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INFLIGHT PERFORMANCE OF THE SDO FINE POINTING SCIENCE MODE

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The Solar Dynamics Observatory (SDO) was successfully launched and deployed from its Atlas V launch vehicle on February 11, 2010. Three months later, on May 14, 2010, the fully commissioned heliophysics laboratory was handed over to Space Systems Mission Operations to begin its science mission. SDO is an Explorer-class mission now operating in a geosynchronous orbit, sending data 24 hours per day to a dedicated ground station in White Sands, New Mexico. It carries a suite of instruments designed to observe the Sun in multiple wavelengths at unprecedented resolution. The Atmospheric Imaging Assembly (AIA) includes four telescopes with 4096x4096 focal plane CCDs that can image the full solar disk in seven extreme ultraviolet and three ultraviolet-visible wavelengths. The Extreme Ultraviolet Variability Experiment (EVE) collects time-correlated data on the activity of the Sun's corona. The Helioseismic and Magnetic Imager (HMI) enables study of pressure waves moving through the body of the Sun.

The SDO attitude control system (ACS) is responsible for four main phases of activity: guaranteeing the physical safety of the spacecraft after separation, providing fine attitude determination and control sufficient for instrument calibration maneuvers, maintaining mission science attitude within 2-arcsecond (3σ) control based on the error signals provided by AIA's guide telescopes, and accurately executing linear and angular momentum maneuvers as required for observatory momentum management and orbit maintenance. This paper provides an update on the current performance of the fine-point Science mode, which utilizes a hybrid approach of incorporating instrument sensing within the control law of the science mode controller. In hybrid Science mode, which has proven to be very accurate and reliable, the controlling AIA guide telescope is used to provide sub-arcsecond level Y-Z axis (boresight) knowledge of the sun's location within the field of view relative to the instruments center. The star trackers are used to provide roll knowledge (knowledge about the boresight). After an in-depth overview of the SDO spacecraft and ACS, this paper provides a comparison of the initial and current performance of the hybrid control scheme. In addi-

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tion, this paper also examines one of the anomalies that had an impact on the performance.

INTRODUCTION

SDO was the first mission launched in NASA's Living With a Star 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. SDO is a sun-pointing, semi-autonomous spacecraft in a geosynchronous orbit that allows nearly continuous observations of the sun with a continuous science data downlink rate of 130 Megabits per second. The ACS pointing knowledge requirements are 35/70/70 (X/Y/Z) arcsec. The control requirements are 2 arcsec (Y/Z, 3cr) relative to the ControlGuide Telescope (CGT) error signals and 10 arcsec over 10 minutes for the X axis (roll about the boresight).

During the design stage, SDO baselined a hybrid pointing control scheme, that uses the science instrument data, to achieve the required pointing accuracy. This hybrid approach of incorporating instrument sensing within the attitude control advanced the current technology and capability of the ACS system. The SDO design was also driven by the large science data rates and a high percentage observation efficiency (on the order of 90%) requirement for the science data efficiency. The high data efficiency drove the mission to minimize the number and length of propulsive maneuver interruptions, maintain low wheel speeds and minimize jitter.

The hybrid approach of incorporating instrument sensing within the attitude control has proven to be accurate and reliable. A comparison of the initial and current performance of the SDO ACS highlights the performance over the 7 highly successful years of operations.

SPACECRAFT OVERVIEW

A mechanical drawing showing the spacecraft, which includes the locations of the ACS sensors, actuators, and science instruments, is provided in Figure 1. The SDO ACS was designed to tolerate any single hardware fault and retain the capability to meet all requirements for science data quality. The suite of ACS sensors, actuators, and computational capabilities was selected and arranged for performance and maximal redundancy; SDO ACS failure detection and correction (FDC) depends to a large extent on hardware redundancy. Additional information on the FDC design and philosophy can be found in the initial overview paper [reference 2].

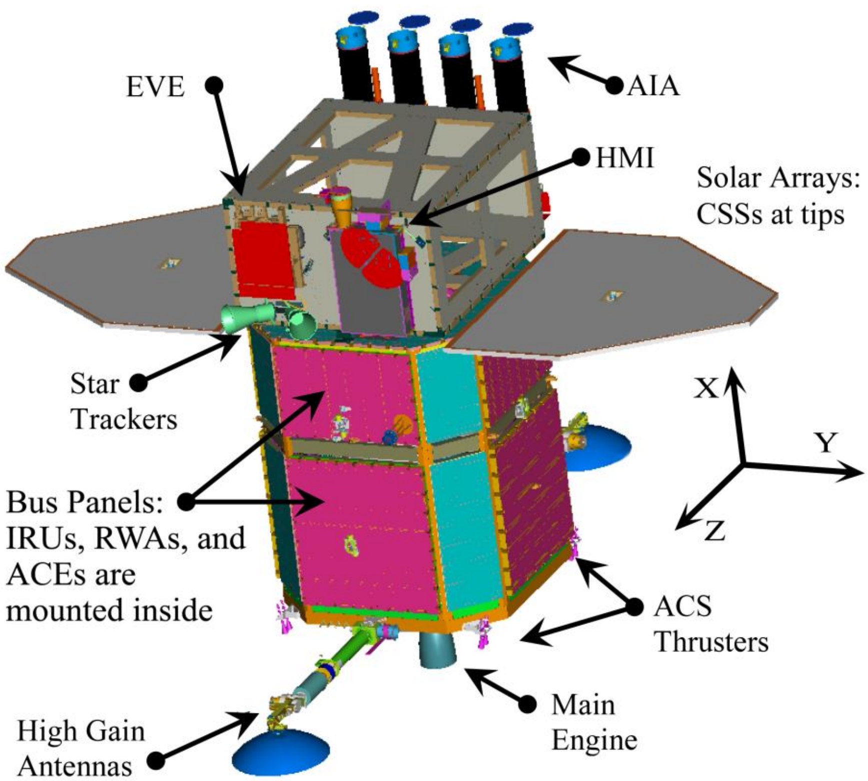

Figure 1: SDO Attitude Control System Hardware

Sensor Suite

The SDO sensor suite consists of sixteen Adcole coarse sun sensors (CSS), one Adcole digital sun sensor (DSS), two Galileo Avionica autonomous, quaternion-output star trackers (ST), and three Kearfott Two-Axis Rate Assemblies used as SDO's inertial reference units (IRUs). The CSSs are the only attitude sensors required in the most basic Sun-pointing mode. The sixteen CSSs are divided into two independent sets of eight sensors each (CSSA and CSSB), and each set of eight can provide an adequate Sun vector with any seven sensors being functional.

