Noise Estimation for Star Tracker Calibration and Enhanced Precision Attitude Determination

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Abstract - *This paper presents the design, development, and validation of a nonlinear least square estimation scheme applied to star tracker noise extraction and identification. The paper is the by-product of a Post-Launch Test (PLT) tool development effort conducted by two independent teams, Swales/NASA and Boeing. The main objective is to have a set of tools ready to provide on-orbit support to the GOES N-Q Program. GOES N-Q employs a stellar inertial attitude determination (SIAD) system that achieves high precision attitude estimation by processing attitude and rate data provided by multiple star trackers (ST) and an inertial reference unit (IRU), respectively. The key component of SIAD is the ST. The ST's star position vector is corrupted by three major noise sources: temporal noise (TN), high spatial frequency noise (HSF), and low spatial frequency (LSF) noise. The last two noise sources are not white and correlated. As a result, the performance of the SIAD filter is no longer optimal, causing the reconstructed attitude knowledge to potentially satisfy requirements with a narrow margin. This tight margin is critical and may affect the GOES N-Q mission, particularly the Image Navigation and Registration (INR) system performance. The PLT tool set is expected to provide the capability to mitigate this potential problem during PLT time.*

1. Introduction

Kalman filter based estimation techniques have been employed during the past four decades for a variety of applications ranging from spacecraft, aircraft, missile, and surface transportation vehicles. It is well known that the optimality of the Kalman filter is conditioned on the noise intensities of both the plant process noise and measurement noise. *The key condition required to preserve this optimality for the Kalman filter is the whiteness of process noise and measurement noise expressed in the form of Q and R covariance matrices, respectively*. If the intensities of the Q and R matrices begin to change or approach “colored” noise level, the optimality will no longer be preserved. This situation reflects the star tracker/gyro based attitude determination filter that is currently being designed and implemented for the GOES N-Q missions. Star tracker measurement is contaminated by several noise sources. These include temporal noise, high spatial frequency noise, and low spatial frequency noise. The last two noise sources are not white and correlated. As a result, the performance of the star tracker/gyro (ST/IRU) based stellar inertial attitude determination (SIAD) filter is no longer optimal, thereby potentially causing the reconstructed attitude knowledge to be out of the requirement specification. In order to meet the GOES N-Q performance specification, the filter is optimized by several approaches [1]. These include physical mounting orientation of the star tracker, optimization of Q and R values, and nonlinear noise filtering/cancellation process. The overall optimization process is depicted in Figure 1.

