

## Solar Dynamics Observatory High Gain Antenna Handover Planning<sup>\*</sup>

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### ABSTRACT

The Solar Dynamics Observatory (SDO) is planned to launch in early 2009 as a mission to study the solar variability and its impact on Earth. To best satisfy its science goal, SDO will fly in a geosynchronous orbit with an inclination of approximately 29 deg. The spacecraft attitude is designed so that the science instruments point directly at the Sun with high accuracy.

One of SDO's principal requirements is to obtain long periods of uninterrupted observations. The observations have an extremely high data volume so SDO must be in continuous contact with the ground during the observation periods. To maintain this contact, SDO is equipped with a pair of high gain antennas (HGAs) transmitting to a pair of ground antennas at the SDO ground station (SDOGS) located in White Sands, New Mexico. Either HGA can transmit to either SDOGS antenna. Neither HGA can be powered down.

During a portion of each year, each of the HGA beams will intersect with the SDO body for a portion of the orbit. The original SDO antenna contact plan used each HGA for the half of each year during which its beam would not intersect the spacecraft. No data would be lost except, possibly, when switching from one antenna to another.

After this plan was adopted, further analysis showed that daily handovers would be necessary for significant periods of the year. This unexpected need for extensive handovers necessitated that a handover design be developed to minimize the impact on the mission.

This antenna handover design was developed and successfully tested with simulated data using the slew rate limits from preliminary jitter analysis. Subsequent analysis provided significant revision of allowed rates requiring modification of the handover plans.

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## Introduction

The Solar Dynamics Observatory<sup>1</sup> (SDO) is expected to launch in the early part of 2009. It will produce a near continuous record of changes on the Sun. Changes will be observed from a high rate series of solar images. Because of this primary purpose, SDO will produce enormous quantities of data which will be sent from a pair of onboard high gain antennas (HGAs) to a pair of dedicated ground antennas designated the SDO Ground System (SDOGS). A crucial mission requirement is near continuous contact with SDOGS.

To maintain long periods of solar visibility and continuous contact with SDOGS, SDO will be placed in a geosynchronous orbit with an inclination of about 29 deg, near the latitude of SDOGS at White Sands. Its attitude will be maintained with the spacecraft X-axis (containing the boresights of the science instruments) pointed at the Sun.

The SDO HGAs are located on opposite sides of the spacecraft (see Figure 1) and referred to as the +Z- and -Z-antennas. Each is pointed using a pair of gimbals. The azimuth gimbals rotate about the body Z-axis and can perform a full, unrestricted rotation. The elevation gimbals rotate about an axis perpendicular to the body Z-axis, and parallel to the body Y-axis when the azimuth gimbal rotation is zero. Their hardware limits their rotation to a range of  $\pm 69$  deg.

