.

A more empirical approach to the problem is to account for the effect of errors in the propagation model in terms of an exponential process.

$$P_{N+1,0} = \left(\phi(T_{N+1},T_N)P_N\phi^T(T_{N+1}T_N)\right)\exp\left((T_{N+1}-T_N)/g_{N+1}\right) \quad (12)$$

The value of g_{N+1} can then be chosen by adaptive techniques.

Both the exponential approach of Equation 12 and the additive approach implied by Equations 11 and 4 were implemented for the real and simulated data reductions discussed in this paper. A totally automated adaptive procedure was not implemented. Instead, the data reductions were performed for numerous values of both σ_x of Equation 11 and g_{N+1} of Equation 12 and the values which maximized performance were chosen.

Data Simulations

In order to test the adequacy of the proposed procedure for data processing, the following simulations were performed.

(i) Simulated data (see Figure 1) of range rate were generated for two stations (Portsmouth, N.H. and San Francisco, Ca.) relative to a satellite with the orbital characteristics of the TIROS-N satellite (see Table 1). The number of passes during which the satellite observed the transmitting stations is shown in Table 2. The satellite orbit was computed using a Goddard Earth Model gravity field [10] truncated to 13 x 13. The simulated measurements were corrupted by the addition of random gaussian noise with a standard deviation of 0.5 meters/second. The choice of a 13 x 13 field was predicated on the assumption that the difference between the 13 x 13 field and that of the real earth would be negligible in comparison with the difference between the 13 x 13 field and the field used in the subsequent orbit recovery.

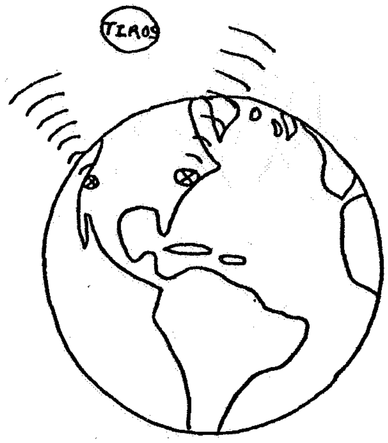

Figure 1. Data Simulation Configuration
Two transmitting stations:
(1) San Francisco, Ca
(2) Portsmouth, NH
TIROS-N IN NEAR POLAR ORBIT WITH A PERIOD OF 100 MIN.

TABLE 1. Orbital Characteristics of TIROS-N

Semi-Major Axis: 7200 KM
Eccentricity: 0.000002
Inclination: 98.7°
Period: 100 Min.

TABLE 2. Number of Observed Passes In The Data Simulations

	0-8 Hr.	8-16 Hr.	16-24 Hr.	Total
DAY 1	1	4	3	8
DAY 2	1	4	3	8
DAY 3	1	4	3	8
DAY 4	2	4	2	8
DAY 5	2	4	3	9
DAY 6	1	5	3	9
DAY 7	1	4	3	8
DAY 8	2	4	2	8
DAY 9	2	4	2	8
DAY 10	2	4	3	9

(ii) Two different fields were used in the orbit recovery: field I, a field containing only the J_2 harmonic coefficient and field II, a 4 x 4 field. The non-zero coefficients of fields I and II differed slightly from the corresponding coefficients of the 13 x 13 field. The filtering algorithm described in the preceding section was implemented to estimate orbits. The resulting orbits were then compared with the orbit used in the data generation. The results are summarized in Figures 2 through 4.

Figure 2 shows the results for the J_2 field, with the covariance matrix of the state noise, as defined in Equation 5, arbitrarily set to zero. As can be seen, the error, which initially is very large, has been substantially reduced by the end of the first day. The error then starts growing. This is caused by force model errors which are not accounted for when the presence of state noise is ignored. The results of Figure 3 were also obtained using a J_2 field but the state noise covariance matrix was obtained from Equation 11 by setting σ_x = 4 M/HR. These results are a substantial improvement over those shown in Figure 2. Figure 4 shows that more impressive results can be obtained with a 4 x 4 geopotential field with σ_x = 2 M/HR. It is also important to notice the long term stability of the filter when the effects of state noise are appropriately modeled. Comparable results were obtained using the exponential model of Equation 12 with g_{n+1} = 2 days.

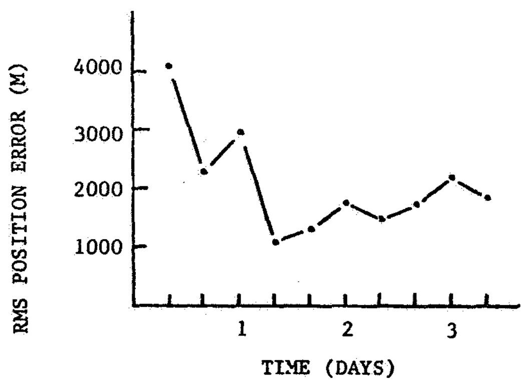

Figure 2.
Satellite Position Error
Recovery Field Includes Only the J_2 Harmonic
TIROS-N Simulated Data
σ_x = 0 M/HR

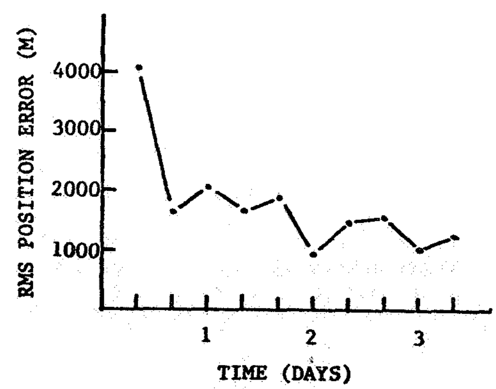

Figure 3.
Satellite Position Error
Recovery Field Includes Only the J_2 Harmonic
TIROS-N Simulated Data
σ_x = 4 M/HR

