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TUNING THE SOLAR DYNAMICS OBSERVATORY ONBOARD KALMAN FILTER

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The Solar Dynamics Observatory (SDO) was launched in 2010. SDO is a sun-pointing semi-autonomous spacecraft in a geosynchronous orbit that allows nearly continuous observations of the sun. SDO is equipped with coarse sun sensors, two star trackers, a digital sun sensor, and three two-axis inertial reference units (IRU). The IRUs are temperature sensitive and were designed to operate in a stable thermal environment. Due to battery degradation concerns the IRU heaters were not used on SDO and the onboard filter was tuned to accommodate the noisier IRU data. Since launch currents have increased on two IRUs, one had to eventually be powered off. Recent ground tests on a battery similar to SDO indicated the heaters would have negligible impact on battery degradation, so in 2016 a decision was made to turn the heaters on. This paper presents the analysis and results of updating the filter tuning parameters onboard SDO with the IRUs now operating in their intended thermal environment.

INTRODUCTION

SDO is the first mission to be launched for NASA's Living with a Star (LWS) program, a program designed to understand the causes of solar variability and its impacts on earth. SDO is contributing to the understanding of the sun's influence on earth and near-earth space by studying the solar atmosphere on small scales of space and time and in many wavelengths simultaneously. The geosynchronous orbit allows nearly continuous observations of the sun with a continuous science data downlink rate of 130 Megabits per second. Figure 1 is an image of the SDO spacecraft and Figure 2 is an image of a recent solar flare captured by SDO.[1]

SDO is equipped with sixteen coarse sun sensors, three two-axis IRUs, two star trackers and one digital sun sensor (DSS). Control is provided by reaction wheels, and thrusters provide orbit maintenance and momentum management. An Extended Kalman Filter (EKF) provides attitude and gyro bias estimates, using data from the star trackers, DSS, and IRUs. There are six software attitude control modes, two modes for safe operations, two thrusters based modes, an inertial mode and finally the science mode. The science mode incorporates measurements from the Guide Telescope and sun pointing is controlled to within 2 arcsec (3σ). The inertial mode is an intermediate mode between the safe and thruster modes and the science mode. The inertial mode is also used for instrument calibrations or for specific targeted operations. The inertial mode relies fully on the

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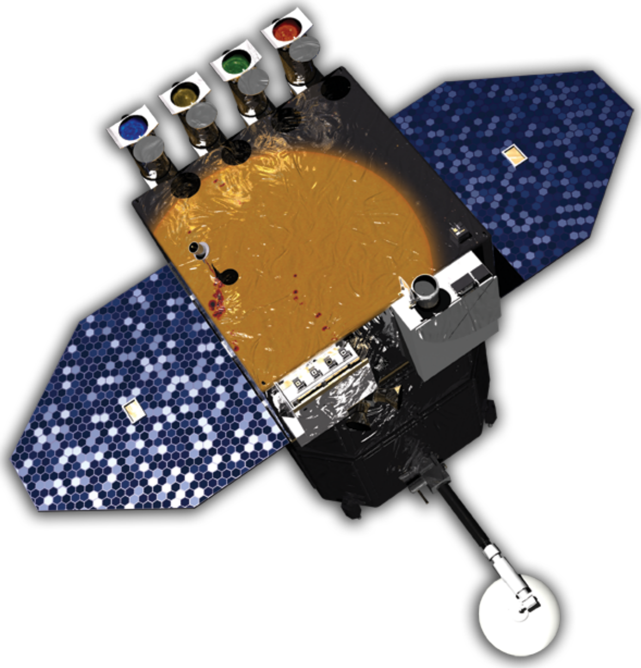

Figure 1. SDO Spacecraft (Courtesy of NASA/SDO and the AIA, EVE, and HMI science teams)

attitude and gyro bias estimates from the EKF. The science mode uses roll information and the gyro biases from the EKF.[2]

The SDO IRUs are Kearfott, two-axis rate assemblies. They have an internal temperature controller, designed to maintain the temperature at approximately 70 deg C in order to minimize changes in bias drift and scale factors. The heaters use 1.5 amps and run at approximately 83 Hz. The SDO batteries were not qualified to operate with that type of load at that frequency, so a decision was made to leave the IRU heaters powered off. After launch the operations team noticed oscillations in the IRU bias estimates, caused by the operating temperature. After analysis of the filter results and ground based testing in a high fidelity simulator, the gyro process noise covariance was increased and the sensor measurement noise covariances were decreased. The filter then relied more on the sensors and was less sensitive to the fluctuations in the IRU bias.[3]

In addition to the bias fluctuation, in late 2010 the current began to increase on IRU1. In 2013 it was taken out of the control system and eventually powered off. In 2015 the current started to increase on IRU2. In late 2015 a test was conducted to evaluate the impact of turning on the IRU heaters over a two week period. During that time the noise in the IRU measurements dropped, the biases stabilized, and the IRU currents dropped. Simultaneously, the Global Precipitation Mission (GPM) was conducting a ground test of their battery (same battery as SDO). GPM also has a large amplitude, high frequency load on their battery and there was no experimental data on whether such a load could affect battery life. After a year of running a high frequency load, and comparing to a control battery, the results indicated the battery degradation was negligible.[4] In September 2016 a decision was made to turn on the IRU heaters. One of the SDO instruments noticed an immediate improvement in their image stability, a direct result of the reduced noise in the IRU data.