For fine attitude determination, an on-board Kalman filter provides attitude knowledge with input from the three fine-pointing units—DSS, ST1, and ST2. To avoid simultaneous blockages of both STs, they are mounted nearly perpendicular to the SDO Sun-pointing axis (X axis) and far enough apart from each other that the Earth and Moon do not block both at the same time throughout the science collection phase of the mission. The IRUs are arranged so that the sensitive axes from two units are aligned with each of the three body axes of the Observatory. Thus, any two out of three IRUs will provide full three-axis rate information.

In addition to these sensors, the ACS also makes extensive use of the guide telescopes (GT) mounted as part of the AIA instrument. Because of the high accuracy of the SDO science instruments, the ACS uses the GT data as the best available knowledge of the Sun center. There are four GTs, with one mounted to each of the four science telescopes; the ACS only needs accurate information from one of the four GTs, selected by SDO scientists as the controlling guide telescope (CGT), to perform its science control duties. Each GT has a field of view (FOV) of 0.5 deg within which sunlight illuminates at least one photodiode, and polarity of the control signal is determined; this is called the acquisition range. When the Sun center is within approximately 90 arcseconds of the FOV center, the GT is capable of providing attitude information relative to the Sun vector accurate to about 2 arcseconds; this is referred to as the GT linear range and is required for accurate science data collection.

Actuator Suite

SDO guidance functions are actuated by four Goodrich 70-Nms reaction wheel assemblies (RWA) and eight Ampac 5-lbf attitude control thrusters. ~~(While not used for attitude control, there is also one Aerojet R-4D model bi-propellant main engine producing 110 lbf of thrust used for orbit raising.)~~ The RWAs are arranged in a pyramidal structure so that any set of three provides full three-axis control capability. The ACS thrusters are grouped into four pairs of thrusters, with one thruster of each pair linked to fuel and oxidizer (monomethyl hydrazine and nitrogen tetroxide) by independent manifolds. In this way, the catastrophic failure of any one thruster can only require the closing of one manifold, leaving the other set of four capable of performing all necessary ACS tasks, including controlling the attitude druing orbit maneuvers (attaining and maintainging a geosynchronous orbit and a deorbit).

ACS MODE OVERVIEW

Figure 2 shows a diagram of the SDO ACS control modes and allowed transitions. The ACS has four RWA-actuated modes and two thruster-actuated modes. More details about the ACS in general and the control modes in particular can be found in References 1, 3, 4 and 5. One RWA-actuated mode resides on the attitude control electronics (ACE) microprocessors; this mode is called Safehold. The other five modes reside on the main processor (MP). Sun Acquisition (SunAcq) Mode performs an attitude function similar to Safehold, in that it simply maintains a power-positive, safe attitude with respect to the Sun using CSS signals. It differs from Safehold in that IRU signals are used for angular rate information at all times.

For all other modes, attitude determination (AD) is performed with some combination of the fine attitude sensors and propagation of IRU-derived rate information. An attitude solution may be initialized either by accepting a valid ST quaternion (nominal) or by uploading an estimate by ground command (available for testing and contingency). Once a solution is available, it may simply be propagated using rate sensors, as is always done in the thruster based modes, or it may be replaced by either using one preferred ST or by ground override command. The most accurate solution is obtained by combining all available fine attitude data from the two STs, the DSS, and the IRUs using a Kalman filter. Whatever AD method is selected in the software, Inertial Mode uses the estimate of the attitude error against the target attitude in all three axes. Inertial has two sub-modes that differ only in the target calculation. One tracks a Sun-referenced target quaternion using the on-board ephemeris to predict the appropriate inertial-referenced quaternion for the Sun-referenced state. The other maintains a commanded, absolute, inertial-referenced quaternion. Science Mode, during which most science data are collected, uses one of the specialized GTs to point a commanded science reference boresight (SRB) accurately at the Sun. The roll error about that SRB is calculated using the same methods as Inertial Mode, except that the target is always Sun-referenced.

The thruster modes are called DeltaH Mode and DeltaV Mode. DeltaH is used to manage system angular momentum. With no magnetic torquers to gradually dump momentum, the thrusters must be used occasionally to remove momentum. To maximize time between uses of DeltaH, the mode allows a non-zero angular momentum to be placed into the body, which can be set to the opposite of any predicted angular momentum change. The attitude target for DeltaH is simply the attitude estimate at mode entry. DeltaV is used for changing or maintaining orbit parameters. It uses an absolute, inertial-referenced target similar to Inertial Mode absolute targeting, and that target may be updated by command during a DeltaV maneuver.

Some transitions between modes are not allowed. In Safehold mode the ACE is in control and the ACS mode running on the MP is ignored. Safehold may be reached from any MP mode. Any MP mode may transition to SunAcq or to Inertial, including self-transitions. Science mode is the only other mode that may self-transition, and it may also be entered autonomously from Inertial Mode when the Sun is in the field-of-view of the controlling guide telescope. DeltaH may be entered from SunAcq or Inertial mode. However, Science and DeltaV may only be entered from Inertial mode, with Science accessible only when Sun-referenced targeting is active and DeltaV accessible only when absolute targeting is active. These restrictions avoid large attitude changes occurring due only to misunderstandings of the two targeting sub-modes in Inertial. Thrusters are always disabled upon exiting DeltaH or DeltaV modes.