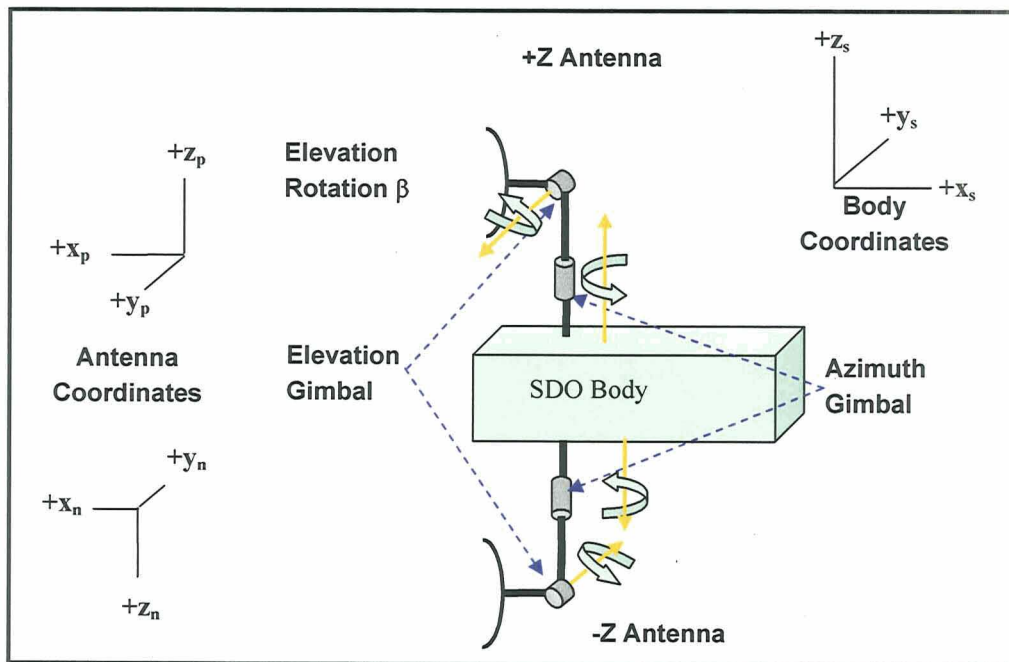


Figure 1. SDO Antenna Placement

This paper describes the mission planning algorithms that were developed for SDO to insure that the HGAs are able to continuously communicate with the ground without violating mission constraints. After this introduction, a general description of the constraints is presented along with a description of antenna handovers necessitated by

them. The constraint description is followed by a description of nominal handover scheduling and design. Next, a description of modifications of the handover design to allow calibration maneuvers to be executed during periods when handovers are required is presented. Finally, a brief summary of conclusions is included. Throughout the paper, descriptions are given of how new analysis resulted in modification of the requirements for handover design and how design options were introduced to accommodate the changing requirements.

### ***HGA Handovers and Constraints***

The gimbals hardware can point the HGAs anywhere in a region within 69 deg of the body XY plane but other constraints limit the permitted pointing directions. If the HGA beam strikes the solar arrays (on the +X end of the spacecraft) communication will be lost. If it strikes the science instruments, they may be damaged. Neither of these pointing directions is permitted.

The regions in which the HGAs are not permitted to point are represented by an antenna mask consisting of azimuth/elevation angle pairs where antenna interference will occur. The +Z-antenna mask is shown in Fig. 2 with the restricted areas shaded. The -Z antenna mask is similar. The azimuth and elevation angles for both antennas are defined in such a way that each antenna approaches the body (and its mask) at large positive elevation angles. The primary gimbals constraint is to avoid the antenna masks and therefore to avoid large positive elevation angles.

The path of required azimuth and elevation angles needed to point at SDOGS during a single orbit can be represented as a trajectory in an azimuth/elevation plot (see blue line in Figure 2). For a constant orbit, the trajectory of the antenna beam depends only on attitude, but because SDO always points its X-axis towards the Sun, its attitude changes with season.

In early mission planning it was thought that the change of trajectory through the year would require use of one antenna for half of the year and the other for the rest of the year. Twice a year handovers from one antenna to the other would be required. As analysis was refined it became clear that there were significant periods (about 70 days long) in the spring and fall when neither antenna could track SDOGS for an entire orbit without interference. The period during which handovers are required is called "handover season." During handover season, handovers are needed twice each day in order to avoid intersection of the two antennas' beams with their mask. A handover consists of moving one antenna from a parked position to tracking SDOGS followed by moving the other antenna from SDOGS to its parked position.

With such frequent handovers required the impact of the handovers had to be minimized and a number of constraints were imposed:

1. The antenna beams must avoid the antenna masks
2. The antenna slew rates must be less than about 30 deg/hour to minimize spacecraft jitter, which is produced by the movement of the antennas<sup>2,3</sup>.
3. The antenna beam must spend as little time as possible impinging on the Earth to minimize interference with ground electronics.

