ADAPTIVE ORBIT DETERMINATION FOR INTERPLANETARY SPACECRAFT

P. Daniel Burkhart* **Robert H. Bishop†**

1 Introduction

The orbit determination problem for interplanetary spacecraft involves the calculation of spacecraft states (i.e. position and velocity) and associated estimation uncertainty measures based on information received from measurements that are corrupted by various errors and random noise. The motivation for the work presented here is to improve the tools used to perform this task, Due to reductions in resources for navigation, the number of navigation team members will be significantly reduced for future missions. For many past missions, navigation teams had twenty members or more, and current projections are for three or four navigation team members. Combined with the navigation requirements for future missions, the amount of work required using current tracking methods is a major burden for the size of the available navigation teams. One main problem is the lack of a systematic method for determining appropriate values for the operational orbit determination filter. In current interplanetary navigation practice, the operational filter parameters, such as time constants, gravitational parameters, noise variances and system parameters, are generally selected by trial and error based on *experience* and *computer simulation.* The filter parameters are selected and the measurement data processed. Based on the results, the filter parameters may be changed and the data processed again, or the current result may be accepted. During this iterative process, often the measurement data is de-weighted, resulting in estimation errors that are generally higher than the data requires. This *ad hoc* approach to filter tuning, in addition to failing to take full advantage of the data accuracy, requires a large number of navigation team members to analyze the results from the data processing. Despite the success of this approach in the past, the current realities do not support its continued use. The orbit determination task

*Research Assistant, Department of Aerospace Engineering and Engineering Mechanics, The University of Texas, Austin, Texas 78712; Member AIAA.

†Assistant Professor, Department of Aerospace Engineering and Engineering Mechanics, The University of Texas, Austin, Texas 78712; Member AIAA.

must, be completed with fewer analysts, similar if not greater tracking accuracy requirements, and less tracking data. Therefore, a new methodology is required for operational interplanetary navigation.

One constraint on any proposed solution to this problem is the utilization of *realistic* error sources and models to accurately determine if the selected approach will be useful in the actual tracking process. In addition, the proposed solution must integrate easily with current navigation approaches. A Kalman filter approach will be used for future interplanetary missions, so the solution must be compatible with this recursive filter method. Due to the desire to minimize tracking station use, personnel costs and complexity, conventional Doppler and ranging data will be the data types used in this analysis. Finally, the approach must be implementable in a modular fashion. This is not only to avoid extensive modification of existing orbit determination software, but to allow the testing of other approaches in a smoother and less complicated fashion.

Along with the change from the least-squares filter to the Kalman filter, another major change in the current filtering practice being studied is reflected in the so-called enhanced *filter* [7]. Current practice involves modeling certain Earth platform and transmission media effects as *consider parameters* in the filter. In other words, these parameters are allowed to affect the covariance of the estimated state, but are not themselves estimated. The enhanced filter calls for inclusion of these parameters in the estimated state vector. When compared with current filtering practices, the result is increased accuracy in the state estimates [7], This filtering strategy is currently being tested using real flight data from Galileo [8]. The enhanced Kalman filter is utilized in this paper.

The approach taken here is to utilize radiometric (Doppler and range) data and to establish navigation improvements through the use of *adaptive filtering* algorithms. There are benefits to this approach in addition to the systematic tuning of the operational filter. Suppose the process noise and/or data noise profile changes during the mission, for example, if the acceleration profile of the spacecraft changes significantly due to unmodeled venting. Then, the need for a non-labor intensive method to detect changes in the data profile and to point to the source of the changes is clear. A Kalman filter bank (proposed here) will allow the analyst to model several filters simultaneously and directly compare the results automatically. The filter bank will determine which filter is operating optimally (where optimal is precisely defined later) with respect to the measurement data, thus helping the process of selecting the filter parameters. For the case where the process and/or measurement noise profile changes, the filter bank can de-select a given filter and choose a different filter that more closely matches the current environment. In this way, in addition to the establishment of a systematic method to choose the operational filter parameters and to detect environmental changes, the orbit determination process can be completed with fewer team members, while potentially increasing the accuracy and timeliness of the results.