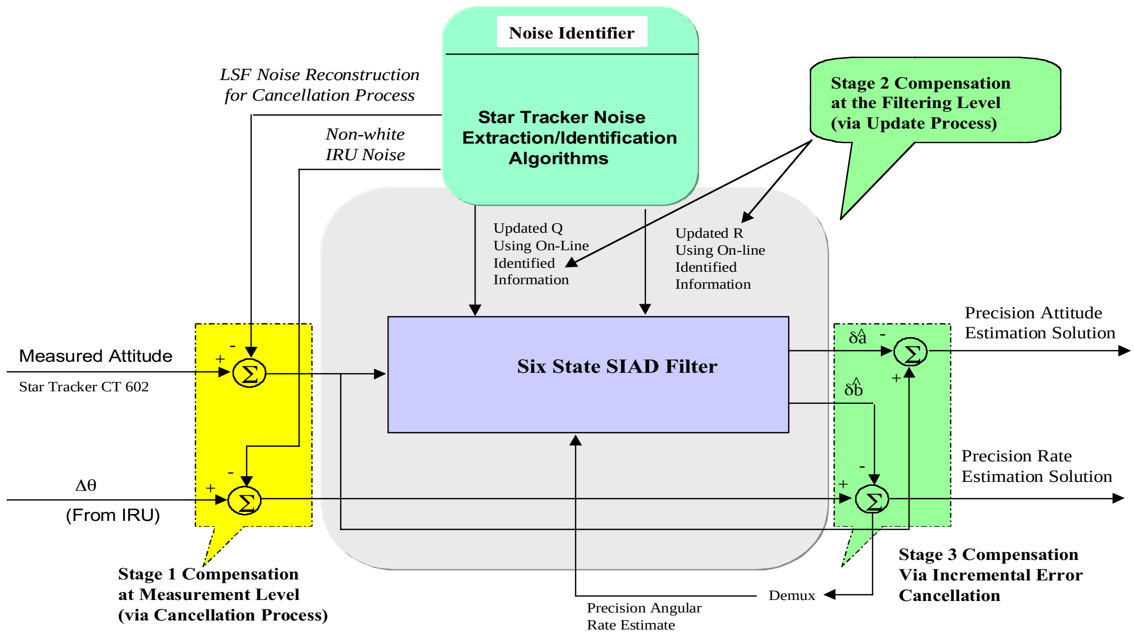

Figure 1: Advanced Nonlinear Estimation

The study conducted in [1] concludes that in order to minimize the effects of the non-white noise processes, namely the ST high spatial frequency (HSF) and the low spatial frequency (LSF) on the SIAD, the star tracker has to be mounted in such a way that when the star crosses the ST field of view, it will cross in a diagonal fashion. This mounting configuration will reduce the effect of the ST HSF. For the ST LSF treatment, a nonlinear estimation and reconstruction of the star's 'trajectory' via coefficient identification needs to be done [2] for the cancellation portion of the compensation process (see Figure 1). These identified coefficients will be uploaded to the on-board SIAD algorithm to compute the LSF noise for cancellation at the measurement level, as applied in stage 1 of the estimation process. Note that since the ST LSF operational frequency is somewhat within the SIAD bandwidth, a straight filtering approach alone is not adequate. Rather, identification and cancellation techniques [3] need to be developed and employed to provide the correct compensation in this situation.

This paper describes the design, development, and validation of the star tracker noise estimator and ground-based SIAD filter. It illustrates how these can be used to enhance the performance of the baseline on-board 6 state SIAD filter as part of the three stage compensation and estimation scheme described in Figure 1. Stage 3 compensation reflects a standard design procedure employed by most of today's spacecraft attitude determination systems. However, the stage 1 and 2 compensations reflect a true nonlinear estimation scheme. The ST noise extraction and identification portion of this tool will be used to support stages 1 and 2 of this compensation scheme.

The current GOES N-Q on-board SIAD flight software design has mechanized stages 1 and 2 as an off-line compensation scheme. In other words, the LSF noise reconstruction process will be done on the ground, be validated, and its identified coefficients uploaded for on-board calculation and compensation of the LSF noise effect. SIAD filter process noise and measurement noise covariance matrices are updated on-board using an automated procedure with low and high values being pre-computed (rather than estimated on-line) to account for different operating conditions.

