Modeling SMAP Spacecraft Attitude Control Estimation Error Using Signal Generation Model

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Abstract

Two ground simulation software are used to model the SMAP spacecraft dynamics. The CAST software uses a higher fidelity model than the ADAMS software. The ADAMS software models the spacecraft plant, controller and actuator models, and assumes a perfect sensor and estimator model. In this simulation study, the spacecraft dynamics results from the ADAMS software are used as CAST software is unavailable. The main source of spacecraft dynamics error in the higher fidelity CAST software is due to the estimation error. A signal generation model is developed to capture the effect of this estimation error in the overall spacecraft dynamics. Then, this signal generation model is included in the ADAMS software spacecraft dynamics estimate such that the results are similar to CAST. This signal generation model has similar characteristics mean, variance and power spectral density as the true CAST estimation error. In this way, ADAMS software can still be used while capturing the higher fidelity spacecraft dynamics modeling from CAST software.

Nomenclature

CAST	=	Control Analysis Simulation Testbed
F_{num}	=	filter numerator polynomial coefficients
F_{den}	=	filter denominator polynomial coefficients
k_{filter}	=	√noise variance
θ_A	=	ADAMS attitude truth
$\hat{\theta}_A$	=	ADAMS attitude estimate
θ_C	=	CAST attitude truth
$\hat{\theta}_C$	=	CAST attitude estimate
θ_R	=	attitude command reference
ε_C	=	true CAST estimation error
$\hat{\varepsilon}_C$	=	signal generation model estimation error
σ^2	=	Noise variance
t	=	time
X	=	body-fixed frame X-axis
Y	=	body-fixed frame Y-axis
Z	=	body-fixed frame Z-axis

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I. SMAP Mission Introduction

The Soil Moisture Active Passive (SMAP) is a NASA-JPL mission whose primary purpose is to map the upper soil moisture content on Earth and its freeze/thaw state [1]. This satellite observatory is launched in a near-polar, sun-synchronous orbit. The mission is in operations phase and was launched in early 2015. SMAP is returning valuable science information for a period of three years. Scientific information returned from SMAP helps improve weather, climate forecast, flood prediction and drought monitoring capability. An artist's rendition for the fully deployed observatory in the Earth orbit is shown in Figure 1.

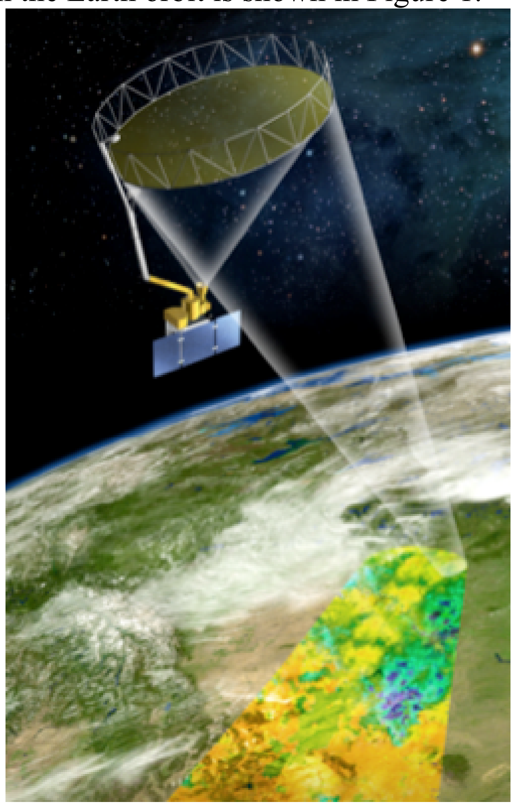

Figure 1: SMAP Concept

SMAP consists of an L-band radar and L-band radiometer. These share a 6-meter aperture rotating reflector antenna that scans a wide 1000-km swath as the observatory orbits the Earth. The radiometer provides passive measurements of the microwave emission from the upper soil (spatial resolution: 40 km) [2]. This radiometer is less sensitive than the radar to the surface roughness and vegetation effects. The radar makes active measurements from the reflected signal (spatial resolution: 3 km) [2]. Unfortunately, a power amplifier anomaly on-board the spacecraft disabled the active radar feature. However, SMAP continues to collect valuable science with the radiometer and passive radar feature.