The adaptive estimation solution described in this work solves the orbit determination problem very effectively given the real-world constraints. The adaptive filter can be used as an effective tool to assist the navigation engineer in selecting filter parameters, thus allowing a closer match of the filter parameters to the true values, leading to a potentially more accurate navigation solution. In addition, this method requires fewer hours of processing and analysis and allows a smaller group of analysts to determine accurate navigation solutions. More importantly, the long term objective of this study is to develop an adaptive filtering methodology that can be used for processing of actual mission data. It is shown in the subsequent analysis that this objective is successfully achieved.

Several methods were investigated in terms of ability to determine both process noise and measurement noise parameters and to be general enough to handle a time-varying problem. Since the Kalman filter is already in usc and is planned for future usc for orbit determination, a method utilizing this approach is desirable for implementation reasons. It was found that the most desirable approach, in terms of these constraints, is the Magill Kalman filter bank [1]. This approach, also known as the Multiple Model Estimation Algorithm (MMEA), has been shown to be a practical algorithm in solving real-world problems [2], [3], [4]. One important problem that can be solved most effectively using the Magill filter bank is that of hypothesis testing, which is to choose from a finite set of filters which hypothesized filter in the bank is the correct one [5], [6]. The Kalman filter bank implemented in this study is utilized as a hypothesis tester, The proposed methodology is a practical extension to current navigation practices for interplanetary spacecraft. in addition, the cost of integrating this approach with the current operational enhanced Kalman filter is minimal. The Kalman filter dots not need to be modified in any way to implement this scheme. All that is required from the filter are pre-update measurement residuals and the covariance associated with these residuals at each data point, which are computed by the Kalman filter already. Finally, the assumptions that are required for application of the filter bank are the same that govern the use of a single Kalman filter. Thus, if the problem is formulated to work properly with the Kalman filter, the filter bank approach can be used without modification [6].

The scenario chosen for this study was the Mars Pathfinder mission, scheduled for launch in December 1996. Specifics of the mission plan including launch and arrival dates and the tracking scenario are presented (See Figure 1). A model was developed to represent accurately, but with moderate complexity, the actual data received by the filter during a mission. This model, consisting of the spacecraft state, solar radiation pressure effects, small unmodeled acceleration effects, transmission media effects and Earth platform effects, is used to generate tracking data.

Various computational algorithms were studied to solve the adaptive filtering problem, and all the methods have the characteristic of increasing in computational cost as the number of filter parameters to be determined increases. For this reason, it is desirable to determine only the most critical error sources and to concentrate effort in the analysis on these areas. The less significant errors will remain as parameters in the filter, but will not participate in the adaptation, A special type of covariance analysis, or error budget analysis, is utilized here to catalog the contributions of particular error sources or error source groups to the overall estimation error. The error budget is presented for X-band range only, Doppler only, and Doppler plus range measurement scenarios for the Mars Pathfinder mission,

Results are given for several different sets of noise parameters included in the adaptive scheme. Tracking schemes considered include range only and Doppler only. Results for the range case estimating parameters for the measurement noise and nongravitational acceleration (N GA) parameters are shown in Figures 2 and 3. The first figure shows the weighting factors for each filter computed by the filter bank. The numbering used corresponds to that shown in 'J'able l, where the scaling is relative to the parameters used to generate the simulated data. The second figure shows the encounter plane plots of the error covariance and the spacecraft state estimates relative to the truth.

The main result is the demonstrated ability of the adaptive Kalman filter bank to determine the under] ying measurement and process noise strengths. In addition, results for the changing noise strengths case show the ability of the filter bank to detect environmental and/or spacecraft changes.

2 References

[1] Magill, D. T., "Optimal Adaptive Estimation of Sampled Stochastic Processes," *IEEE Transactions on Automatic Control*, Vol AC-10, No. 4, October, 1965, pp. 434-439.