4. The antenna beam must intersect with the Clarke belt<sup>†</sup> as little as possible to minimize irradiation of geostationary satellites.
5. Between handovers, the antenna that does not track must be parked at an orientation that does not impinge on the antenna masks or intersect the Clarke belt.
6. In the times between handover seasons, when one of the antennas continuously tracks SDOGS, the other antenna must be continuously parked at an orientation that does not impinge on the antenna masks or intersect the Clarke belt

The problem addressed by this paper is the design of handover sequences that best meet the mission constraints. Modified handover sequences were also required during regularly scheduled instrument calibration maneuvers.

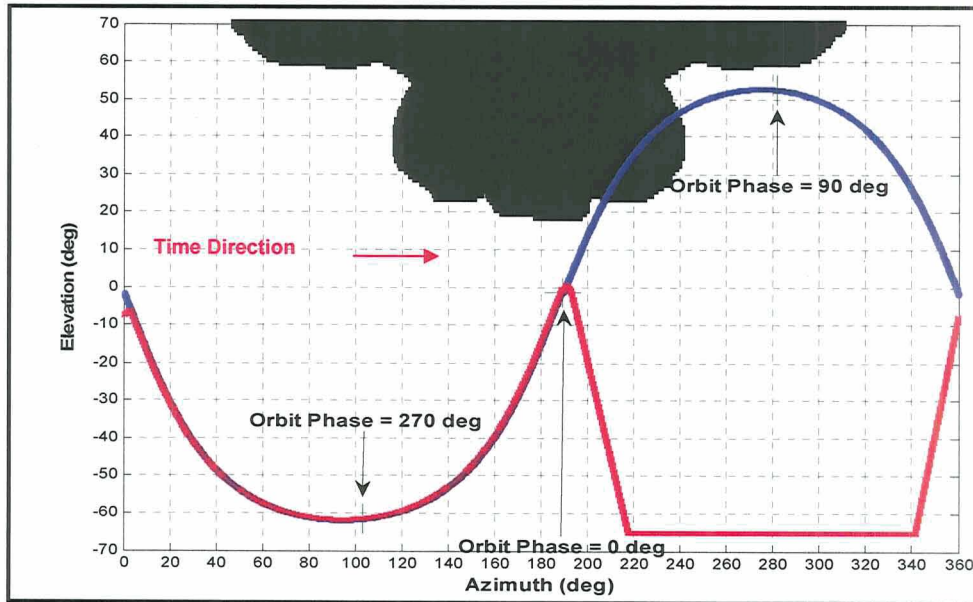


Figure 2. +Z-antenna Mask With Trajectories (blue = without handover, red = with handover) on 21 March 2009

### Basic Handover Design

In addition to the antenna mask, Figure 2 shows a trajectory (blue) computed for 21 March, 2009. As indicated, azimuth increases with time. The handover design consists of definition trajectories for each antenna that best satisfy the mission requirements. The trajectories are specified by selection of a park position as well as times, rates, and directions of antenna movements between SDOGS and the park position.

From Figure 2 it is clear that the maximum elevation of the +Z-antenna occurs near orbit phase of 90 degrees. It varies little from this orbit phase through the year. Similarly, the

<sup>†</sup> The Clarke belt designates the region in space occupied by geostationary satellites. For the purposes of this paper it is a belt, approximately 42000 km from the Earth center, and extending 15 deg on either side of the equatorial plane.

maximum elevation of the  $-Z$ -antenna always occurs near an orbit phase of 270 deg. Because handovers near orbit phases of zero and 180 deg will avoid positive gimbal angles and therefore avoid the masks, the optimum handover times must occur near the orbit nodes. The optimum handover from tracking with the  $-Z$ -antenna to tracking with the  $+Z$ -antenna should occur near the ascending node (orbit phase of 0 degrees). The optimum handover needed to return to tracking with the  $-Z$ -antenna should occur near the descending node (orbit phase of 180 deg). Selection of these times always avoids the mask. The trajectory of the  $+Z$ -antenna in such a handover is shown as a red line in Figure 2.