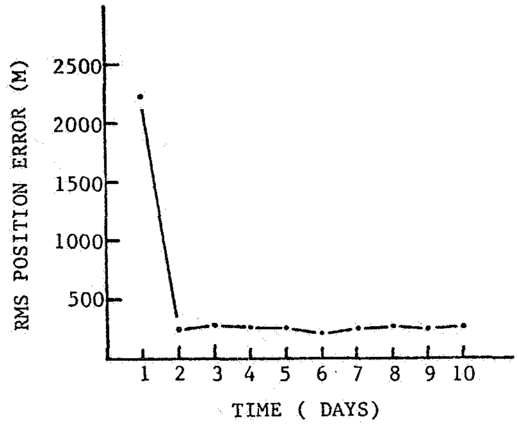

Figure 4.
Satellite Position Error
4 x 4 Recovery Field
TIROS-N Simulated Data
σ_x = 2 M/HR

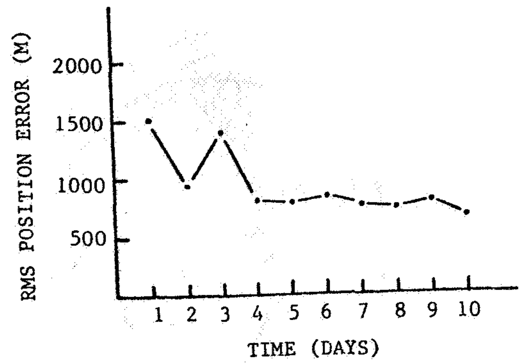

Figure 5.
Satellite Position Error
4 x 4 Recovery Field
NIMBUS-6 Doppler Data
σ_x = 0.5 M/HR

Reduction of NIMBUS-6 Doppler Data

The orbit/transmitter station geometry for the NIMBUS-6 real data reduction experiment was similar to that used in the TIROS-N simulations. The NIMBUS-6 orbit constants are given in Table 3. Data from two transmitter stations were used in the NIMBUS-6 orbit recovery, one station being located at Fairbanks, Alaska and the other one at Goddard Space Flight Center, Maryland. The nominal transmission frequency was 401.2 MHz for both stations. A gravity field complete through order 4 was used in the real data reduction. Data for the first ten days of June, 1977 were processed using the previously described recursive filter.

The NIMBUS-6 orbit, determined as part of this study, was compared with an independently derived orbit based on Mini-track observations processed at GSFC, which has a claimed accuracy of about 500 meters. The orbit position differences shown in Figure 5 are less than 1 km RMS from the third day onward. As in the case of the simulated results, the filter's performance displays both accuracy and long term stability. The number of passes of Doppler data used in the recovery is shown in Table 4. The noise in the Doppler data was approximately 1 m/s RMS. Data corresponding to elevation angles below 5 degrees were ignored. The data were not corrected for atmospheric refraction. The state noise covariance was chosen from Equation 11 with σ_x = 0.5 M/HR. This constant was selected after a few trial runs. No attempt was made to fine tune the system. Comparable results were obtained with the exponential model with g_{n+1} = 5 days.

In reducing the NIMBUS data, the oscillator bias and the bias drift rate were recovered for each transmitter. For the bias model constants actually used, the effective unmodeled drift rate contribution to the bias is shown in Table 5.

TABLE 3. Orbital Characteristics of NIMBUS-6
Semi-Major Axis: 7490 KM.
Eccentricity: .001
Inclination: 99.9°
Period: 107 MIN.

TABLE 4. Number of Passes Used in the Real Data Reduction

	0-6 HR	6-12 HR	12-18 HR	18-24 HR	Total
DAY 1	0	2	3	1	6
DAY 2	1	1	3	1	6
DAY 3	0	2	2	1	5
DAY 4	1	3	3	1	8
DAY 5	2	1	4	3	10
DAY 6	1	4	3	2	10
DAY 7	2	1	2	2	7
DAY 8	1	2	3	3	9
DAY 9	0	3	1	1	5
DAY 10	0	0	4	1	5

TABLE 5. Growth of Bias Uncertainty as a Function of Time

Time From Last Determination of Bias (Hours)	Standard Deviation of Bias Uncertainty (M/S)
1	0.5
2	1.4
4	4.0
8	11.3

Conclusions

For a class of satellite applications which involve a one-way Doppler positioning system, on-board orbit determination would be advantageous. This paper has presented a proposal for on-board orbit determination which would rely entirely on reference Doppler beacons located within the Continental United States.

To demonstrate the feasibility of this concept it is necessary to develop algorithms which are compatible with small computing machines and sufficiently accurate to maintain an adequate satellite ephemeris. The simulations and real data reductions discussed in this paper suggest that an on-board computer equipped with a recursive filter with a fading memory to account for dynamic modeling errors, and two reference beacons, are adequate for the task.

The filter should include a gravity field model with geopotential coefficients complete to degree and order 4. The fading memory characteristics of the filter can be set in advance based on a priori simulations and real data reductions. An alternative possibility is to equip the filter with a feedback mechanism by which the memory would become a function of previous residuals. Several such procedures have been discussed in the literature. The core storage requirements of the resulting algorithms should be compatible with on-board computers.

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