A JITTER-MITIGATING HIGH GAIN ANTENNA POINTING ALGORITHM FOR THE SOLAR DYNAMICS OBSERVATORY

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INTRODUCTION

This paper details a High Gain Antenna (HGA) pointing algorithm which mitigates jitter during the motion of the antennas on the Solar Dynamics Observatory (SDO) spacecraft. SDO has two HGAs which point towards the Earth and send data to a ground station at a high rate. These antennas are required to track the ground station during the spacecraft Inertial and Science modes, which include periods of inertial Sun-pointing as well as calibration slews. The HGAs also experience handoff seasons, where the antennas trade off between pointing at the ground station and pointing away from the Earth.

The science instruments on SDO require fine Sun pointing and have a very low jitter tolerance. Analysis showed that the nominal tracking and slewing motions of the antennas cause enough jitter to exceed the HGA portion of the jitter budget. The HGA pointing control algorithm was expanded from its original form as a means to mitigate the jitter.

OVERVIEW OF SDO AND HIGH GAIN ANTENNAS

SDO is a Sun-pointing spacecraft which is planned to launch in early 2009 into a geosynchronous orbit. The spacecraft has five nominal modes of operation (Sun Acquisition, Inertial, Science, Delta-H, and Delta-V), plus a Safehold. During the Science mode, three science instruments study solar variability, and instrument calibration maneuvers are performed in the form of small-angle slews during Inertial mode. Two of the science instruments, Atmospheric Imaging Assembly (AIA) and Helioseismic and Magnetic Field Investigation (HMI), have high jitter sensitivities and are of interest in this study.

Data from the science instruments is sent to the ground by way of a pair of HGAs which take turns pointing at an SDO dedicated ground station. The instruments have a high data volume, and require continuous ground contact. The HGA control algorithm must provide continuous communications coverage for the pair of antennas while ensuring that the HGA gimbal motion does not excite jitter on the spacecraft.

Further details about the SDO mission are located in Reference 1.

COORDINATE SYSTEMS AND ANGLE DEFINITIONS

The coordinate systems used in the HGA algorithm are described below and can be seen in Figure 1.[†]

Frames designated with a '+' refer to axes and angles measured on the $+Z$ HGA, and frames designated with a '-' refer to the $-Z$ HGA. When no symbol is present, the explanation of the frame is valid for either antenna.

Spacecraft Body Frame

The spacecraft body frame, $\mathcal{F}_S$, defines the x_S-axis in the direction of the instrument boresights. The z_S-axis is along the +HGA boom, and the y_S-axis is orthgonal. When the spacecraft is in its nominal science-pointing attitude, the x_S-axis is oriented towards the Sun.

[†]Details of the SDO Coordinate System were compiled by Joseph A. Hashmall of a.i. solutions, Inc. in Flight Dynamics Task Order 85, *Solar Dynamics Observatory (SDO) High Gain Antenna (HGA) Calibration Analysis*, delivered to the NASA/GSFC Flight Dynamics Facility

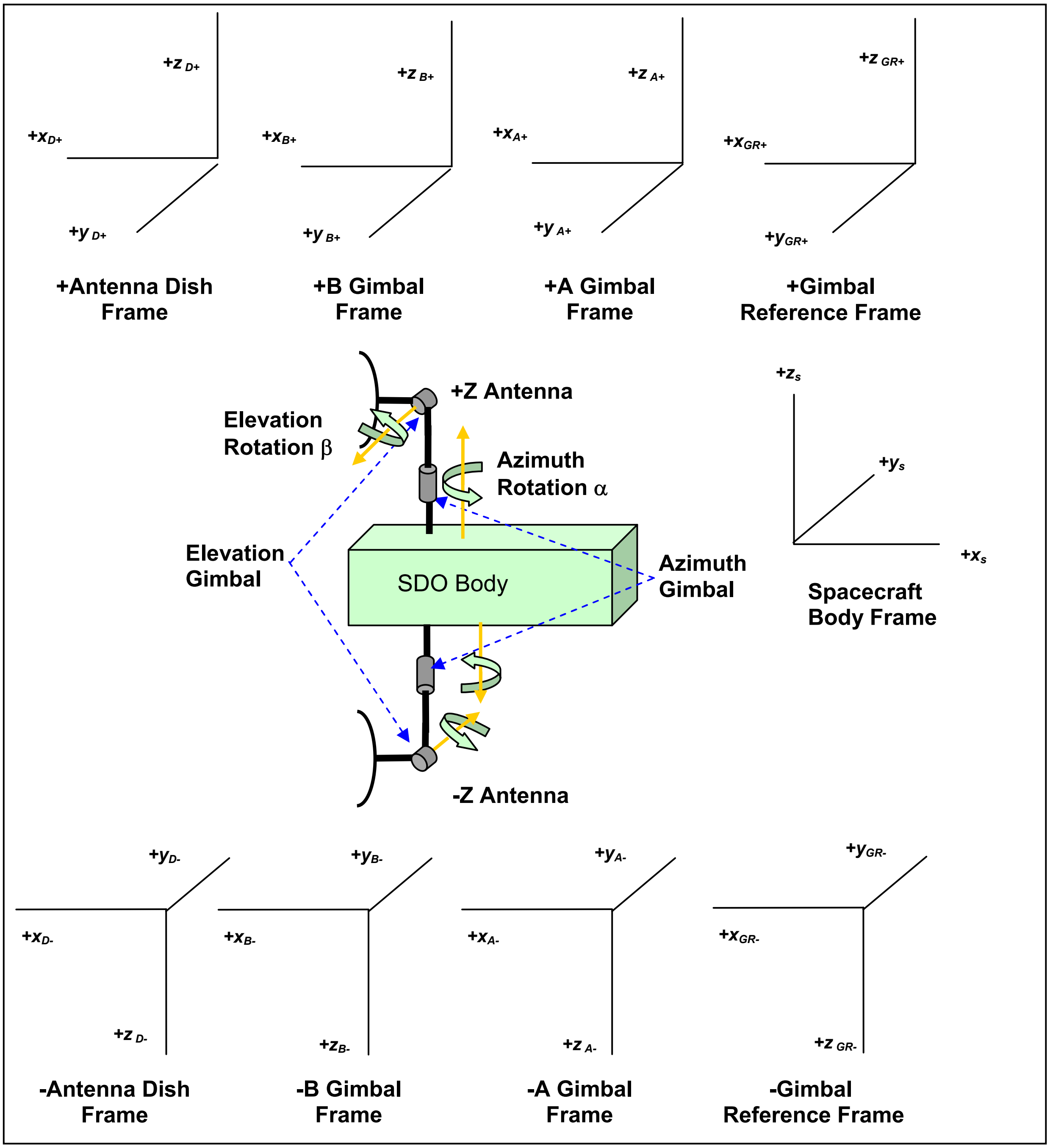

Figure 1: HGA Coordinate Systems (Courtesy of J. Hashmall, a.i. solutions, Inc.)