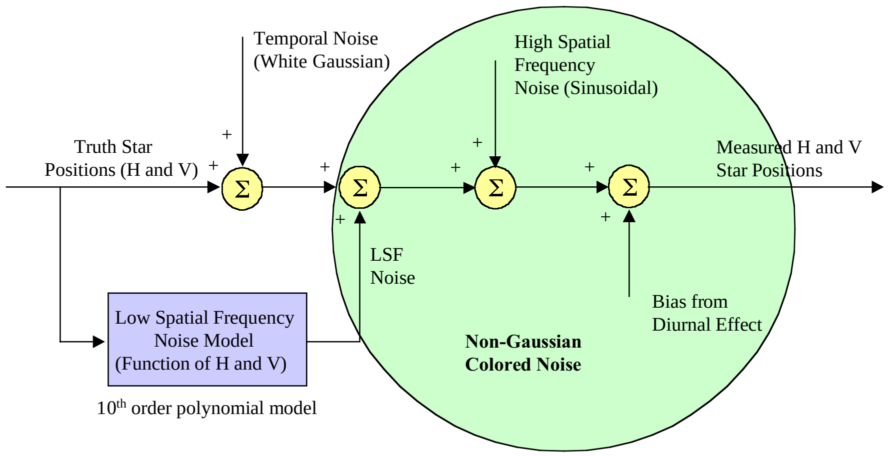

Figure 2: Star Tracker CT 602 Noise Model

A mathematical model of the Ball CT 602 star tracker (ST) is shown in Figure 2, presenting the corruption of the true star positions h and v by several noise sources. These noise sources include (1) LSF, (2) HSF, (3) temporal noise as a combination of constant and rate dependent noise, and (4) bias arising from diurnal effect. Among these noise sources, LSF noise has been identified as the most dominant source degrading the SIAD performance.

2. PLT Tool Definition

Figure 3 is a block diagram illustrating the noise isolation/separation and estimation scheme utilized in this tool which uses star tracker and gyro rate telemetry data as input. The output data includes ground computed dH and dV, predicted H and V vector, ground determine spacecraft attitude direction cosine matrix, and most importantly the computed LSF noise coefficients for true nonlinear compensation. This path of noise isolation and estimation alone will definitely provide some valuable insights into the GOES N-Q SIAD performance optimization and is hoped to be useful at the PLT time for tuning the SIAD system.

An important component of the LSF characterization process is the isolation of the LSF noise from other sources. As such, the LSF characterization tool consists of two components. One portion is the identification and isolation of the component of the ST position error caused by LSF noise. The next block of the tool is then to estimate new LSF compensation coefficients that could be used by the on-board flight software to correct for this error source.

The ST noise separation process is presented in Figure 4. Five low pass filters, five high pass filters, and five band pass filters have been designed and configured in a parallel fashion in order to isolate the LSF noise, HSF noise, and temporal noise, respectively, per virtual tracker (i.e., each tracked star). The coefficients of these filters are selected in such a way that they will retain each individual ST noise source within its operational bandwidth.

Figure 5 presents the power spectrum density (PSD) of the star tracker total noise per virtual tracker (VT). This PSD plot is generated using the total noise signature of the h position measurement (i.e., dh(3)). In fact, all filter coefficients chosen for the noise separation process are shaped to satisfy the bandwidth of each individual noise presented in Figure 5. During the preparation of this paper, we perceive that there is no need to perform ST noise extraction and characterization on all VTs since the 'quality' or observability of ST noises may not equally appear in all VTs. As a result, the PSD analysis process can also be used, in addition to filter design, to select appropriate VT data for the ST extraction and characterization.

2.1 Low Spatial Frequency Noise Estimation

- *LSF Error Model*

For testing of the LSF coefficient identification portion of the tool, representative pure LSF errors in star position were generated using a 10^{th} order polynomial approximation of the actual LSF error process. The H and V LSF error components across the 8 degree field of view (FOV) of the Ball CT 602 ST are illustrated in Figures 6 and 7, respectively. This modeled error data, was then used to corrupt truth star measurements for evaluation of the tool's LSF noise identification algorithm.
Results of testing utilizing this ideal error model are presented in figures 8 and 9. Results show perfect reconstruction of the LSF noise using the tool with this ideal data.

2.2 LSF Noise Coefficient Estimator

A modified *spatial-based* Least Square Estimation (LSE) scheme was developed to identify the LSF noise coefficients necessary to compensate for the non-white LSF noise. Due to the LSF noise nature (i.e., extremely nonlinear at FOV corners), conventional time-domain-based LSE scheme is not a good candidate for this application. Two test conditions were employed to test the performance of the LSF noise coefficient estimator, deterministic and non-deterministic data. The first test condition is the ideal LSF noise generated using truth model described in Figure 2. The second test condition is the truth data corrupted with white noise. The second condition is intended to evaluate the performance of a situation where the LSF noise was not completely isolated from other noise sources.