II. Spacecraft Pointing Dynamics Control Loop Models

The SMAP spacecraft pointing dynamics are modeled in the ADAMS software. This software includes the spacecraft plant, controller and actuator models. A higher fidelity model exists in the Control Analysis Simulation Testbed (CAST) software, which also has the effects of the sensor and estimator. The ADAMS model assumes a system with a perfect sensor and estimator. The main source of attitude control system (ACS) error in CAST is the estimation error, ε_C . The control loop diagrams for CAST and ADAMS are shown in Figure 2.

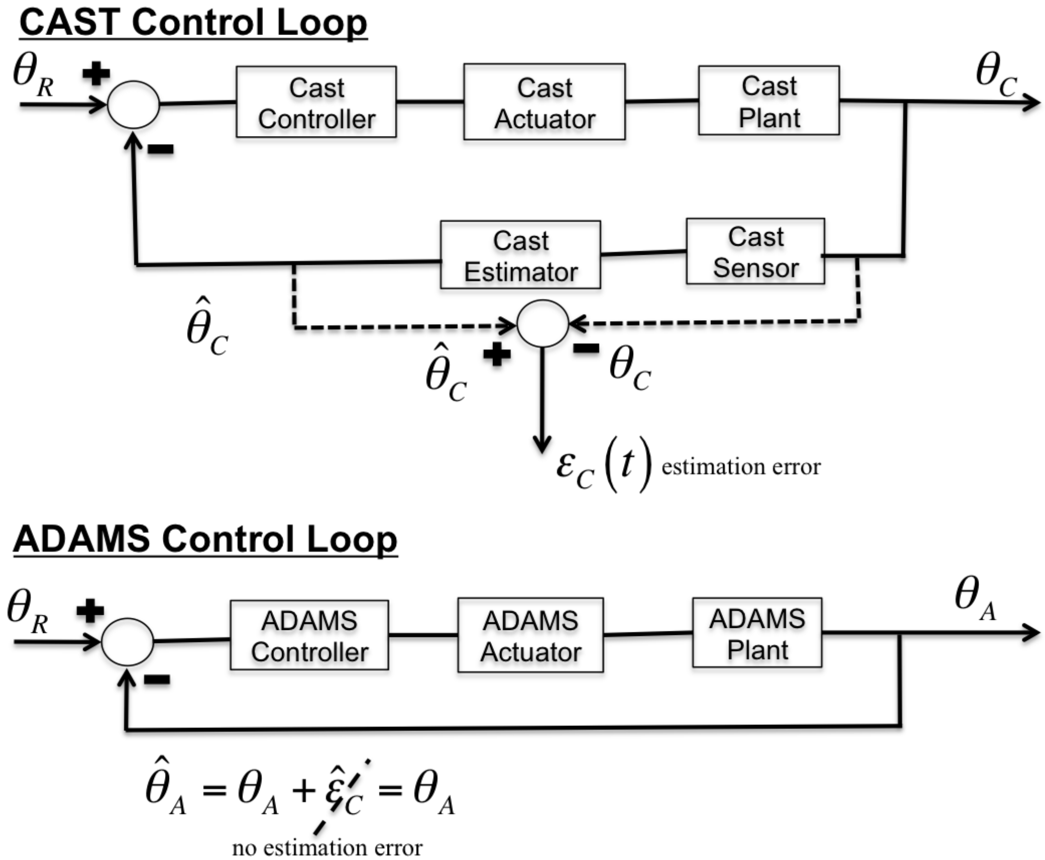

Figure 2: CAST and ADAMS Control Loop

In Figure 2, θ_R , θ_C , $\hat{\theta}_C$, θ_A , $\hat{\theta}_A$, ε_C , $\hat{\varepsilon}_C$ and t are attitude command reference, CAST attitude truth, CAST attitude estimate, ADAMS attitude truth, ADAMS attitude estimate, true estimation error, estimation error estimate and time, respectively. Due to time and resource limitations, a sensor and estimator model cannot be implemented in ADAMS. The ADAMS software fidelity is however increased to comparable levels of the CAST software by capturing the effects of the CAST estimation error, and adding the effect to the ADAMS control loop. The estimate of this estimation error is included in the ADAMS control loop to yield more accurate attitude control pointing dynamics. A signal generation model is developed to estimate this true CAST attitude control estimation error, and then it is added to the ADAMS control loop.