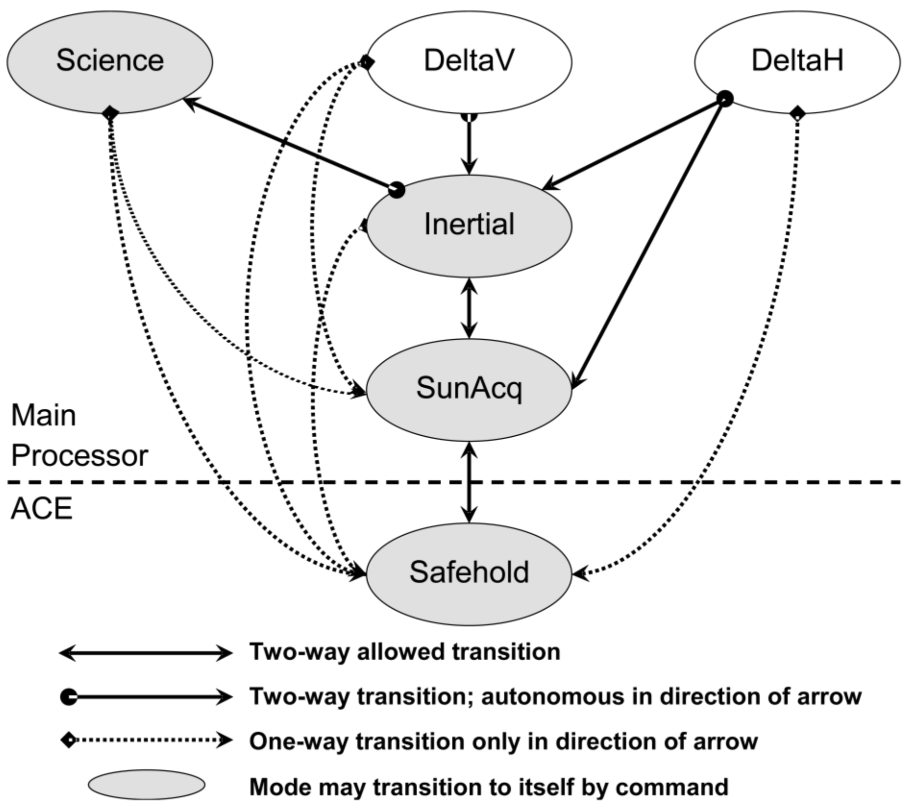

Figure 2: SDO Mode Transition Diagram

ACS PERFORMANCE (SCIENCE MODE)

In Science mode, the spacecraft Y and Z attitude is controlled using the CGT measurements. The controller acts both to null the IRU-sensed rates and the CGT errors such that the SRB of the spacecraft points toward the Sun. Each GT measures the offset from the center of the solar disk along the Y and Z axes (Figure 3). Because the Science mode controller acts to zero the attitude errors, biases are added to the GT measurements such that when the GT measurement plus bias is zero, the spacecraft points at the SRB. All four GTs are processed in this manner, but the spacecraft only uses the CGT errors in the controller.

After the control torques are calculated, they are filtered using a second-order elliptical filter on the X axis, a second-order low pass filter on the Y axis, and a third-order elliptical filter on the Z axis. The resulting filtered torques are distributed to the four RWAs as in the other wheel-based modes. The torque distribution law distributes the 3–axis commanded torque to the four RWAs using the nullspace to minimize the separation between wheel speeds.

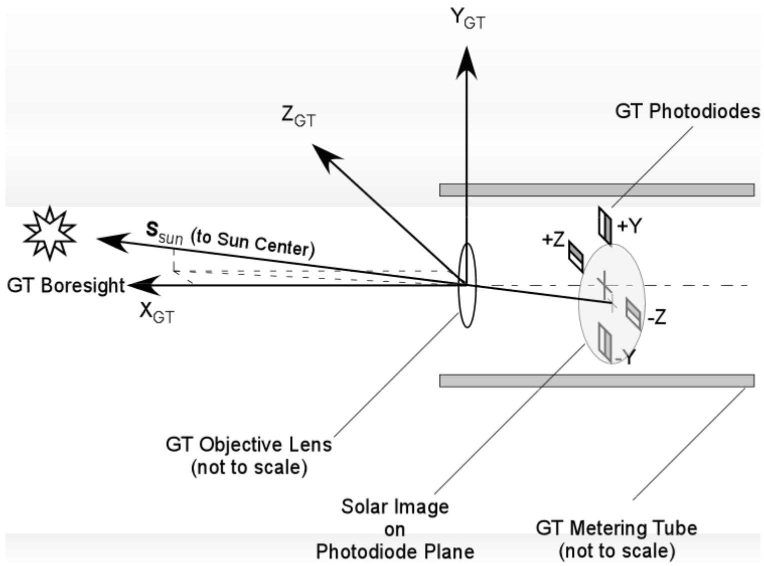

Figure 3: Guide telescope geometry

POST COMMISSIONING ACS PERFORMANCE (SCIENCE MODE)

The post commissioning flight results in which Inertial mode performs a slew and then transitions automatically to Science mode is shown in Figure 4. The transition behavior illustrates the effectiveness of the hybrid approach to drive the errors down and maintain them at the desired level within a reasonable amount of time. For the SDO hybrid ACS, the transition from a 90 arcsec error to under 2 arcsecs is less than 2 minutes. A key attribute of the effective transition of the hybrid approach is the region of control overlap. A small transition can result in dithering and poor performance in that zone. If the overlap region is too large, the transition to a fine point controller is delayed and the performance may be slower and less accurate. Figure 5 highlights Science mode pointing performance, which is less than an arcsecond. However, there is a distinct oscillation in the attitude errors. It was determined that these oscillatory errors are due to the IRU thermal instability, which will be discussed in the next section of the paper.