2.3 Ground-Based SIAD PLT Tool # 2

The ground-based SIAD filter is structured exactly as the on-board filter (i.e., six-state EKF containing three attitude error estimates and three gyro bias error estimates); nevertheless, its overall design configuration reflects a completely different compensation scheme. It is implemented such that it can be used to effectively monitor the on-board SIAD filter performance and offer several benefits to the system designers. The major benefit will be the ability to test and validate SIAD filter optimization options that could be used to enhance the on-board SIAD system should some unanticipated behaviors occur on-orbit. Figure 3 illustrates the following design and performance evaluation options available using this portion of the tool:

- Optimization of SIAD filter Q and R matrices by extracting and characterizing the gyro noise and ST noise, respectively. ST noise extraction and characterization to fine-tune the R matrix and to provide the right treatment to the non-white noise is discussed at length in this paper. The gyro noise extraction and characterization process and how it can be used to update the Q matrix for SIAD performance improvement is discussed in [2].
- Estimation of LSF noise coefficients based on TLM data.
- Monitoring of other performance parameters such as ground reconstructed dH and dV, ground reconstructed predicted H and V.
- Evaluation of on-board attitude estimation.
- Prediction of attitude performance subject to two major design compensations (i.e., stages 1 and 2) that can be used to identify the optimal operational parameters for updating the on-board SIAD system via data upload.

These options can be selected during PLT time to optimize the SIAD filter parameters in order to fine-tune its performance under actual on-orbit flight conditions.

3. Test and Validation Plan for the PLT Tool

As part of the design and validation of the SIAD PLT tool set, we plan to use the following steps to get the PLT tools ready for GOES N-Q:

- Step 1: Use LSF truth model to generate the data for first step proof-of-concept validation of the LSF noise identification process, and then test the performance of the modified LSE again by corrupting the truth LSF error with some additional noise.
- Step 2: Use high fidelity spacecraft simulation data output from the Boeing designed and built spacecraft emulator (BSE) to validate the design, and in particular the LSF noise isolation process given a known set of input noise parameters.
- Step 3: Use EO-1 ST data to validate the overall design concept and finalize the design architecture for this ground-based software tool.
- Step 4: Use spacecraft telemetry from the GOES BSE [4] to build and validate the tool interfaces necessary for the operational environment

We have completed step 1. Step 2 is underway. Steps 3 to 4 are currently planned and will be accomplished within the next 3 months.

4. Concluding Remarks

The design, development, and validation of this PLT tool set is important for the GOES N-Q SIAD system performance evaluation, monitoring, and optimization after launch. SIAD performance requirement compliance is critical to the GOES Image, Navigation and Registration (INR) system performance budget and overall instrument performance.

The availability of this tool set will be useful at the PLT time to truly monitor how well the SIAD system is performing. If unanticipated performance degradations occur from the SIAD system point of view, either due to unexpected conditions, or errors in parameters estimated prior to launch, this tool clearly offers the capability to monitor and extract the right set of parameter values (e.g., LSF noise coefficients or SIAD Filter Q and R values) for SIAD software optimization.

References:

[1] Q. Lam, R. Welch, and Y. Lee, "Performance Enhancement of the Stellar Inertial Attitude Determination System Via System Optimization Techniques," A Welch Engineering IR&D Report Prepared for Hughes Space and Communication, May 1997.

[2] Q. Lam, C. Woodruff, S. Ashton, and D. Martin, "Ground-Based Software Tool Development for GOES Post-Launch Test Support," To be presented at the AIAA GN&C Conference 2002, August 2002, Monterey, CA.

[3] B. Widrow and S. Stearns, Adaptive Signal Processing, Prentice Hall 1985, ISBN 0-13-004029-0

[4] Boeing GOES N-Q Training Manual, December 2001.