III. Signal Generation Model for Attitude Control Estimation Error

The ADAMS control loop is altered by including the estimated CAST estimation error.

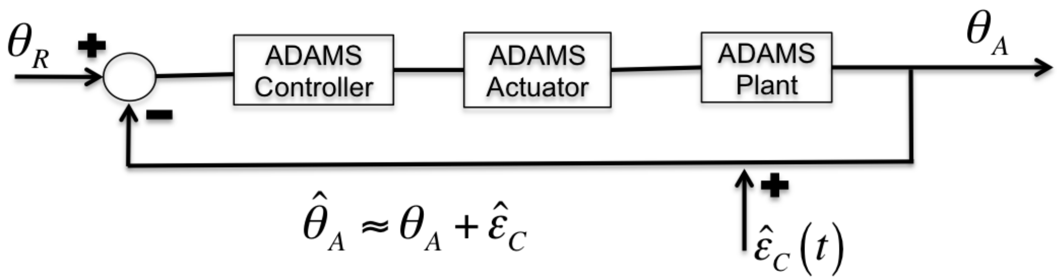

Figure 3: Added Estimation Error in ADAMS Control Loop

In Figure 3, the $\hat{\varepsilon}_C$ is the estimate of the true CAST estimation error, ε_C (Figure 2), and can be modeled by the signal generation model, $\hat{\varepsilon}_C$. With the $\hat{\varepsilon}_C$ addition to the ADAMS control loop, the ADAMS attitude control estimate, $\hat{\theta}_A$ approaches the CAST attitude control estimate, $\hat{\theta}_C$ as given by Equation 1.

$$\begin{aligned} \hat{\theta}_C &= \theta_C + \varepsilon_C \\ \hat{\varepsilon}_C &\approx \varepsilon_C \\ \theta_A &\approx \theta_C \\ \hat{\theta}_A &\approx \theta_A + \hat{\varepsilon}_C \approx \theta_C + \varepsilon_C \approx \hat{\theta}_C \end{aligned} \tag{1}$$

Hence, the higher fidelity CAST attitude estimate is captured in the ADAMS software by adding the signal generation model for the estimation error. This signal generation model, $\hat{\varepsilon}_C$ has similar mean, variance and power spectral density characteristics as ε_C, and is described by Equation 2.

$$\hat{\varepsilon}_C = \frac{F_{num}}{F_{den}} \cdot k_{filter} \cdot wgn \tag{2}$$

where F_{num}, F_{den}, k_{filter} and wgn are the numerator and denominator polynomial coefficients of the filter, √noise variance and white Gaussian noise, respectively. Next, the steps to obtain the signal generation model are described.