[2] Brown, R. G. and Hwang, P. Y. C., "A Kalman Filter Approach to Precision GPS Geodesy," *Navigation, Journal of the Institute of Navigation, 30:*, No. *4,* Winter 1983-84, pp. 338-349.

NGA Scaling	Filter Number		
0.1	1	6	11
0.2	2	7	12
1.0	3	8	13
5.0	4	9	14
10.0	5	10	15
	0.1	1.0	10.0
	Measurement Noise Scaling		

Table 1: Scaling factors: Measurement and NGA Parameters

[3] Mealy, G. L., "Application of Multiple Model Estimation to a Recursive Terrain Height Correlation System," *IEEE Transactions on Automatic Control,* Vol. AC-28, No. 3, March, 1983, pp. 323-331.

[4] Girgis, A. A. and Brown, R. G., "Adaptive Kalman Filtering in Computer Relaying: Fault Classification using Voltage Models," *IEEE Transactions on Power Apparatus and Systems,* Vol. PAS-104, No. 5, May, 1985, pp. 1168-1177.

[5] Brown, Robert G. and Huang, Patric Y. C., *Introduction to Random Signals and Applied Kalman Filtering,* Second Edition, John Wiley and Sons, 1992, pp. 398-402.

[6] Brown, R. G., "A New Look at the Magill Adaptive Filter as a Practical Means of Multiple Hypothesis Testing," *IEEE Transactions on Circuits and Systems,* Vol CAS-30, No. 10, October, 1983, pp. 765-768.

[7] Estefan, J. A., Pollmeier, V. M. and Thurman, S. W., "Precision X-Band Doppler and Ranging Navigation for Current and Future Mars Exploration Missions," *Advances in the Astronautical Sciences,* J. Teles and M, V. Samii, Editors, Vol. 84, Part I, pp. 3-16, 1993.

[8] Bhaskaran, S., Thurman, S. W. and Pollmeier, V. M., "Demonstration of a Precision Data Reduction Technique for Navigation of the Galileo Spacecraft", *Advances in the Astronautical Sciences,* J. E. Cochran et al., Editors, Vol. 87, Part II, pp. 785-798, 1994.