Although handovers centered at the orbit nodes avoid the antenna masks, they may not be optimum in terms of gimbal rates, impingement on the Earth, and impingement on the Clarke belt. When an antenna is tracking SDOGS the beam obviously intersects the Earth and therefore can not impinge on the Clarke belt.

Antenna park positions must be selected to avoid both the antenna masks and the Clarke belt. An elevation angle less than about 15 deg will always avoid the masks.

Since it is at geosynchronous altitude with an inclination of about 29 deg, SDO is within the Clarke belt for a large portion of each orbit. Therefore, over a considerable range of azimuth angles, the parked antenna beam intersects with the Clarke belt at any elevation. To avoid the Clarke belt while parked, both the azimuth and the elevation must be specified.

If the antenna beam is in the same plane as the spacecraft, the Earth, and the Earth's axis and the beam is directed on the side towards the Earth, then the range of elevation angles for which an antenna beam avoids the Clarke belt is maximized. It is convenient to park the antenna at a variable azimuth selected as the same azimuth that would track SDOGS. This choice of azimuth also minimizes the time needed for a slew from park to tracking.

The shortest path from tracking to park continues to move the azimuth gimbal as if it were tracking and moves the elevation gimbal to the park position. It is possible to insert an intermediate point in the path to maximize the shielding of the Clarke belt by the Earth. The capability of using an intermediate point was also desirable because it is possible that, if the antenna beam path across the Earth nears critical ground antenna locations, modified paths might be required. The intermediate point that maximizes shielding is one at which the antenna beam is tangent to the Earth and passes through the Earth's spin axis. This geometry is shown in Figure 3.

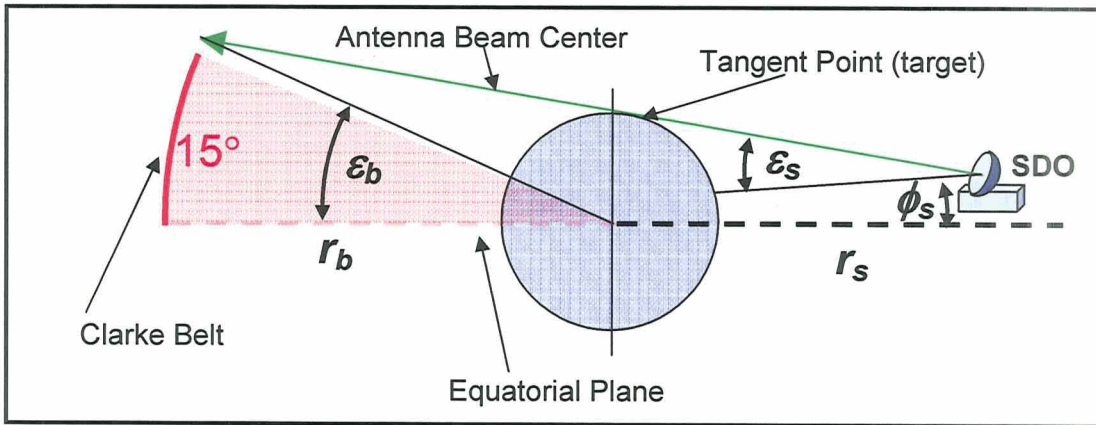


Figure 3 Geometry of Shielding of Clarke Belt by Earth

Clearly the position of the target depends on SDO's elevation,  $\phi_s$ , at the time the beam leaves the Earth. This time depends on the both the gimballed rate and on the angle,  $\epsilon_s$ , that the beam traverses between SDOGS and the tangent point. An iterative approach was developed to find the time and position of the beams intersection with the Earth limb given a specified maximum gimballed rate.