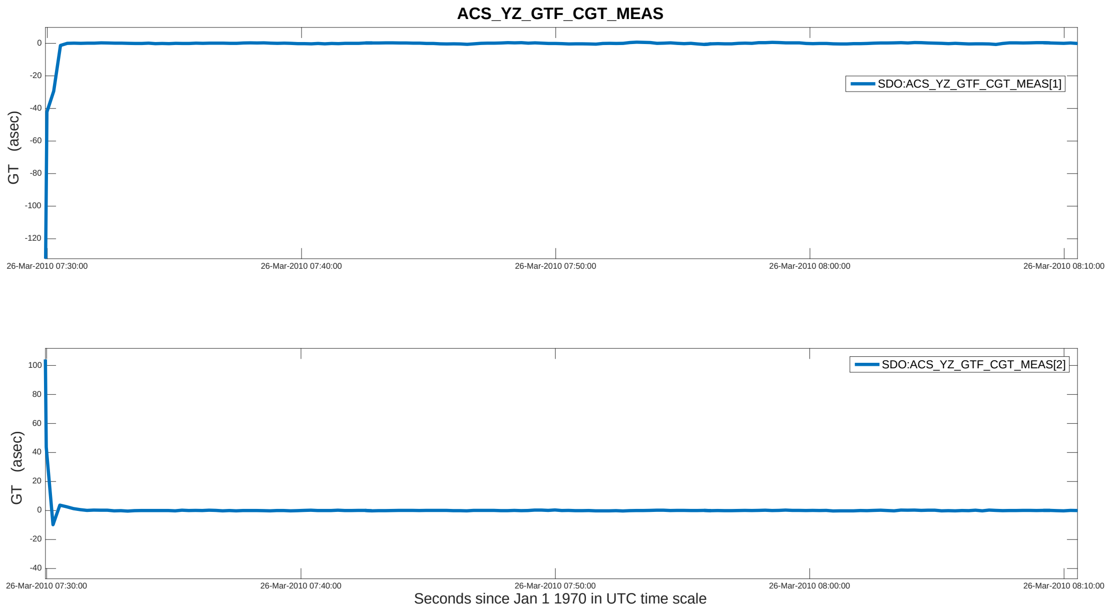

Figure 4: Post Commissioning GT Errors during Science mode

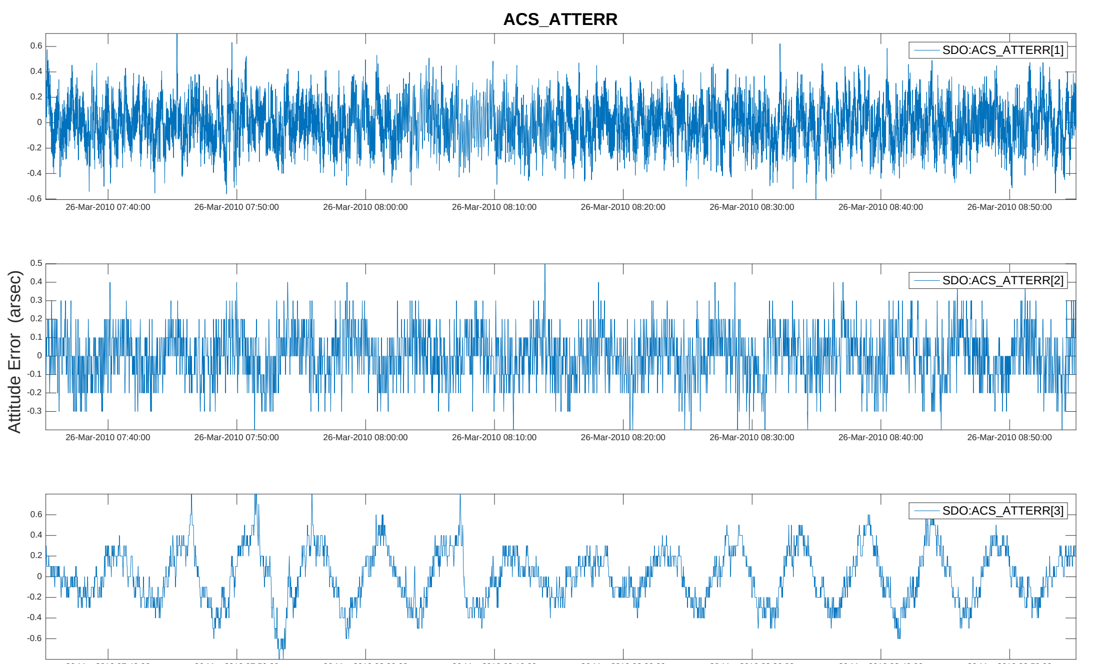

Figure 5: Science Mode Attitude Error Post Commissioning

Figure 6 contains the post commissioning rate bias estimates. These Kalman filter estimates contain underdamped dynamics, which ~~are~~ will be show to be a result of ~~assumed to be a result of the Kalman filter design and~~ the gyro performance. Even in the presence of these errors, the filter ~~nearly always~~ maintains convergence and the controller meets the desired pointing requirements.