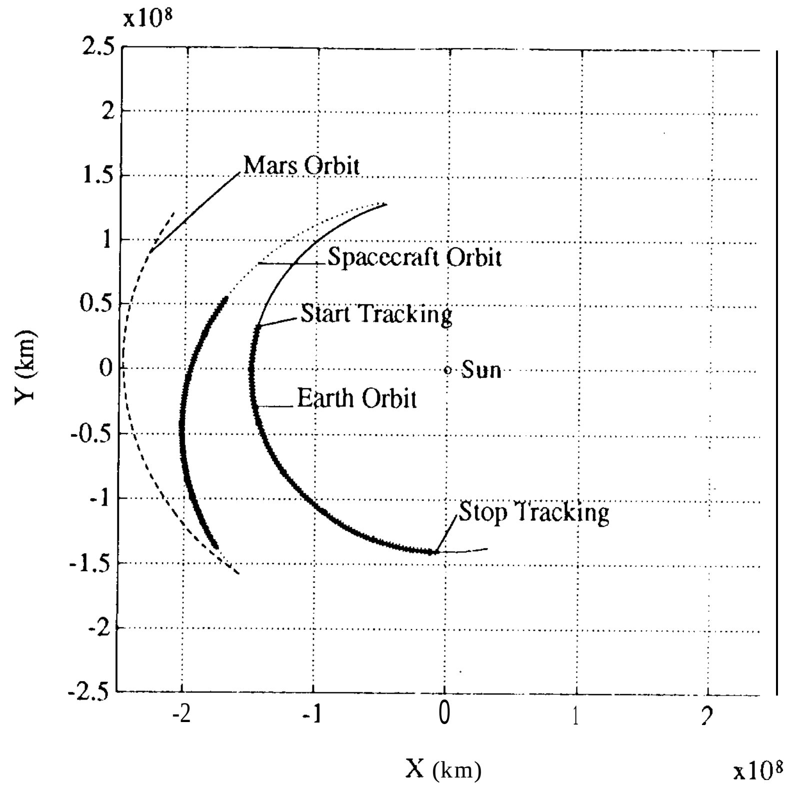

Figure 1: Mars Pathfinder Trajectory

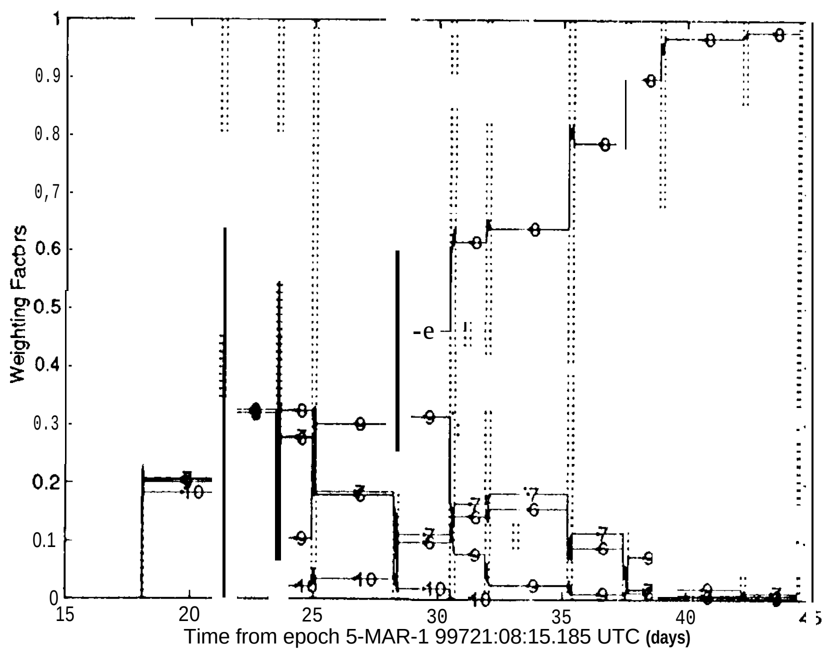

Figure 2: Weighting Coefficients - Measurement and NGA Parameters Adapted

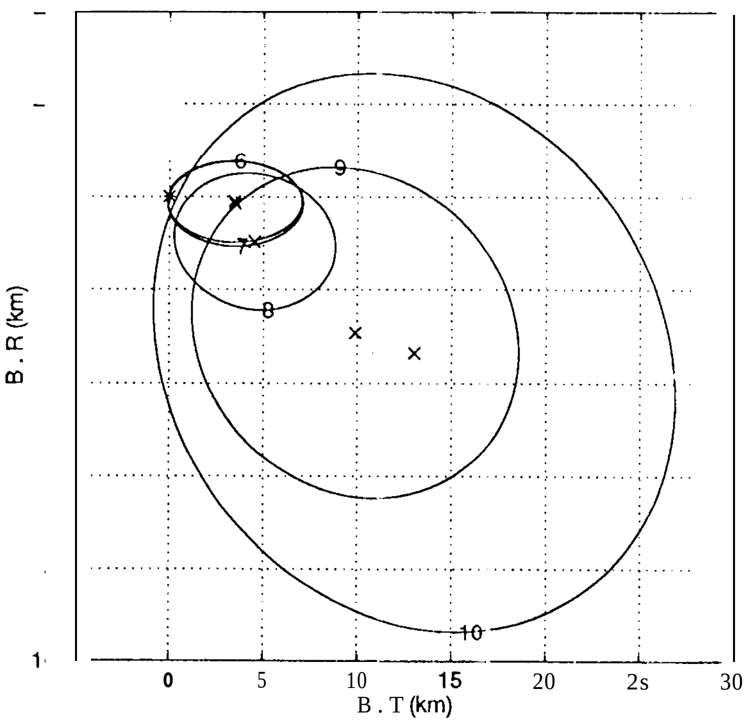

Figure 3: Encounter Results - Measurement and NGA Parameters Adapted