Gimbal Angles

Each antenna has two gimbals, A and B, to point the antenna dishes at the target. The A, or azimuth, gimbal is the innermost of the two gimbals and causes a rotation about the $+z_S$ or $-z_S$ axes of angle α. The B, or elevation, gimbal is on the outer portion of the HGA and is attached to the antenna dish. When deployed with no A rotation, the B gimbals rotate about the $+y_S$ or $-y_S$-axis with an angle β.

The gimbal home position is defined with no rotation about the A or B gimbals, with the dish pointing in the $-x_S$ direction.

Gimbal Reference Frames

The orientation of the antennas when in their deployed configuration with the gimbals in their home position is defined with the gimbal reference frames, $\mathcal{F}_{GR^+}$ and $\mathcal{F}_{GR^-}$. These frames are constant with respect to the spacecraft, and are defined as:

$$\mathbf{R}_S^{GR^+} = \begin{bmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \qquad \mathbf{R}_S^{GR^+} = \begin{bmatrix} -1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -1 \end{bmatrix} \tag{1}$$

where $\mathbf{R}_S^{GR}$ is the rotation from $\mathcal{F}_S$ to $\mathcal{F}_{GR}$.

Azimuth Gimbal Frame

The azimuth gimbal frames, $\mathcal{F}_{A^+}$ and $\mathcal{F}_{A^-}$, describe the position of the A gimbals relative to the $\mathcal{F}_{GR}$ frame. When no misalignments are present, the $\mathcal{F}_A$ and $\mathcal{F}_{GR}$ frames coincide.

Elevation Gimbal Frame

The elevation gimbal frames, $\mathcal{F}_{B^+}$ and $\mathcal{F}_{B^-}$, define the position of the B gimbals relative to the A gimbals. These frames are a function of the azimuth angles α^+ and α^-, and consist of a rotation about the $+z_A$-axis.

Antenna Dish Frame

The coordinate frames that are fixed to the antennas are known as the dish frames, $\mathcal{F}_{D^+}$ and $\mathcal{F}_{D^-}$. The dish frames have their x_D-axis along the boresight of the antennas, and when the antennas are in their home position, the dish frame is equivalent to the gimbal reference frame. The dish frames are a rotation of the elevation angles β^+ and β^- around the $+y_B$-axis.

Earth-Centered Earth-Fixed Frame

The Earth-Centered Earth-Fixed frame, $\mathcal{F}_{ECEF}$, has its origin at the center of the Earth and is fixed to the Earth as it rotates. The z_{ECEF}-axis points along the Earth spin axis, and the x_{ECEF} axis goes through the Greenwich meridian. The ground station target is defined in this frame.

GIMBAL CONTROL ELECTRONICS

Commands for the HGAs are sent from the flight software to the Gimbal Control Electronics (GCE). The GCE runs at 200 Hz and receives commands from the Attitude Control System (ACS) flight software at 5 Hz. During one ACS cycle, up to 40 steps, or pulses, can be commanded to the GCE. One step of the gimbal motor is equal to 0.0075°, resulting in a maximum commandable rate of 5400°/hour. However, the GCE hardware is only able to respond as fast as 66 pulses per second, or 1782°/hour.

The ACS flight software command to the GCE contains five pieces of information: Pulse counts, Direction, First step delay, Interval time, and Type ID. These commands are issued separately for each of the four gimbals.

The pulse counts, p, is the number of 0.0075° steps for the GCE to command during one ACS cycle. The Type ID defines the pulse count type as either relative to the current position or an absolute angle position. In this case, the ACS is constrained to only send relative pulses.

The direction command informs the GCE whether the steps should be taken in the positive or negative gimbal directions during the ACS cycle.

The first step delay command, d, is defined as the number of GCE cycles from the beginning of the ACS cycle to wait before moving.

The interval time, t_{int}, is the number of GCE cycles between two commanded pulses. In this algorithm, t_{int} is calculated by:

$$t_{int} = \frac{f_{GCE}}{\omega_{slew} c} \tag{2}$$

where f_{GCE} is the GCE cycle frequency of 200 Hz, ω_{slew} is the slew rate in degrees/hour, and c is the conversion from degrees/hour to counts/second.

These GCE commands are shown pictorially in Figure 2. For simplicity, the GCE cycle frequency is represented as 50 Hz instead of the mission's 200 Hz both here, and in similar figures in this paper.

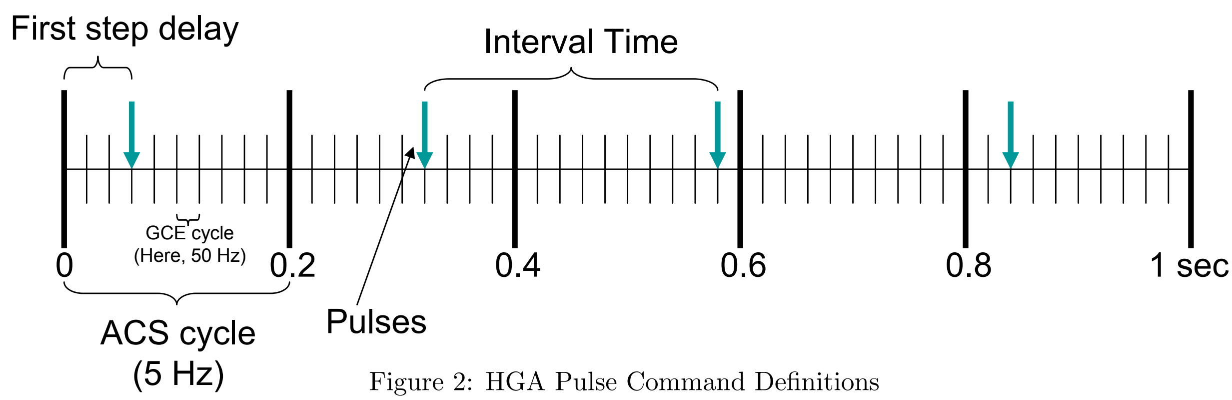

Figure 2: HGA Pulse Command Definitions

In order to move the HGA at the times shown in Figure 2, the commands in Table 1 are sent to the GCE.