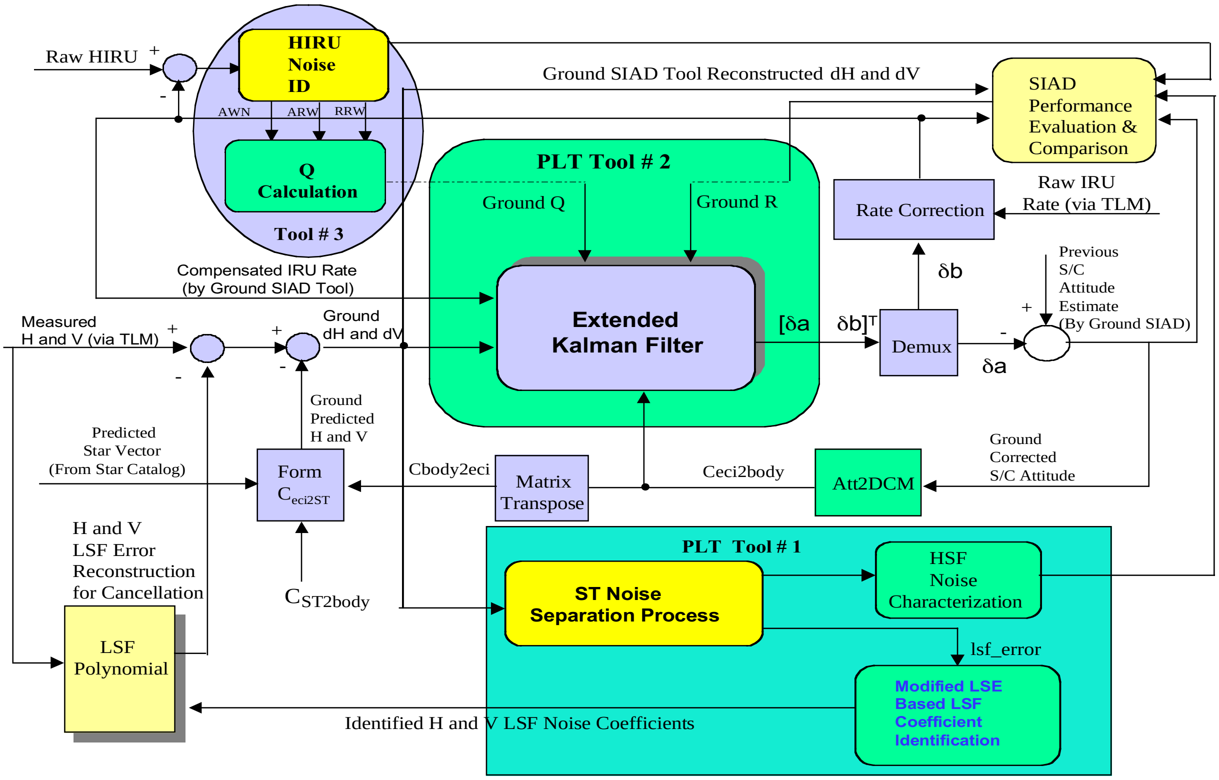

Figure 3: Diagram of PLT Tool Set Definition

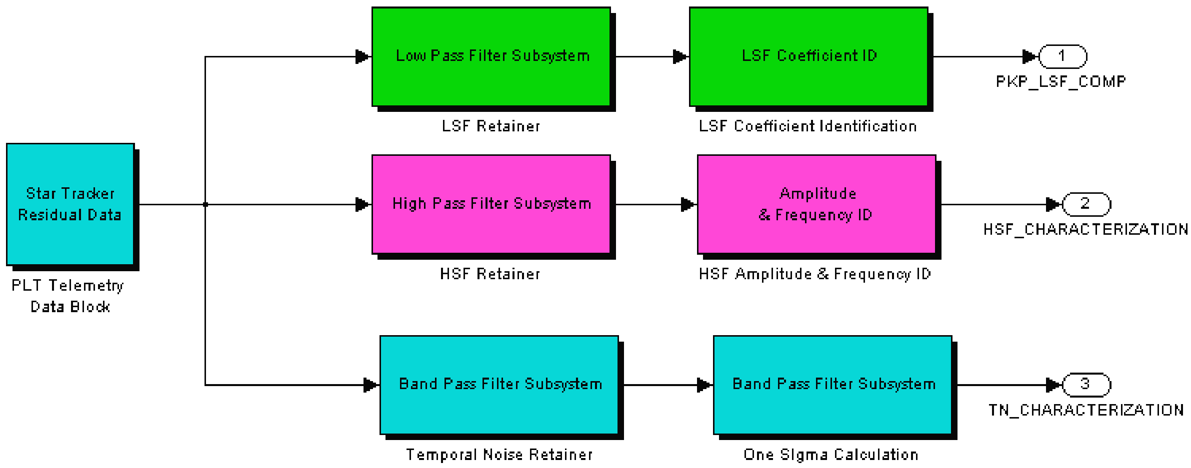

Figure 4: Star Tracker Noise Separation Tool