1. Obtain true CAST attitude control estimation error, ε_C
2. Use *iddata* and *armax* functions on ε_C and *polydata* function in MATLAB© to obtain the filter coefficients, F_{num} and F_{den}, and noise variance (which yields filter gain, k_{filter}) [3]
3. Use *wgn* and *filter* functions in MATLAB© to obtain the signal generation model, $\hat{\varepsilon}_C$
4. Model the signal generation model in Simulink© to add to the ADAMS software model as shown in Figure 4

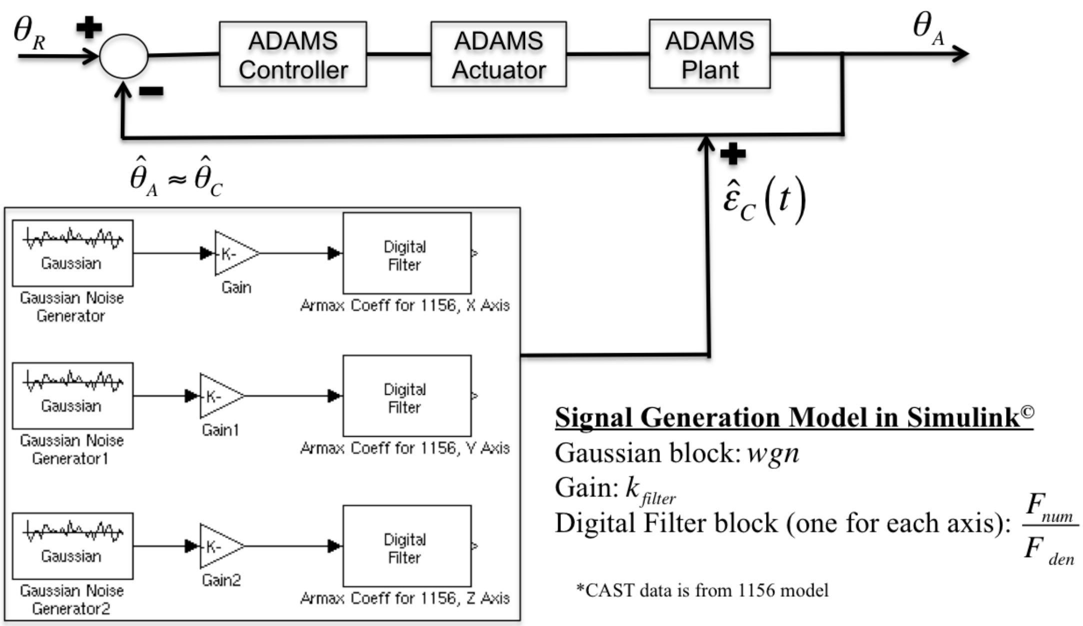

Figure 4: Updated ADAMS Control Loop with Simulink© Signal Generation Model

In Figure 4, the Simulink© blocks capture the signal generation model. The *Digital Filter* block models the filter using the filter coefficients obtained in Step 2.

IV. Results

The results show the true CAST estimation error, ε_C and the time history and characteristics comparison with the signal generation model, $\hat{\varepsilon}_C$.