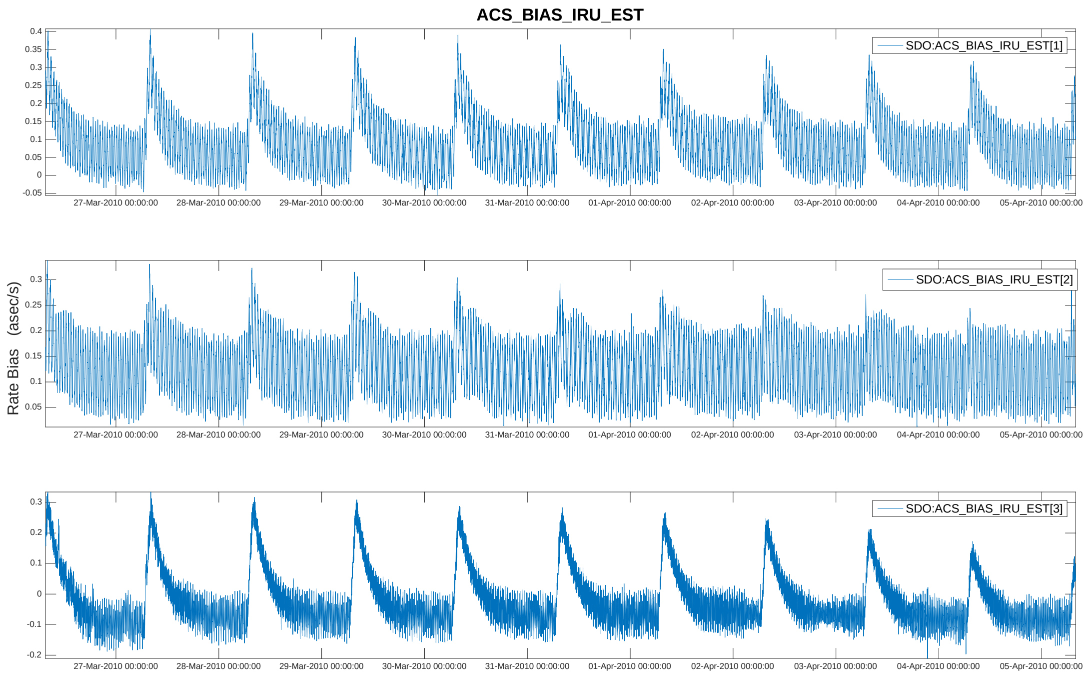

Figure 6: Post Commissioning Estimated Rate Bias

The next section, provides a description of the IRU issues that are cause this behavior.

IRU ISSUES

During the spacecraft checkout phase, oscillations were observed in the IRU bias estimates calculated by the onboard Kalman filter. This 0.0005 Hz bias estimate oscillation was well within the bandwidth of the controller. Therefore, the controller followed the oscillating error, which resulted an actual spacecraft motion. The oscillations seen on all of the different tests were approximately 10–20 arcsec in Inertial mode. Even though the Science mode errors were within requirements, the team was concern. Analyzing the data from the various attitude determination tests, it was determined that the IRUs were the cause of the oscillations, and that the frequency and the amplitude of the oscillations were temperature related.

The IRUs used on SDO are required to be thermal stable to meet the specification performance.The IRU's internal heaters operate at a frequency of 87 Hz, causing concern that operation of the heaters could affect the spacecraft battery. The 3 gyro units operate at 87 Hz and can require a maximum combined current draw of 3 Amps during operations. During this current spike, the battery could see a charge/discharge at 87Hz , which the power team thought could potentially reduce the life of the battery. The decision was made not to use the heaters in flight except during a few crucial operations or failure/contingency situations. As a result, the IRUs experienced temperature variations that were different from the manufacturer's design and testing profile. An early test with the heaters on confirmed that the bias oscillations were a result of the temperature variations [Reference 6]. Figure 7 contains a plot of the IRU bias oscillations.

After the first IRU internal heater test, the flight support team ran two additional tests using a software-based control of the IRU heaters. The first test used a setpoint of 40 C; the second a setpoint of 67 C. The software control was relatively coarse, allowing peak-to-peak variations about the setpoint of roughly 2 C. As expected, changing the temperature setpoints resulted in changes to the amplitude and frequency of the observed oscillations in the bias.

Following the heater tests and the examination of their results, the team decided that the lowest-impact solution to the problem would be to adjust the gains of the Kalman filter to make it less sensitive to the low frequency oscillations of the gyro biases caused by the thermal variations. The adjustments resulted in a reduction of the oscillation magnitude and resulting in acceptable errors that were within requirements.