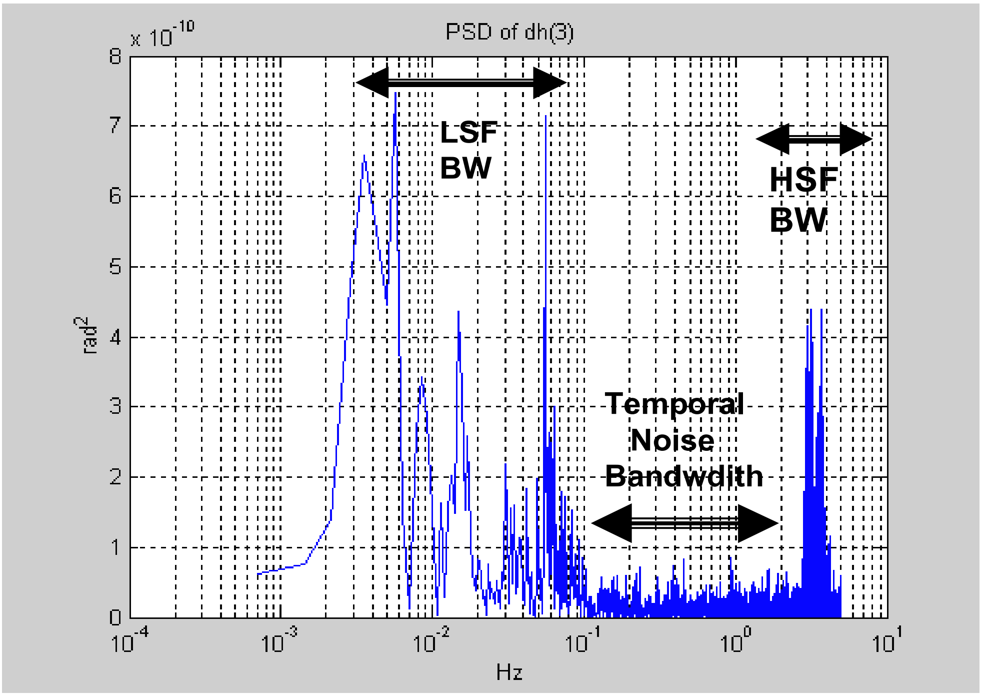

Figure 5: Power Spectrum Density of the ST Total Noise

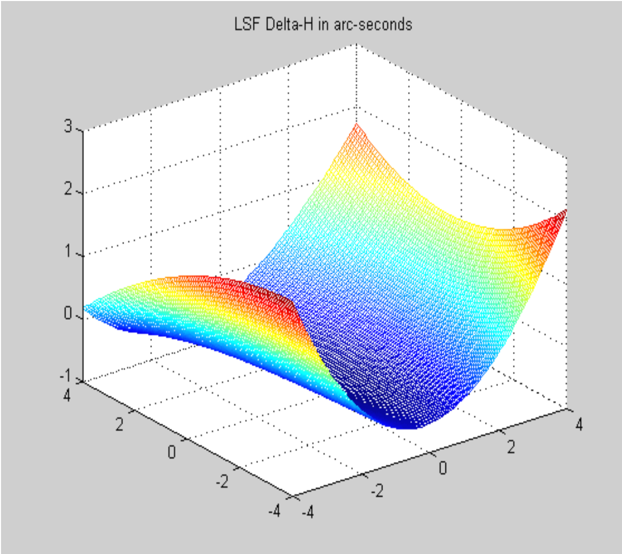

Figure 6: LSF Noise in H Measurement

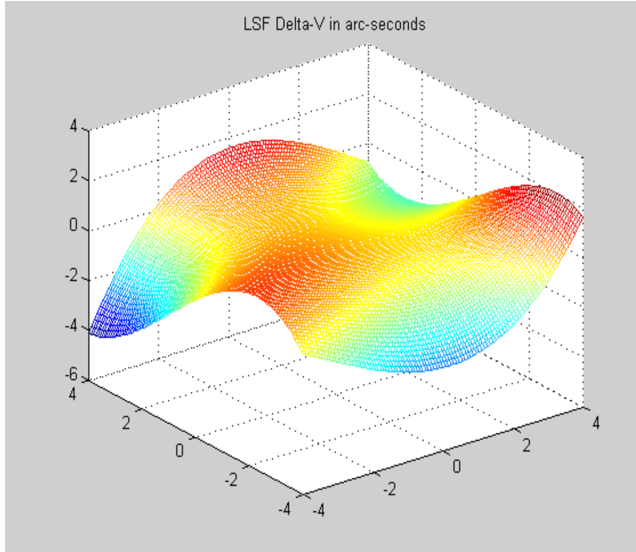