To continue avoiding the Clarke belt after the beam leaves the Earth the beam elevation must increase faster than the spacecraft elevation. Since SDO traversed about 29 deg in a quarter-orbit (6 hours) the gimballed elevation rate must be greater than about 5 deg/hour which is easily achieved.

Figures 4 through 7 provide output information for a typical handover starting with the +Z-antenna tracking and the -Z-antenna parked and ending with the functions reversed.

Figure 4 shows the gimballed angles vs. time. The light lines in this figure represent the gimballed angles that would be necessary to track SDOGS were there no handover and the heavier lines the gimballed angles with the handovers.

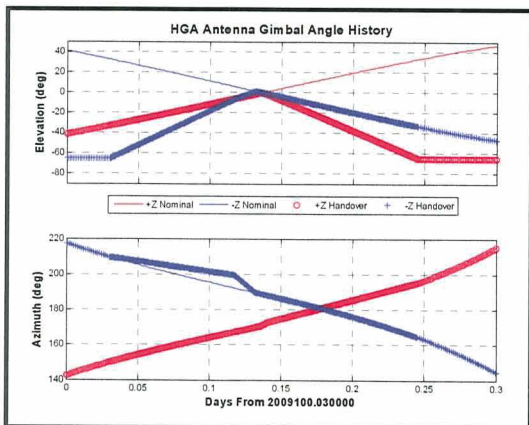


Figure 4. Gimbal Angles for Typical Handover

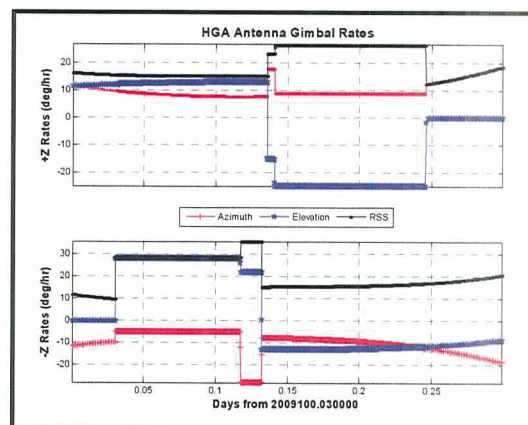


Figure 5. Antenna Rates for Typical Handover

Figure 5 shows the gimbal rates for the +Z- and -Z-antennas. Separate lines are plotted for the azimuth gimbal rate, the elevation gimbal rate, and the root-sum-square (RSS) of these.

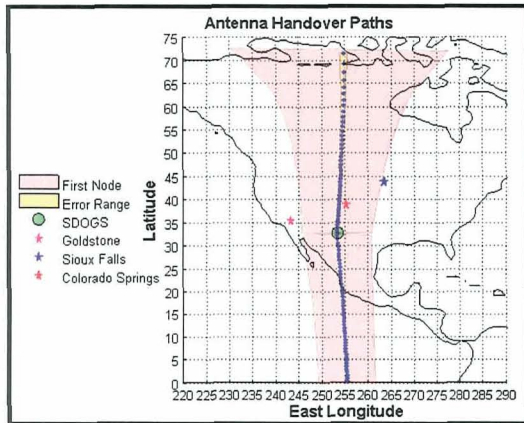


Figure 6. Antenna Beam Path over Earth

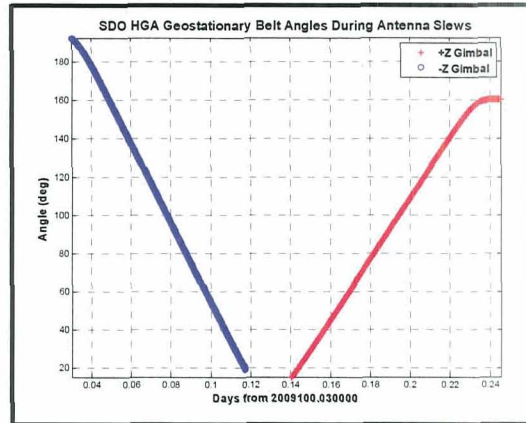


Figure 7. Clarke Belt Intersection Angle

Figure 6 shows the path of the beams over the Earth during a handover. Also shown on this plot is the range of paths that are possible due to errors in the gimbal alignment knowledge (Error Range), the path of the entire beam within an angle corresponding to the antenna radio frequency (RF) node (First Node), the location of SDOGS, and the location of other ground antenna stations that might be susceptible to interference (at Goldstone, Sioux Falls, and Colorado Springs).