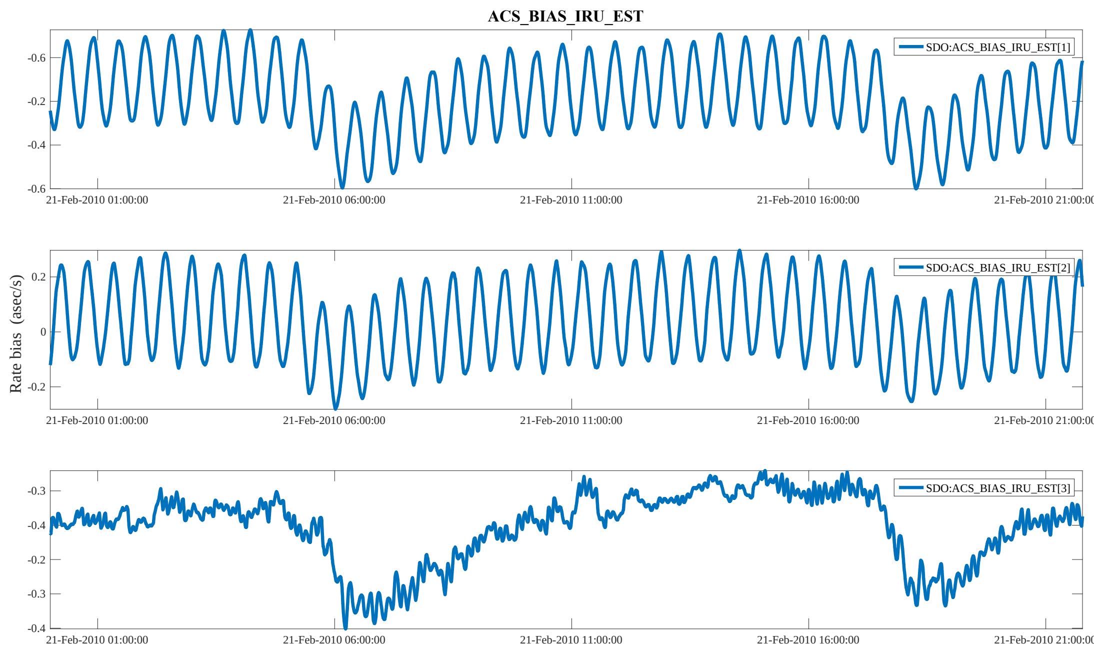

Figure 7: Rate Bias oscillations

In late 2010, the current began to increase on IRU1, and in 2013 a decision was made to take IRU1 out of the control loop and eventually power it off. In 2015 the current started to increase on IRU2. Late in 2015 a test was conducted to evaluate the impact of turning on the IRU heaters over a two week period. The noise in the IRU measurements dropped and the estimated biases stabilized. The IRU currents also dropped. These results are not shown here. However, the current performance, which is shown later, is representative of this performance. Simultaneously, the Global Precipitation Mission was conducting a ground test of their battery (same battery as SDO) to determine the effects of micro-cycling the battery. The results indicated that after a year of running a high frequency load the battery degradation was negligible. In September 2016 a decision was made to turn on the SDO IRU heaters. As with the test in late 2015, the IRU currents dropped, the measurement noise decreased, and the biases stabilized. Figure 8 shows the transition in biases in all three body axes after turning on the IRU heaters. The SDO instruments also noticed an improved response due to the improved pointing accuracy. Figure 9 shows one of the GT error responses when the IRU heaters were turned on. There is a distinct reduction in the error magnitude and the oscillations are removed. It is believed that the battery performance will not be impacted. However, the operations team will continue to monitor the SDO battery performance. More details about the analysis and root cause determination can be found in Reference 6.