Table 1: Resulting Commands

ACS Cycle	Number of Pulses	First Step Delay	Interval Time
1	1	3	13
2	1	6	13
3	1	9	13
4	0	0	13
5	1	2	13

The number of pulses that can be commanded during an ACS cycle is limited to the following constraint:

$$(t_{int}\,(p-1)+d) \le \frac{f_{GCE}}{f_{ACS}} \tag{3}$$

where t_{int} is the interval time between pulses, p is the number of pulses, d is the first step delay time, f_{GCE} is the GCE cycle frequency, and f_{ACS} is the ACS cycle frequency. This value is rounded up to the next integer to ensure that the commanded slew rate, ω_{slew}, is never exceeded.

TARGETING ALGORITHM

The desired target of the High Gain Antennas is defined in terms of the α and β angles for each antenna. These values are calculated by rotating the ground station's target vector from the spacecraft body frame to the antenna dish frame. The following section details the method of calculating the α and β angles. In addition, the operational maneuvers required for SDO are are described, along with the targeting commands sent to accomplish the maneuvers. A command filtering technique is then described and compared to the unfiltered target command.

Target Calculation

As described in Reference 2, the transformation from the spacecraft body frame to the antenna dish frame, $\mathbf{R}_S^D$, is calculated in Equations 4 and 5 for the positive and negative dishes.

$$\mathbf{R}_S^{D^+}(\alpha^+,\beta^+) = \mathbf{R}_{B^+}^{D^+}(\beta^+)\mathbf{R}_{A^+}^{B^+}(\alpha^+)\mathbf{R}_{GR^+}^{A^+}\mathbf{R}_S^{GR^+} \tag{4}$$

$$\mathbf{R}_S^{D^-}(\alpha^-,\beta^-) = \mathbf{R}_{B^-}^{D^-}(\beta^-)\mathbf{R}_{A^-}^{B^-}(\alpha^-)\mathbf{R}_{GR^-}^{A^-}\mathbf{R}_S^{GR^-} \tag{5}$$

The desired pointing vectors are defined as

$$\hat{\mathbf{u}}^{D^+} = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} = \mathbf{R}_S^{D^+}(\alpha^+,\beta^+)\hat{\mathbf{u}}^S \tag{6}$$

$$\hat{\mathbf{u}}^{D^-} = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} = \mathbf{R}_S^{D^-}(\alpha^-,\beta^-)\hat{\mathbf{u}}^S \tag{7}$$

where $\hat{\mathbf{u}}^S$ is the target vector in the spacecraft body frame.

For the positive antenna, this equation can be expanded to:

$$\begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} \cos\beta^+ & 0 & -\sin\beta^+ \\ 0 & 1 & 0 \\ \sin\beta^+ & 0 & \cos\beta^+ \end{bmatrix} \begin{bmatrix} \cos\alpha^+ & \sin\alpha^+ & 0 \\ -\sin\alpha^+ & \cos\alpha^+ & 0 \\ 0 & 0 & 1 \end{bmatrix} \mathbf{R}_{GR^+}^{A^+} \begin{bmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \hat{\mathbf{u}}^S \tag{8}$$

by using geometry to implement the gimbal frame and gimbal reference frame rotations. To solve this equation for gimbal angles α^+ and β^+, the following substitution is made:

$$\mathbf{u}'^+ = \mathbf{R}_{GR^+}^{A^+} \begin{bmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \hat{\mathbf{u}}^S \tag{9}$$

leading to a solution for the positive gimbal angles of:

$$\alpha^+ = \text{atan}\left(\frac{u_y'^+}{u_x'^+}\right)$$
$$\beta^+ = \text{asin}\left(-u_z'^+\right) \tag{10}$$

Similarly, the negative gimbal angle solutions are

$$\alpha^- = \text{atan}\left(\frac{u_y'^-}{u_x'^-}\right)$$
$$\beta^- = \text{asin}\left(-u_z'^-\right) \tag{11}$$

where

$$\mathbf{u}'^- = \mathbf{R}_{GR^-}^{A^-} \begin{bmatrix} -1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -1 \end{bmatrix} \hat{\mathbf{u}}^S \tag{12}$$

Operational Maneuvers

The ground station for SDO is located in White Sands, New Mexico. The HGAs are required to have uninterrupted contact with the ground station because the instruments have a high science data capture rate. In addition, the antennas must not irradiate the spacecraft, and can not irradiate the Clarke Belt, which is the portion of the sky where Geosynchronous satellites are located. Only one antenna is in contact with the ground at a time and the non-active antenna must be parked in a direction where its beam does not intersect other spacecraft. Additionally, when the HGAs slew, they must move such that they are Earth-irradiating for minimal time. During some times of the year, neither antenna can transmit for an entire orbit without irradiating the spacecraft, and control of the communications must be transferred between the two HGAs every day. This portion of the year is known as handover season.

During handover season, the two HGAs take turns being the active antenna once per day. At the start of a handover, one HGA is parked in a position facing away from the Earth, and the other antenna tracks the ground station. To begin the handover, the parked antenna slews to the ground station. Both antennas track the ground station for a few minutes to hand over communications. The previously tracking antenna then slews away from the ground station to the parked position. A more detailed description of the SDO HGA handovers is available in Reference 3.

Targeting Commands

The ground system sends targeting commands to the spacecraft, which define the required HGA targets and maximum slew rates. These ground commands are used to calculate GCE commands that slew and point the HGAs to the target determined by the operations team.

The first targeting command is 'Hold Target'. This command slews no faster than a specified rate to acquire and track a target position vector. It takes inputs of a target position in the $\mathcal{F}_{ECEF}$ frame, and azimuth and elevation maximum slew rate limits. This command is used to track a position on the earth, such as a ground station.