Figure 7: LSF Noise in V Measurement

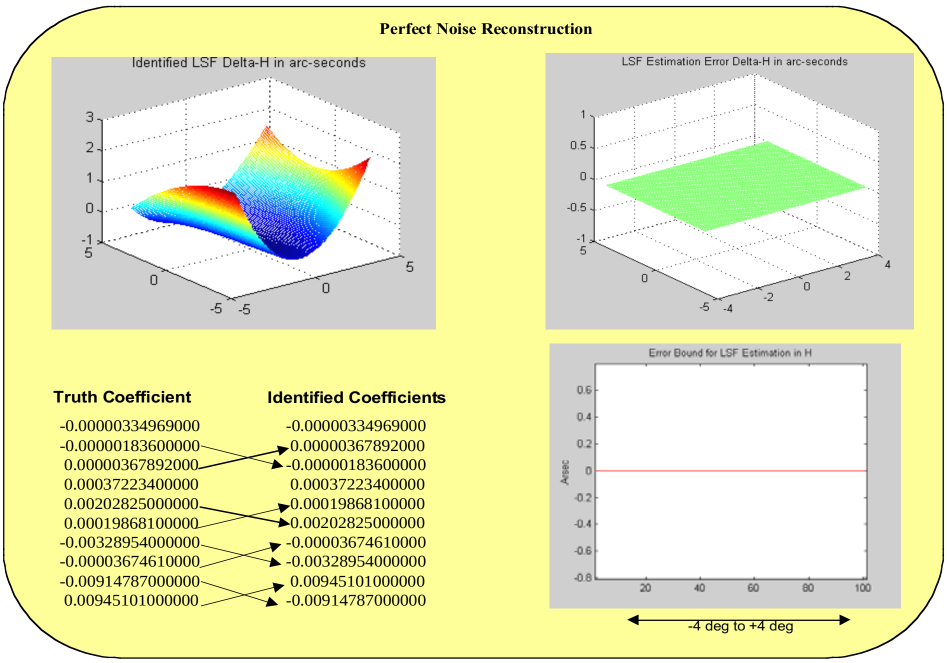

Figure 9: LSF V Error Estimation Performance with Deterministic Data

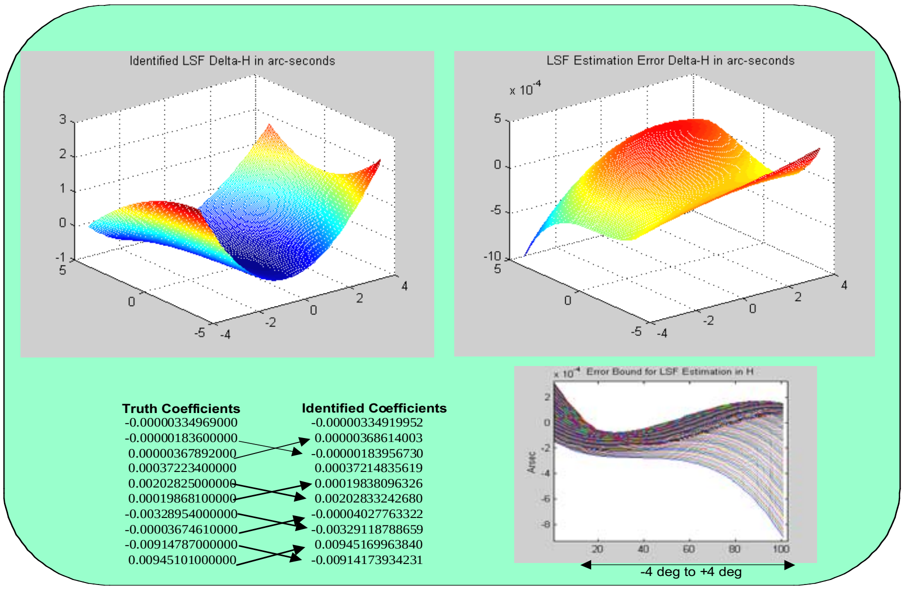