Figure 7 shows angles from the Earth center to the point at which beam intersects with a sphere at geosynchronous altitude ( $\epsilon_b$  in Figure 3).

After the basic handover design was established analysis brought into doubt the ability to meet jitter requirements during handovers, even at low gimbal rates. In order to minimize the impact of jitter requirement violation on the mission, two options were investigated. The first option was to minimize the handover time while keeping the basic handover design by changing the elevation angle at which an antenna would be parked between handovers. The second option was to move directly between tracking and park positions at the highest rates the gimbals are capable of moving—degrading data quality but decreasing the degradation period. For this second option, both antennas slew simultaneously and the total handover time is only a few minutes.

Both of these options have been implemented in SDO ground support software. After launch, when spacecraft jitter is observed and compared to predictions, a decision will be made of which option will be used in normal operations. The ground software includes all of the optional algorithms and is ready for use.

## ***Handover Design During Calibration Maneuvers***

The SDO science instruments require attitude maneuvers for calibration and their calibration must be repeated regularly through the mission life. Some of the calibration related attitude maneuvers are small enough so that they will not induce HGA interference. Two of them have the potential to induce interference if they are not coordinated with the handover schedule. These are a roll maneuver used to calibrate the Helioseismic and Magnetic Imager (HMI) and the Atmospheric Imaging Assembly (AIA) and a “Cruciform” maneuver used to calibrate the Extreme Ultraviolet Variability Experiment (EVE).

Calibration maneuvers have less impact on mission objectives if they are performed during periods when continuous Sun observations are not possible (due to the spacecraft passing through the Earth’s shadow—eclipse season). Eclipse seasons are shorter than, and occur within, handover seasons.

The required maneuvers have the following characteristics:

- HMI/AIA Roll Maneuver
  - Rotation about the roll-axis (body X)
  - Roll can be in either direction but can not be reversed during the maneuver
  - 360 degree roll in 22.5 degree steps<sup>‡</sup>
  - 15 minute dwell times between steps for calibration
  - About 10 minutes for each 22.5 degree roll step
  - 22.5 degree roll step done in two parts with the rate going to zero momentarily between them
  - About 7 hours duration
  - Twice a year (near eclipse season preferred)
- EVE Cruciform Maneuver
  - Rotations about the pitch-axis (body Y) and yaw-axis (body Z) separately
  - Maximum of 2.5 degree offset from nominal attitude
  - Small steps offset pitch between –maximum and + maximum offset at yaw of 0
  - Small steps offset yaw between –maximum and + maximum offset at pitch of 0
  - Total of about 9 hours duration
  - Repeated four times a year (twice near eclipse season preferred)

The times of handover seasons, eclipse seasons, and nominal calibration maneuvers are shown for 2009 in Figure 8.

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<sup>‡</sup> The 22.5 degree roll steps may be subdivided into smaller steps if desired