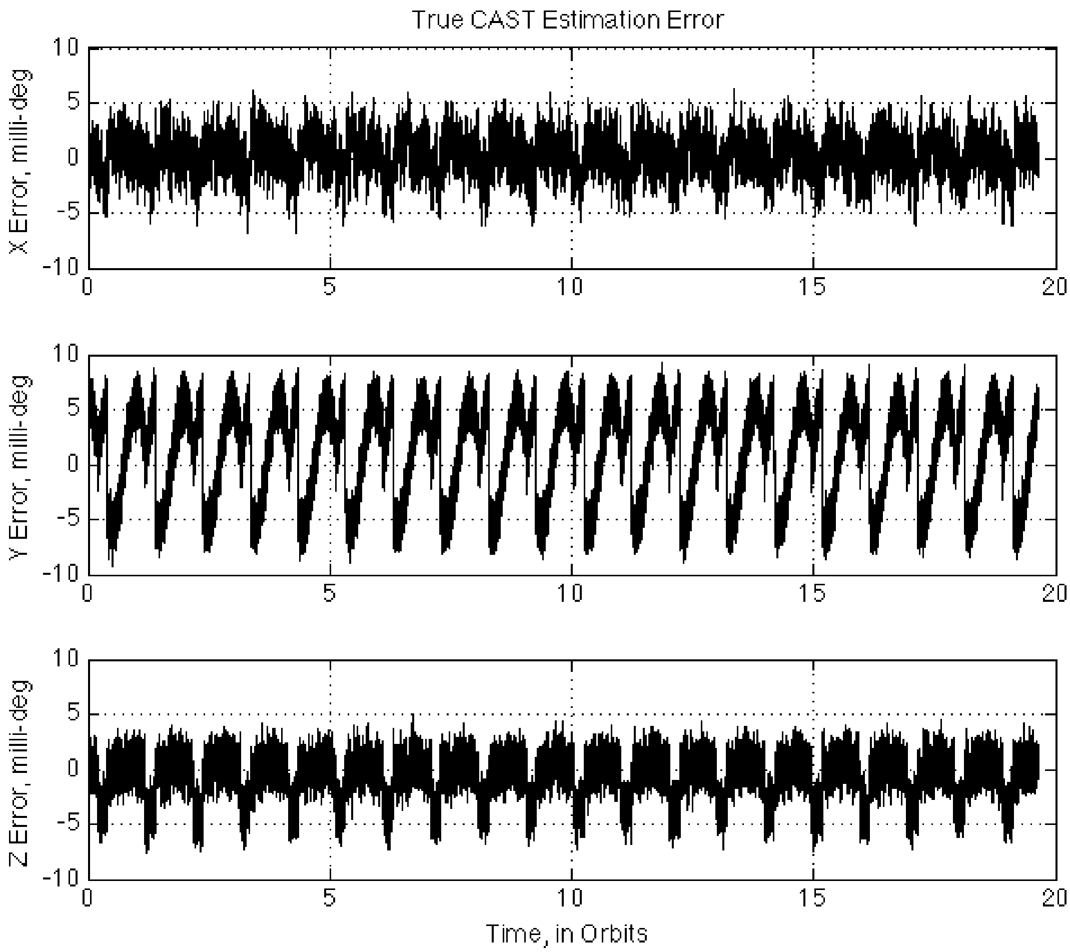

Figure 5: True CAST Estimation Error Time History

In Figure 5, the estimation error is on the order of 10^1 milli-deg. The error also exhibits cyclic behavior at the orbital rate. A 12[th] order signal generation model is developed with the following filter coefficients and gain.

Table 1: Signal Generation Model Parameters

X		Y		Z	
F_{num}	F_{den}	F_{num}	F_{den}	F_{num}	F_{den}
1	1	1	1	1	1
0.599606066	0.492148238	-1.987311322	-2.116797755	0.033889859	-0.084970611
0.170200806	0.017867804	1.180203745	1.353755544	-0.290522063	-0.376394157
-0.515202199	-0.667730784	-0.366109152	-0.431398302	-0.369402133	-0.414456633
-0.408736013	-0.487793397	-0.372665819	-0.337892654	0.186804738	0.185450707
-0.448320514	-0.480285154	0.414075905	0.47664522	-0.180389635	-0.213681497
-0.231433493	-0.212233113	0.917095903	0.909805253	-0.12256595	-0.127129131
-0.074752211	-0.037608847	-1.124285779	-1.236767689	-0.337192496	-0.331222515
-0.036182271	0.004697535	0.74942054	0.824116955	0.156338314	0.200791887
0.0744432	0.112401732	0.018234271	-0.049093637	-0.302932535	-0.290125983
0.061091414	0.088643792	-0.874314886	-0.91439187	0.213163854	0.264337952
0.010735827	0.030551437	0.325730008	0.406032331	0.100335527	0.113167729
0.125150725	0.141790209	0.120382966	0.11598703	0.065995691	0.07497141
k_{filter} (milli-deg)	0.611		0.609		0.608

In Table 1, the filter coefficients and gain for each spacecraft axis are from Equation 2. The F_{num} coefficients range from c_0 to c_{12}, and F_{den} coefficients range from a_0 to a_{12}. Using the parameters in Table 1, the time history comparison of the signal generation model versus the true CAST estimation error for 20 orbits is shown in Figure 6.