Figure 10: LSF H Error Estimation Performance with Non-Deterministic Data

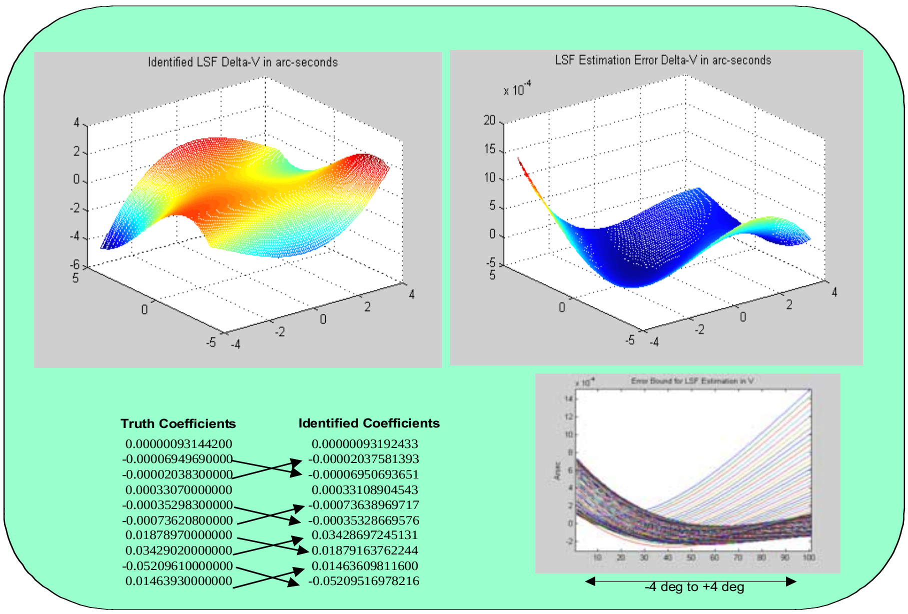

Figure 11: LSF V Error Estimation Performance with Non-Deterministic Data