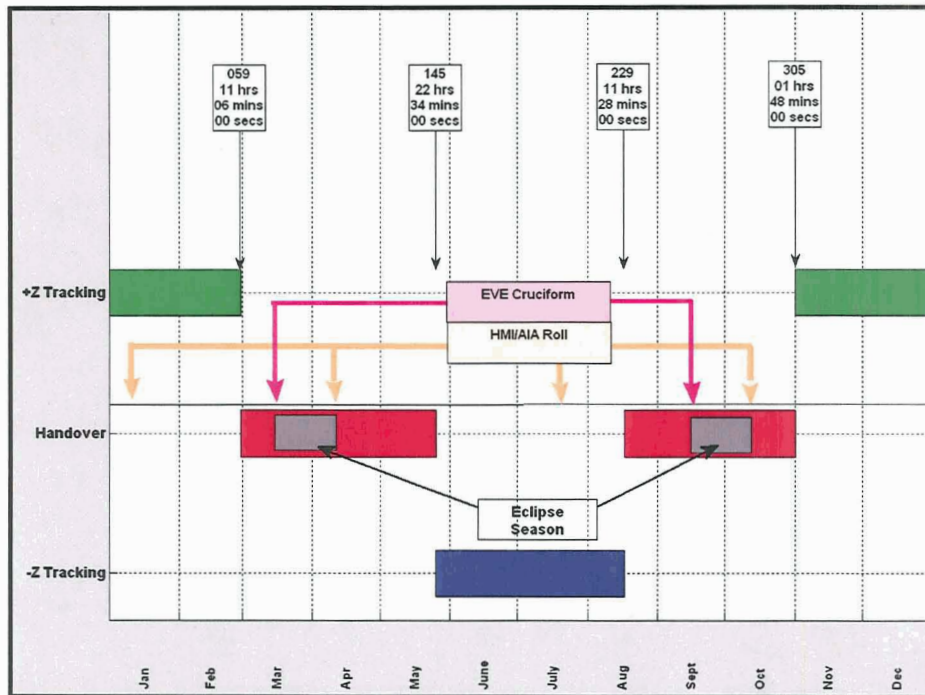


Figure 8. Handover Seasons, Eclipse Seasons, and Approximate Calibration Times in 2009

Changing the spacecraft attitude changes the antenna trajectory (as in Figure 2). Attitude changes that move the antenna in one direction can be visualized as a corresponding motion of the mask in the opposite direction while keeping the trajectory fixed. For a Yaw maneuver the mask would be moved from side to side, for a pitch maneuver up and down, and for a roll maneuver rotating it about the coordinate center.

The danger of interference with the mask is large near the time of maximum gimbal elevation angle because, at that time, the trajectory is closest to the mask. It is clear that if EVE cruciform maneuver is centered about the time in the trajectory when minimum gimbal angle occurs that a movement of the trajectory of 2.5 degrees will not intersect the mask.