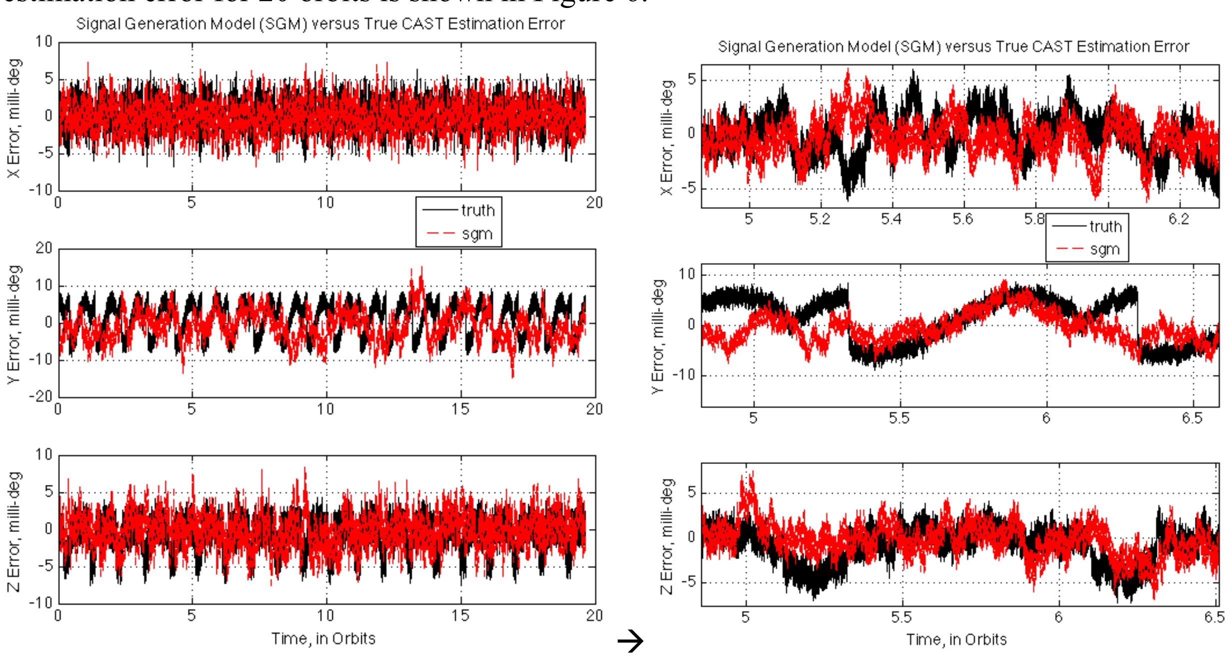

Figure 6: Estimation Error Time History Comparison

Figure 6 also shows a zoomed view of a single orbit. The signal generation model time history is on the same order of magnitude as the true error, and compares well with the truth overall. However, each data point does not match identically with the truth (see zoomed figure on the right). While the characteristics (mean, variance and power spectral density) of the signal generation model compare well with the truth, this point-to-point discrepancy is acceptable. Table 2 presents the characteristics comparison over 20 orbits.

Table 2: Signal Generation Model versus True CAST Estimation Error Characteristics

	Mean		
	X	Y	Z
Signal generation model, milli-deg	-0.063	-0.916	-0.181
True CAST estimation error, milli-deg	0.203	1.091	-0.636
Percent error, %	131	184	72
	Variance		
	X	Y	Z
Signal generation model, milli-deg^2	2.714	14.916	3.763
True CAST estimation error, milli-deg^2	2.704	17.441	3.397
Percent error, %	1	14	11

From Table 2, the mean and variance are on the same order of magnitude for the signal generation model and true estimation error. The mean lies within the variance range for both of the signals, hence the large percent error in the mean is acceptable. Figure 7 shows the power spectral density comparison.