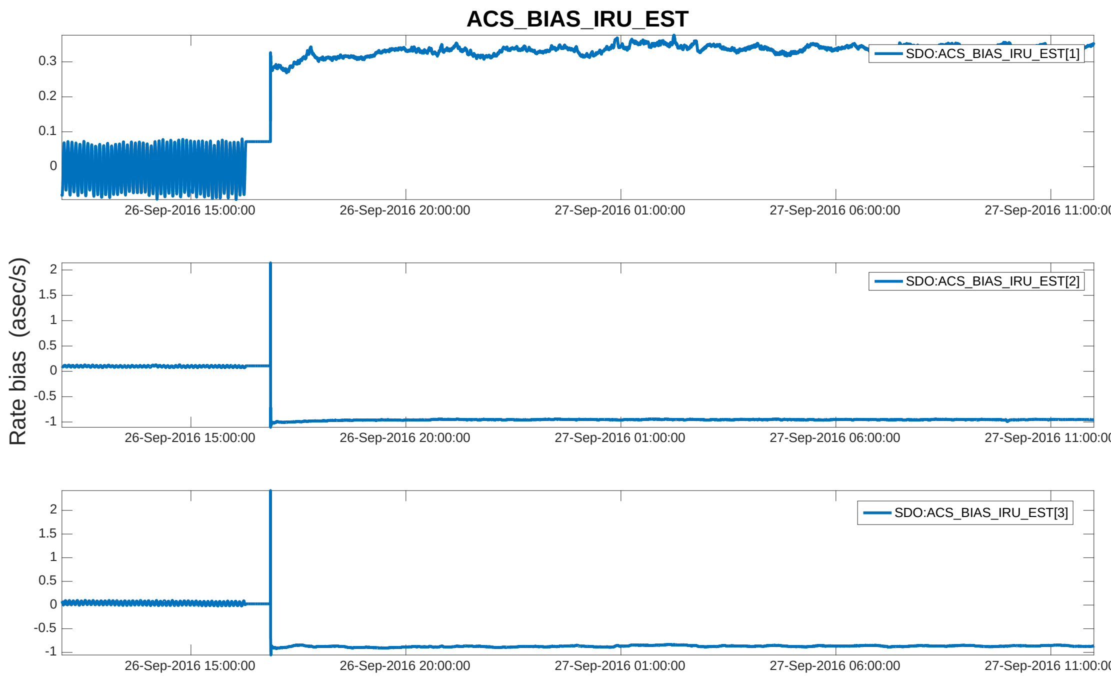

Figure 8: Gyro Biases Following Heater Turn On

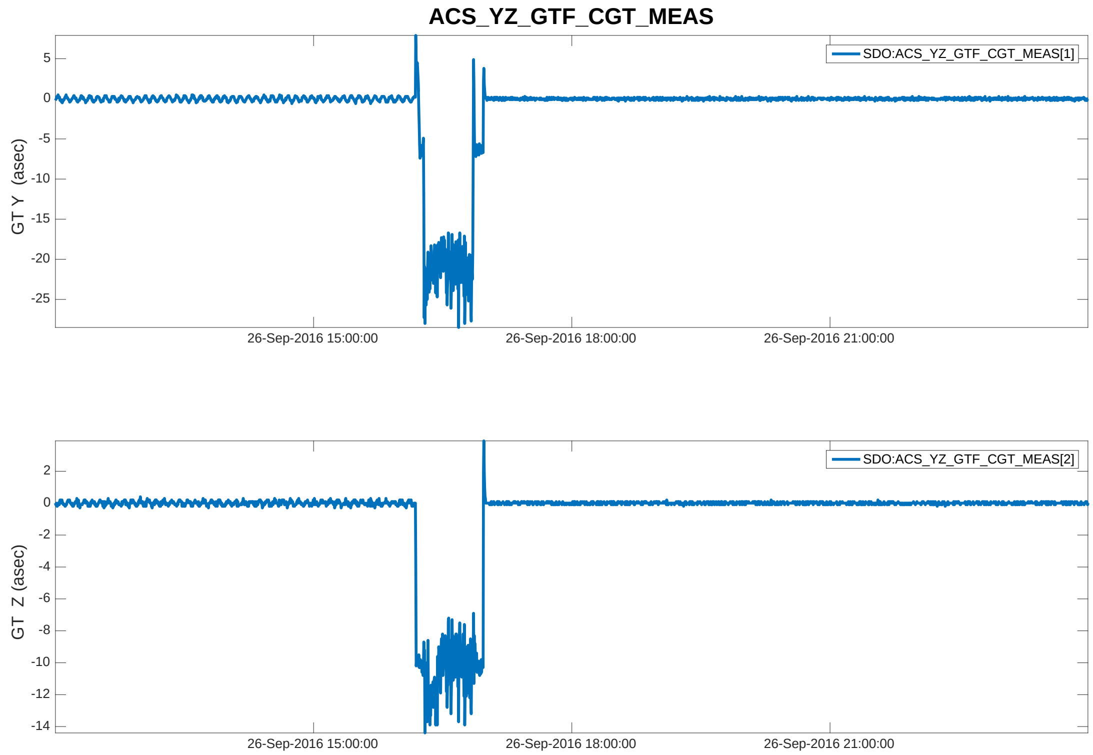

Figure 9: GT Errors Following Heater Turn On

CURRENT ACS PERFORMANCE (SCIENCE MODE)

The SDO attitude control system is still performing within requirements. SDO has flown for 7 years and has performed numerous maneuvers and calibrations while meeting the desired science goal of 99% science observation time. Table 1 provides a summary of the number of maneuvers and calibrations that have been performed to date.

Table 1 SDO maneuvers/events completed

	2010	2011	2012	2013	2014	2015	2016	2017	Total
Delta-H	2	4	5	4	4	3	3	1	26
Statonkeeping	1	2	2	2	2	2	2	0	13
Instrument Calibrations	13	24	26	20	20	20	23	3	149
Lunar Transits	3	2	2	3	4	2	2	0	18
Eclipse Seasons	1	2	2	2	2	2	2	0	13
HGA Handover Seasons	2	2	2	2	2	2	2	0	14
Other	1	2	0	3	0	1	0	0	7

IRU calibrations are part of the 'Other events' category. These calibrations are necessary in the event of a configuration change, testing or tuning. The number of Delta-H and Stationkeeping events are significantly less than what was planned. This is primarily due to an increase in the wheel speed limits. The initial limits were based on conservative analysis and testing. Within a year after commissioning, a jitter analysis was performed and the momentum buildup model was updated with flight trends. This analysis and data were used to determine new wheel speed limits.

The current hybrid ACS performance leverages all the tuning and configurations changes that have occurred over the past 7 years. The Science mode performance is provided in the figures below. Figure 10 contains the CGT measurement in Science mode. Unlike early flight results, both the Y-axis and the Z-axis are centered about zero with a maximum deviation of 0.4 arcsec. The attitude errors in Figure 11 are significantly better than the errors at commissioning. This is due to the improved IRU performance with the IRU heaters in use. Figure 12 contains the current estimated biases, which are now well behaved and constant.