A second command is 'Full Park'. The 'Full Park' command slews no faster than a specified rate to specified actuator angles. It requires inputs of azimuth and elevation angles, and azimuth and elevation maximum slew rate limits. This command is used to park the HGAs at defined gimbal angles.

The third HGA ground command is 'Elevation Park'. This command is a combination of the above two commands. It slews the elevation actuator no faster than a specified a rate to a specified actuator angle. At the same time, the azimuth actuator is slewed at a specified rate to acquire and track the azimuth component of a specified position target. This command accepts a target position vector, an elevation angle, and azimuth and elevation maximum slew rate limits as inputs. The 'Elevation Park' is used during handoff seasons to point the HGA to a position off the earth, but still keep the azimuth gimbal close to the nominal target direction.

Filtered Target Commands

When a change of target command requires a slew to a new orientation, there is a large jump in the desired gimbal angle. This command must be constrained such that the HGA pointing error is not large and the issued command follows the actual desired trajectory.

Figure 3 shows the difference between a filtered command that follows the desired trajectory and a non-filtered command. The thin solid line shows a sample elevation tracking profile with no handoffs. The dotted line shows the desired trajectory as the HGAs slew back and forth between tracking the ground station and parking at an angle of $-35°$. The thick solid line shows the commanded target with no filtering.

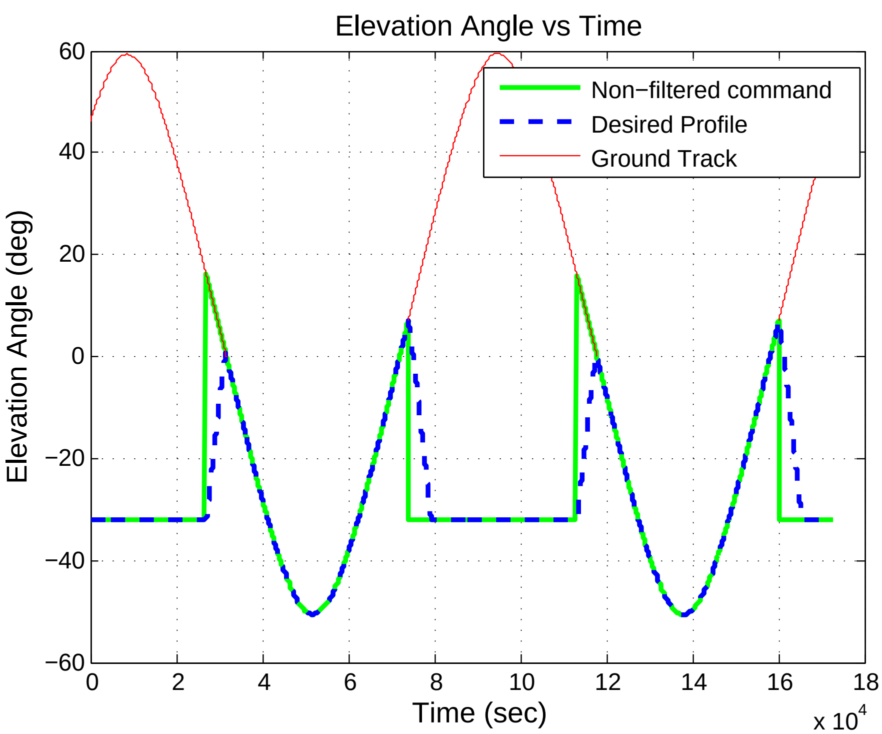

Figure 3: Desired Trajectory vs Non-Filtered Commanded Trajectory

The desired slew rate is input from the issued pointing command. This value is also the maximum rate that the gimbals are allowed to move, or ω_{max}. The first step in filtering the target command is to determine what the slew rate would be if the antenna was capable of moving completely to the target during one ACS timestep. This value is calculated as:

$$\omega_{slew} = \frac{\theta(k) - \theta_f(k-1)}{\Delta t} \tag{13}$$

where ω_{slew} is the calculated slew rate, $\theta(k)$ is the current commanded gimbal angle, $\theta_f(k-1)$ is the previous filtered commanded angle, and Δt is an ACS timestep.

The slew rate, ω_{slew}, is limited to the commanded maximum rate:

$$\omega_{slew} = \begin{cases} \omega_{slew} & : \quad \omega_{slew} \le \omega_{max} \\ \omega_{max} & : \quad \omega_{slew} > \omega_{max} \end{cases} \tag{14}$$

The new filtered command, $\theta_f(k)$ is determined by stepping from the previous filtered command by the allowed slew rate:

$$\theta_f(k) = \omega_{slew}\Delta t + \theta_f(k-1) \tag{15}$$

When $\omega_{slew} \le \omega_{max}$, the filtered command, $\theta_f(k)$, is equal to the current unfiltered command, $\theta(k)$.

The command filtering is shown in Figure 4 for a set of ACS cycles. The dashed line represents the desired tracking profile, with the $\times$ showing the unfiltered commanded angle. The slew rate before limiting is represented by the dotted line, and the diamonds show the command after filtering.

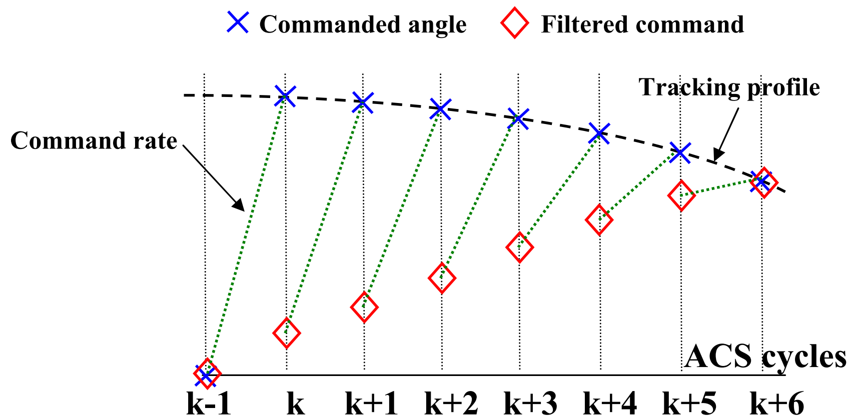

Figure 4: Filtered HGA Commands

SIMPLE CONTROL ALGORITHM

Once the HGA target has been determined, a pointing control algorithm is implemented that uses logical statements to calculate the pointing command sent to each gimbal in the form required by the GCE. This command is constrained by rules levied by the gimbal motor hardware, the software command limitations, and the slew restrictions from the attitude control system.