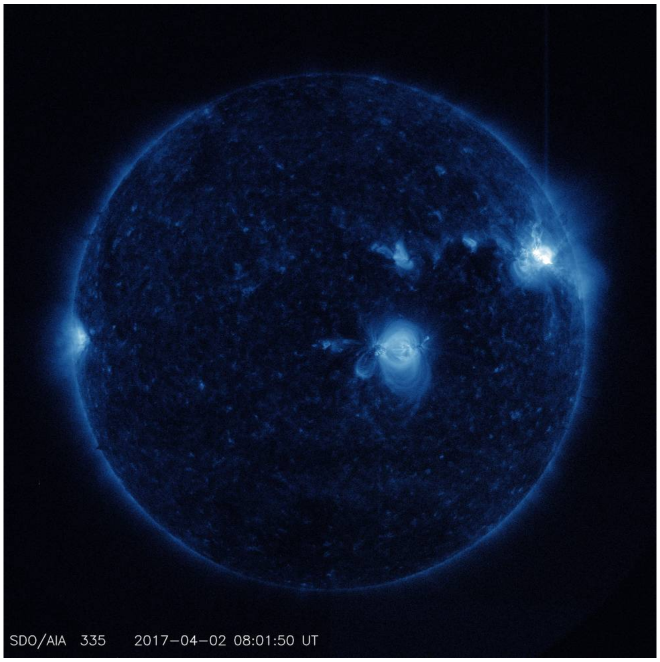

Figure 2. Solar Flare Captured by SDO (Courtesy of NASA/SDO and the AIA, EVE, and HMI science teams)

The remaining sections will provide the history and an overview of the SDO EKF, the process followed to update the filter tuning parameters, results of the filter tuning, conclusions, and future work.

SDO EXTENDED KALMAN FILTER

The SDO filter traces its history to an algorithm proposed by Murrell in 1978.[5] Several NASA missions used independent modules designed for replacement and were known as Multimission Modular Spacecraft (MMS). The first such mission was the Solar Maximum Mission.[6] Murrell proposed a Kalman filter design for the attitude determination in the MMS that utilized scalar updates, avoiding matrix inversion and reducing the computational load. Several NASA missions after SMM made use of this onboard filter, including the Tropical Rainforest Measuring Mission (TRMM) and the Wilkinson Microwave Anisotropy Probe (WMAP). The SDO filter is based heavily on the TRMM and WMAP filters.

The final paper will include an overview of the filter algorithm and its implementation onboard SDO.

PRELIMINARY RESULTS

The onboard filter was developed in Matlab and tested with real spacecraft data. Figure 3 shows the filter estimated biases from March, 2016 before the heaters were turned on, and the biases from March, 2017 after the heaters were turned on. The test case from 2016 uses the same sensor and gyro noise parameters that are currently onboard the spacecraft, and have not been changed since 2010. The test case from 2017 uses the same sensor noise parameters that are currently onboard the spacecraft, but uses the gyro noise parameters (angle random walk and rate random walk) provided by Kearfott when they delivered the IRUs to SDO during development. This preliminary result shows significant improvement in the noise and removes much of the oscillation present in the Z axis in particular.

The final paper will include additional test results of the filter, including improvements that result from updating the star tracker alignment in addition to the star tracker and DSS measurement noise parameters.

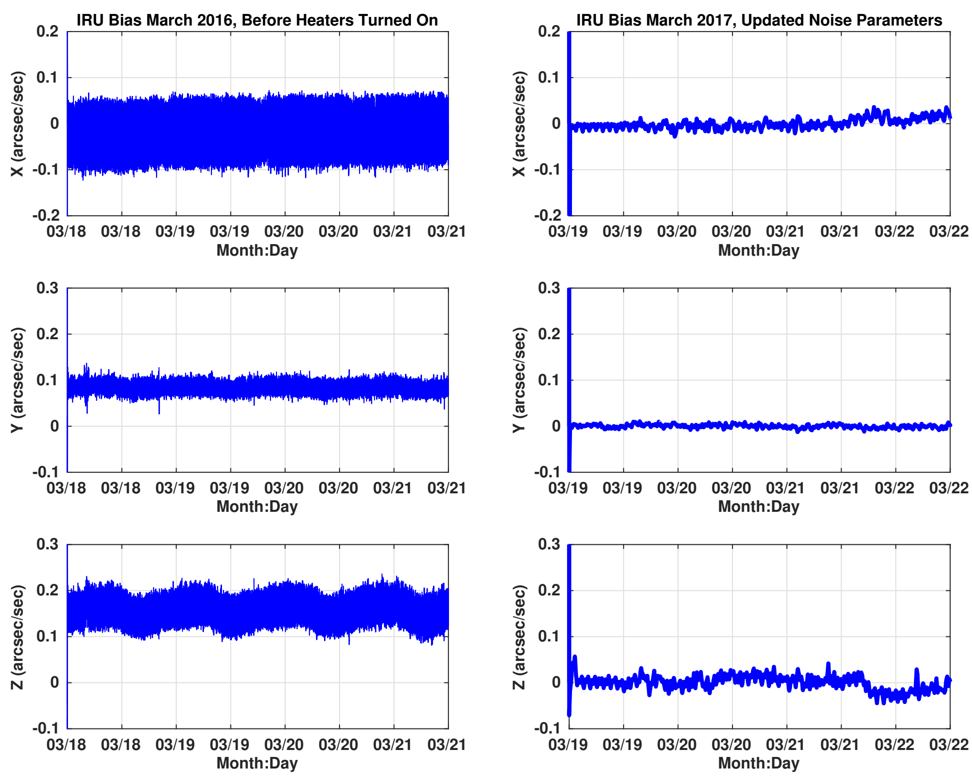

Figure 3. Comparison of Filter Estimated Biases With and Without the IRU Heaters

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