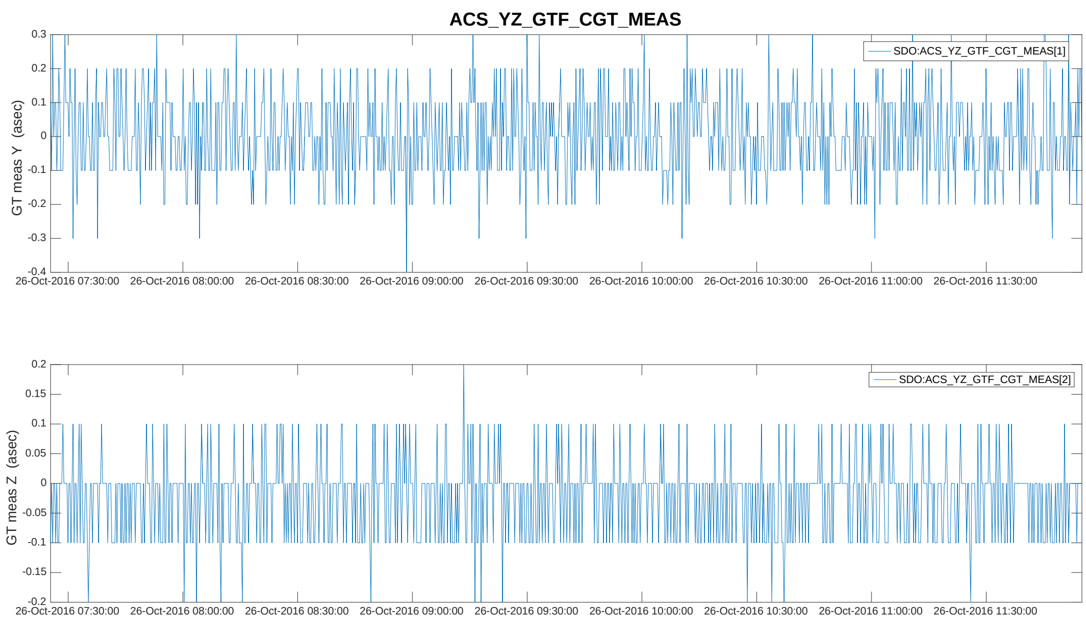

Figure 10: Current GT Errors during Science mode

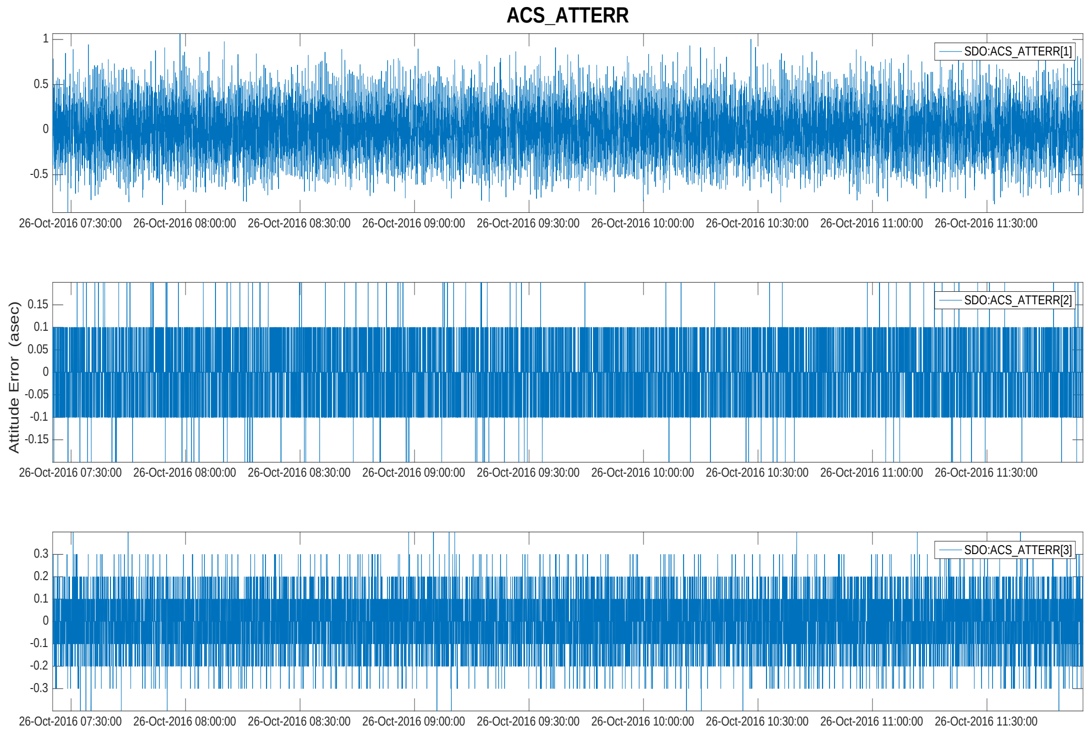

Figure 11: Current Science mode Attitude Error

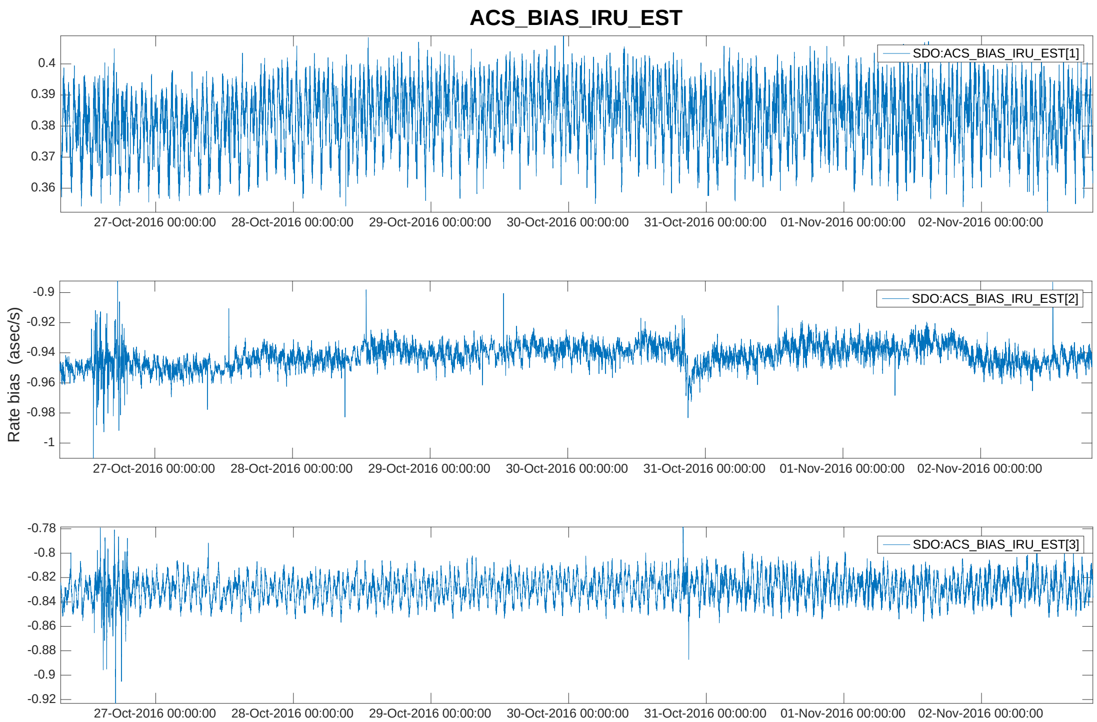

Figure 12: Current Science mode Estimated rate bias

COMPARISON

The figures above provide the performance of the hybrid approach during early commissioning and the current performance. Turning on the gyro heaters improved the performance. The lessons learned from SDO are being used on future missions that use a guide telescope (WFIRST). This is especially true for the hybrid controller design, rate bias estimation, stability analysis and the jitter performance.

CONCLUSION

This paper provided an update of the SDO attitude control system performance after 7 years on orbit. After the overview of the SDO ACS, this paper presented the post commissioning performance of the hybrid Science mode control scheme. This performance was within the requirements but contained attitude oscillations that were a result of an unexpected IRU bias that resulted from thermal sensitivity. In the presence of degraded IRU performance, the SDO team analyzed and made the configuration changes that would not have a large impact of the system or operations. These changes consisted of filter parameter changes. After current growth, the SDO team reevaluated the root cause and the resolutions. After examining the battery data it was determined that turning on the IRU heaters would not have a significant impact on the battery life and would improve the IRU performance. The configuration change produced noticeable improvement in performance of the spacecraft attitude control system. It is expected that the IRU heaters will remain on for the life of the mission. Based on the SDO IRU experience, future missions such as WFIRST will place more emphasis on the interactions between thermal, power, and ACS hardware components. In summary, the hybrid ACS that is described in this paper has been very successful for SDO.

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