The HGA control algorithm moves the HGAs to the target or parking position as fast as the slew rates allow. Once the HGA reaches its desired position, the algorithm tracks the target or holds the parked angle.

The first step in pointing the HGAs is determining the desired pointing position of each of the antennas. Depending on the targeting method, this position may be given directly as gimbal angles or calculated as angles from a target vector, as described previously. The target command is filtered to the allowed rate.

Once the desired gimbal position has been determined, the difference between the current and desired position is calculated. This amount represents the total number of pulses that the gimbals must move to reach their target.

After the desired number of pulses are calculated, the algorithm implements constraints to limit the the number of commanded steps. One constraint is a result of the maximum commanded slew rate. The interval time, calculated earlier in Equation 2, is examined along with a measure of how many GCE cycles have passed since the last gimbal step in order to determine if the gimbals are permitted to move during the current ACS cycle, and also if they must delay motion until later in the cycle. Any other necessary gimbal-stepping restrictions, such as jitter restrictions described later, are also implemented at this time.

While tracking the ground station, the HGAs are expected to slew at a rate of approximately 15°/hour, which is 1 pulse every 9 ACS cycles (1.8 seconds). The expected maximum commanded slew rate is 30°/hour, or 1 pulse every 4.5 ACS cycles (0.9 seconds).

Since the GCE issues commands in discrete motor steps that can only be issued at discrete times, there is a slew rate loss due to quantization. The effect on the commanded slew rate due to quantization is shown in Figure 5. Here, the solid line represents no slew rate loss and the dotted line shows the resulting rate when a discrete motor is implemented. Other slew rates in the figure are described in future sections.

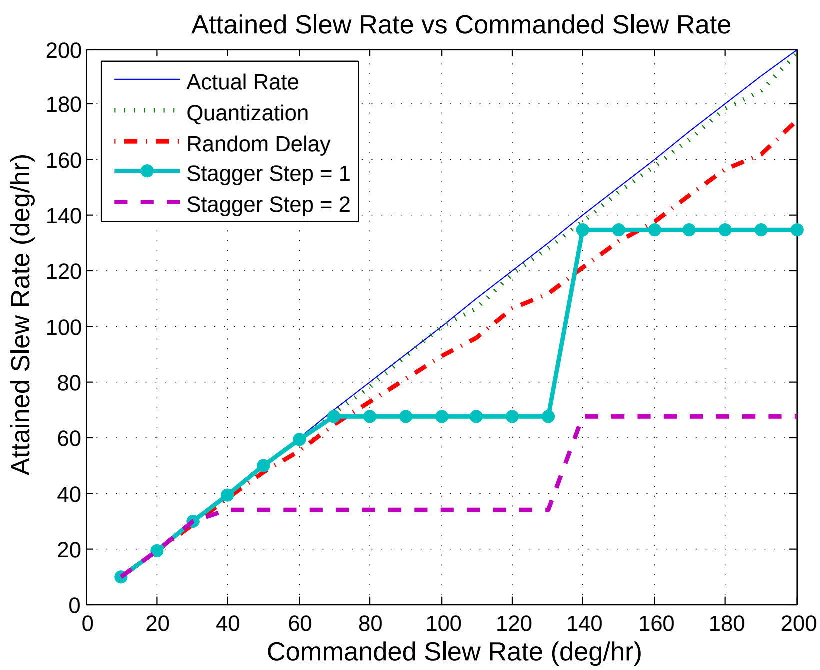

Figure 5: Attained vs Commanded Slew Rate Comparison

JITTER MITIGATION

Analysis has shown that the amount of jitter on the spacecraft due to the motion of the HGAs exceeds the budget allotment (Reference 4).

The jitter induced by a single motor step has a peak value that is within the allocations for the AIA and HMI instruments. However, interaction between steps can cause a substantial increase in the peak jitter response and thus exceed the requirements by a significant amount. Interaction can occur between the jitter response due to successive steps of a single actuator, and also between the response to steps of different actuators. Each effect is addressed with a separate mitigation approach.

Interaction from successive steps occurs when the step rate (or multiples of it) lies on a jitter-critical structural mode. In this case, each step imparts a jitter response that adds to the responses from previous steps. Because the step rates vary through a significant range, there will be substantial periods of time when the steps lie on jitter-critical modes, and thus the modal response will "ring up" to nearly the maximum steady state value. In order to prevent this, a random stepping algorithm is used. Successive steps from the same actuator are output at partially randomized times. This technique ensures that multiple steps do not excite the same modal frequency, and thus that the worst-case jitter from a single actuator is not higher than that from two successive, worst-case interval time steps.

Interaction between different actuators occurs when one actuator takes a step during the ringdown period of a step from another actuator. Such interaction can be constructive, increasing the response, or destructive, decreasing it. Again, because of the constant change in step rates, there is high probability that there will be frequent constructive interaction (half of the time, in fact). In order to reduce the effect of this, a stagger step solution is implemented, which prevents actuators on the +Z and -Z sides from taking steps during the same ACS cycle. In this way, the response from one actuator has time to partially decay before the next actuator can impart additional jitter. The details of both of these algorithms are presented below.

Random First Step Delay

As described previously, one of the commands sent to the GCE is the first step delay, or the number of GCE cycles to wait before stepping the motor. If a small pseudo-random number is added to this value each cycle, the interval between pulses is no longer constant. These values are not truly random, but instead are predetermined and loaded into sufficiently large flight software tables. The random first step delay implementation is shown in Figure 6.