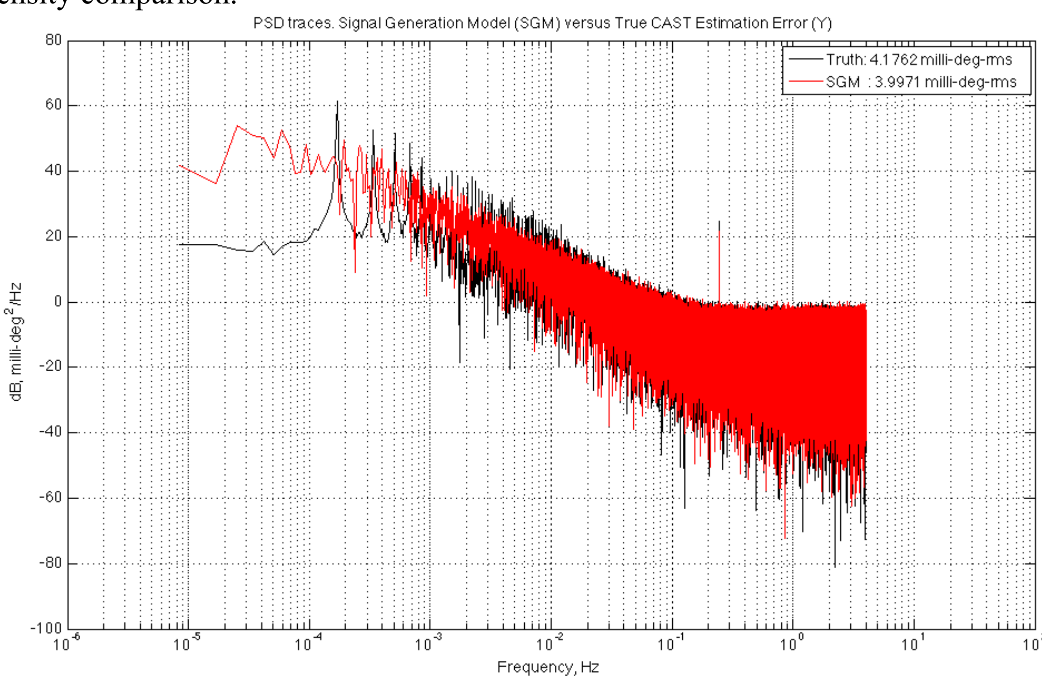

Figure 7: Power Spectral Density Comparison

The power spectral density is shown for the Y-axis error. The signal generation model captures the frequency content at frequencies >10^{-3} Hz. The lower frequency capturing is unimportant for the spacecraft operations application for which this signal generation model is used. Hence, the discrepancy in the lower frequency domain is acceptable. The frequency of importance is around 0.25 Hz, where the peak in the true power spectral density is captured by the signal generation model with a <1% error.

V. Conclusion

This work presents an interesting application of using a signal generation model to improve modeling fidelity when higher fidelity software cannot be developed due to time and resource limitations. In this study, a signal generation model is used to capture the effects of SMAP attitude control estimation error. This model is added to the ADAMS software in order to match the spacecraft dynamics estimation results from the higher fidelity CAST software. The signal generation model is evaluated against the true CAST estimation error using the mean, variance and power spectral density comparision. The mean and variance compare well overall with the truth (<15% error in variance), and the power spectral density compares well at higher frequencies (<1% error). The discrepancies in the signal generation model and the true CAST estimation error are within an acceptable range for the spacecraft application that uses this signal generation model.

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