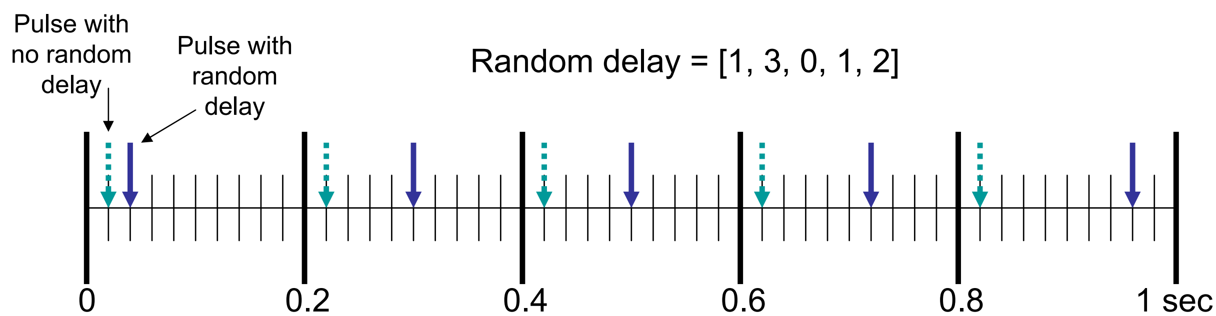

Figure 6: Random Step Delay

The dashed arrows show a nominal set of pulses which occur 10 GCE cycles apart. When random stepping is implemented with the given random sequence, the set of solid arrows defines the new pulse commands. The random delays are cumulative per cycle, and are based on where the new command would be each cycle as opposed to the original pulse set.

While the random step delay avoids the possibility of constructively exciting a mode, it is at the penalty of never allowing a reduced response due to cancellation. The jitter level in the random step delay case becomes equal to the average of the maximum and minimum response levels.

Using the random step delay affects the slew rate of the HGAs. Since there is a longer interval between pulses, the slew rate is decreased. The level of decrease is based on the magnitude of the random numbers, the commanded maximum slew rate, and the placement of the pulses within the ACS cycle. A comparison of the commanded nominal slew rate to a rate subject to a random step delay is shown in Figure 5. Here, the GCE cycle is 200 Hz and the random delays average to five pulses per cycle.

Stagger Stepping

When two gimbals step at the same time, the effects of their jitter may either constructively add or cancel each other, depending on whether the gimbals are in phase and moving in the same direction, or out of phase and moving in opposite directions.

As will be shown, this difference is greatest when the +HGA and -HGA both move their elevation angles in phase. A stagger stepping method is implemented to ensure that both antennas are not allowed to step during the same ACS cycle. In addition, the algorithm has the capability of allowing empty ACS cycles between the antenna steps depending on the argument to the command.

The implementation of the stagger stepping method is shown in Figure 7. The top set of pulses shows a sample stepping sequence with stagger stepping disabled. The pulses on the top of the line are steps of the +HGA, and the pulses below the line are steps of the -HGA. In this case, the +HGA and -HGA are allowed to step during the same ACS cycle.

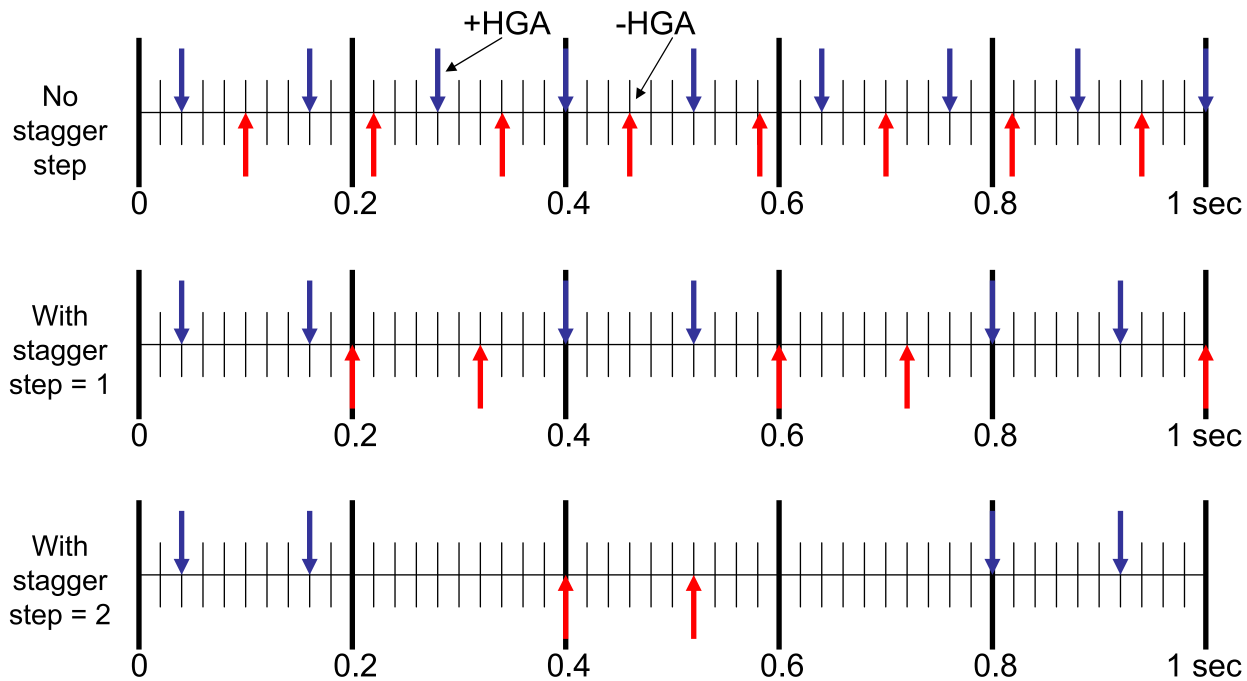

Figure 7: Stagger Stepping

The middle set of pulses show the result of the same pulse sequence when the stagger step is selected to command a one cycle separation between +HGA and -HGA commands. The bottom set of steps is the same pulse sequence when the stagger step is commanded to request a two cycle separation between commands from the two antennas.

Figure 8 shows the peak jitter on AIA caused by simultaneous $+Z$ elevation and $-Z$ elevation stepping, both in-phase and out-of-phase. The jitter response to each actuator has the same sign, so in-phase motions create an increased jitter response, and the out-of-phase jitter response is lower. When the stagger stepping algorithm is switched on, the jitter response of the first actuator has time to die out before the second actuator moves. Therefore the responses to each actuator do not interact, and actuator phasing no longer affects the jitter level. Note that the response level with the stagger step algorithm operating is roughly the average of the in-phase and out-of-phase responses, demonstrating that the approach reduces the worst-case response at the (acceptable) penalty of increasing the lowest jitter response.

It is important to note that the slew rate of the antennas is reduced when stagger stepping is implemented. In addition, because the opportunities for each antenna to step is reduced, the number of possible attainable slew rates is limited. This phenomenon is apparent in Figure 5, where the attained slew rate is plotted against the commanded rate.

Implementation of Random First Step Delay and Stagger Stepping

Figures 9 and 10 show the final jitter level over a full year for the AIA and HMI instruments with the stagger step and random step implemented. The data is plotted in the form of a histogram, showing the percent of the year for which jitter is below a specified level. The solid horizontal line is the allocation to each instrument. The dashed line is the desired 100% margin level. The percent of time that each instrument

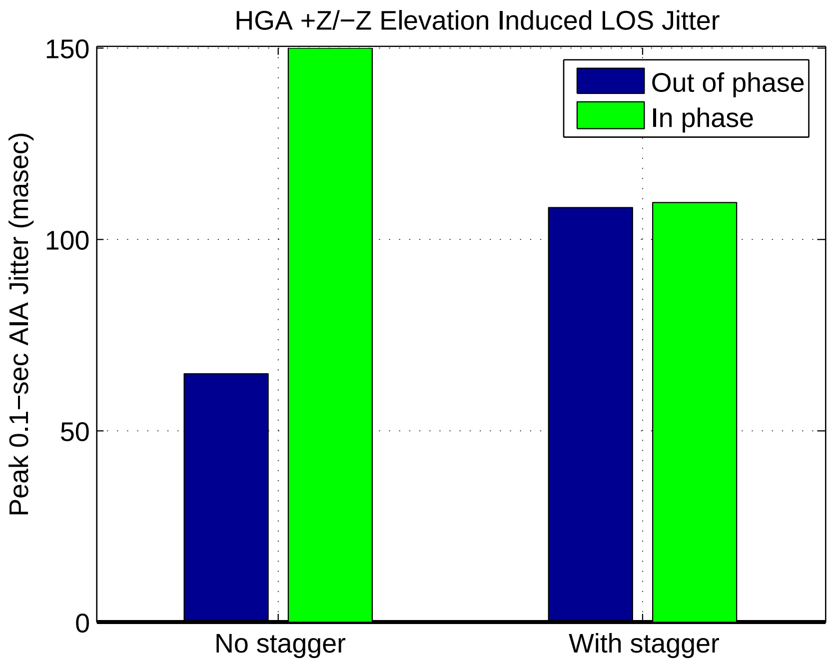

Figure 8: Jitter Caused by Stepping Two Gimbals Simultaneously

meets the allocation, and the 100% margin requirement, is called out, as is the peak jitter level over the year. The results demonstrate that the peak jitter level in both cases is much higher than the allocation: 181.5 masec in the case of AIA, where the allocation is 106 masec, and 160.6 masec for HMI, compared to the allocation of 94 masec. However, these jitter levels are only reached for a small percentage of the time, essentially at the peak of a single step a few times per orbit for a fraction of a second. The allocations are met for a significant fraction of the time, over 99% in both cases. Even in the case of a significant prediction error, where the jitter level is underpredicted by a factor of two, the allocations are met over 91% of the time.

Instrument Delay Request

The time when the spacecraft is the most concerned about reducing jitter is when the science instruments are taking pictures. An additional method of jitter mitigation was implemented which allows the instruments to request during which ACS cycles they would like the HGA to avoid stepping. This request is administered during the cycles that the camera shutters are open, as well as the cycle before, so that jitter from an HGA pulse has enough time to damp out.

Figure 11 illustrates the operation of the no-step request. The no-step request is sent 400 ms before an instrument shutter opens. The jitter level due to a HGA step dies away as the modes ring down while no pulse steps are issued. Two ACS cycles after the no-step request is sent, the instrument begins to take an exposure in a significantly reduced jitter environment. During the exposure, the instruments continue to issue no-step requests so that the jitter level remains low. At the end of the exposure, the no-step request flag is lowered and the antennas can begin to step again.

If the ACS deems it necessary, the request from the instruments may be rejected by the HGA algorithm. The amount of error between the current gimbal position and the filtered command is calculated, and if this value exceeds a tolerance, the instrument request is rejected and the step command is issued. If the instruments follow their projected cadence, the gimbals should follow their expected trajectories without needing to reject requests. If the instruments request a large number of no-step requests, the gimbals may

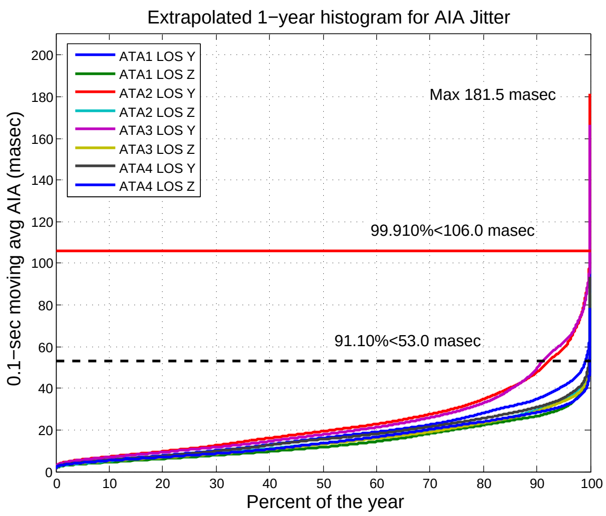

Figure 9: AIA Jitter

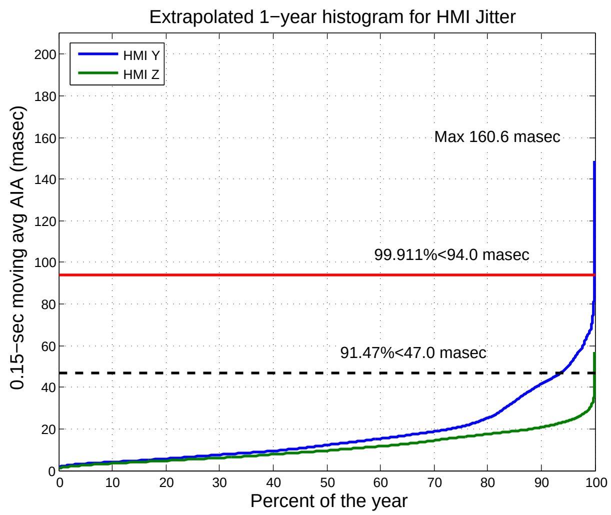

Figure 10: HMI Jitter

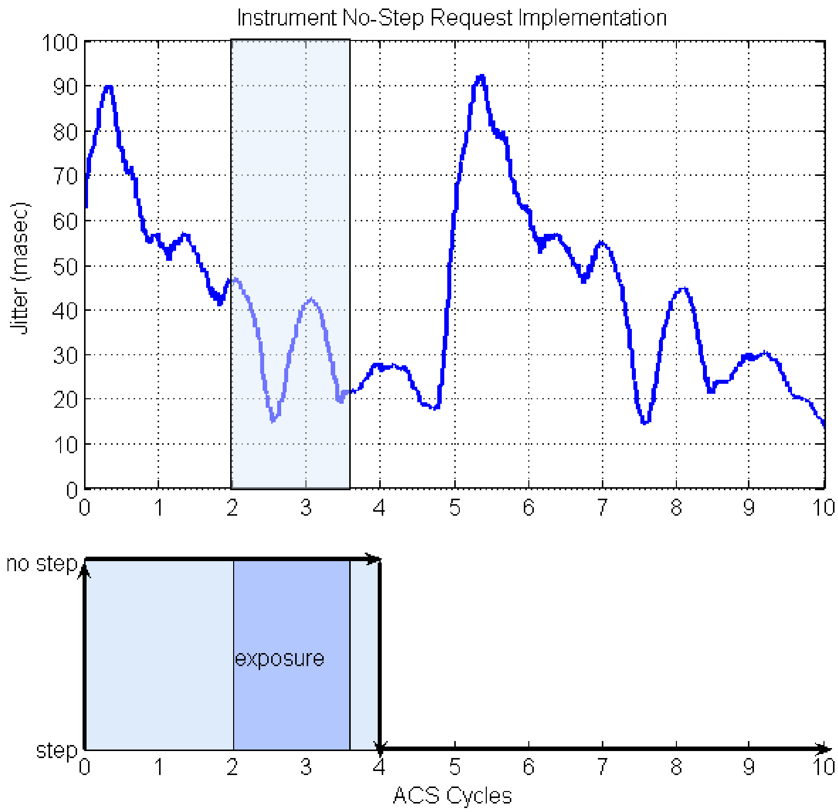

Figure 11: Instrument No-Step Request

fall behind in their targeting. In order to catch up and not have to reject requests, a new command may be sent with a higher slew rate, allowing an increased number of gimbal steps in each ACS cycle.

IMPLEMENTATION

The amount of jitter on the spacecraft is difficult to predict pre-launch due to the uncertainties in the mass properties and flexible modes. After launch, tests will be done to see to what extent jitter affects the instruments, and which method or methods of mitigation should be used. It is expected that not all methods of jitter mitigation will be used simultaneously.

Figure 12 show the results of the implementation of stagger stepping and the random step delay in the HGA control algorithm for 24 hours during handover season. At the start of the plot, the +HGA is tracking the ground station, and the -HGA is in an Elevation Park configuration with an elevation of $-65°$. After three hours, the -HGA begins the handover by slewing to the ground station. After the -HGA begins tracking the ground station, the +HGA slews to the Elevation Park configuration. After remaining at an elevation of $-65°$ for a few hours, the +HGA begins slewing back to the ground station, where it tracks upon arrival. The -HGA then slews back to the Elevation Park configuration where it began at the start of the plot.

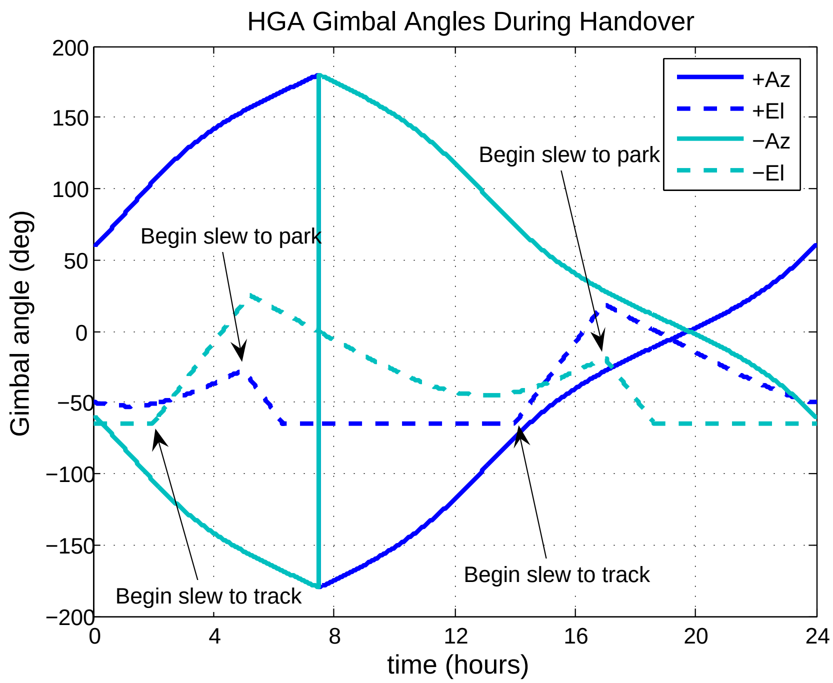

Figure 12: Gimbal Angles Over One Day During Handover Season

CONCLUSIONS

The science instruments on the SDO spacecraft require one of two High Gain Antennas to point at the ground station at all times in order to meet data download requirements. The instruments are very sensitive to jitter, and it was determined that stepping the HGA motor is enough to exceed the jitter limit. The HGA control algorithm is required to keep an antenna pointing at the ground station by allowing antenna handovers, while not exciting jitter.

An HGA algorithm was developed that contains three jitter mitigating techniques, each of which can be used for different jitter purposes. The first technique, adding a random step delay, eliminates step rates lying on jitter critical modes. Stagger stepping is used to minimize the constructive interaction of jitter from stepping the motors of different actuators. For the third jitter mitigating technique, the science instruments can request no motion from an antenna during times that their shutter is open.

The three methods of jitter mitigation will be included in the onboard flight software. After launch, the amount of jitter caused by the HGA motor stepping will be evaluated and the appropriate mitigation technique or techniques will be implemented to ensure a high data collection rate for the instruments.

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