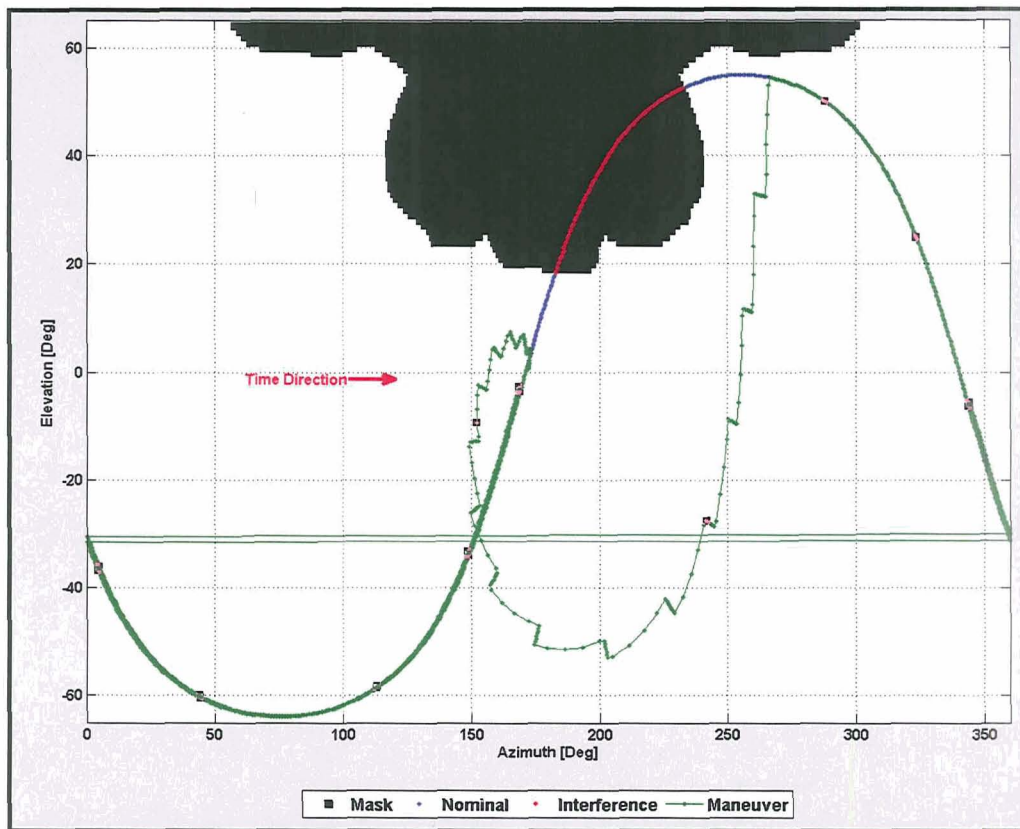
Pitch movement primarily changes the elevation of the trajectory relative to the mask. Specifying the maneuver so that the maximum pitch offset occurs at the time of minimum elevation angle provides a margin of safety. In non-handover season, since a single antenna is tracking, the maneuver will be over before the antenna approaches the danger region (maximum elevation angle) which occurs 12 hours after the maneuver center (minimum elevation angle).

The gimbal angles necessary to track SDOGS are approximately out of phase for the two antennas. When one antenna would require a maximum gimbal angle to track, the other would be near a required minimum gimbal angle. During handover season, specifying the center of the EVE cruciform maneuvers at the time of minimum gimbal angle of a tracking antenna ensures that when the handover occurs (about 6 hours after minimum elevation) the other antenna is well past its maximum gimbal elevation and moving towards its minimum. Therefore, even during handover season, centering the EVE

cruciform maneuver near a time of minimum elevation for a tracking antenna prevents mask interference.

Design of the HMI/AIA Roll Maneuver is somewhat more complicated. Examination of Figure 1 shows that at 180 degrees roll, the orientations of the two antennas in inertial space are interchanged. Thus a 180 degree roll has a similar effect to a handover. Although it would be possible on some days to schedule an HMI/AIA Roll Maneuver between handovers, it is more general, safer, and easier, to replace a handover with the roll maneuver.

The center of the roll maneuver (180 degrees roll) is selected to be the center of the interference time (if there were no handover) for an antenna. This provides 4 choices of maneuvers: +Z-antenna with positive roll, +Z-antenna with negative roll, -Z-antenna with positive roll, and -Z-antenna with negative roll. An example of the gimbals trajectory for one of these is shown in Figure 9 along with the trajectory that would have caused interference had no roll maneuver (or no handover) been commanded.



**Figure 9. Trajectory for the +Z-antenna Gimbals With and Without an HMI/AIA Roll Calibration Maneuver During Handover Season**

Although the HMI/AIA roll maneuver is nominally done during eclipse season and therefore during handover season, it is conceivable that a maneuver might be needed during non-handover season. If such a maneuver is required its timing must be specified so that no new interference is produced. Non-handover season is the time when one of the antennas can continuously track SDOGS without interference while the other has

periodic interference. At a roll of 180 degrees, the tracking antenna will have interference at some times in the orbit.

To avoid introduction of interference the roll maneuver is centered at the time when the elevation would be maximum were there no maneuver. Since the roll decreases the elevation angle centering the maneuver at this time avoids interference. The trajectory for this case is shown in Figure 10.

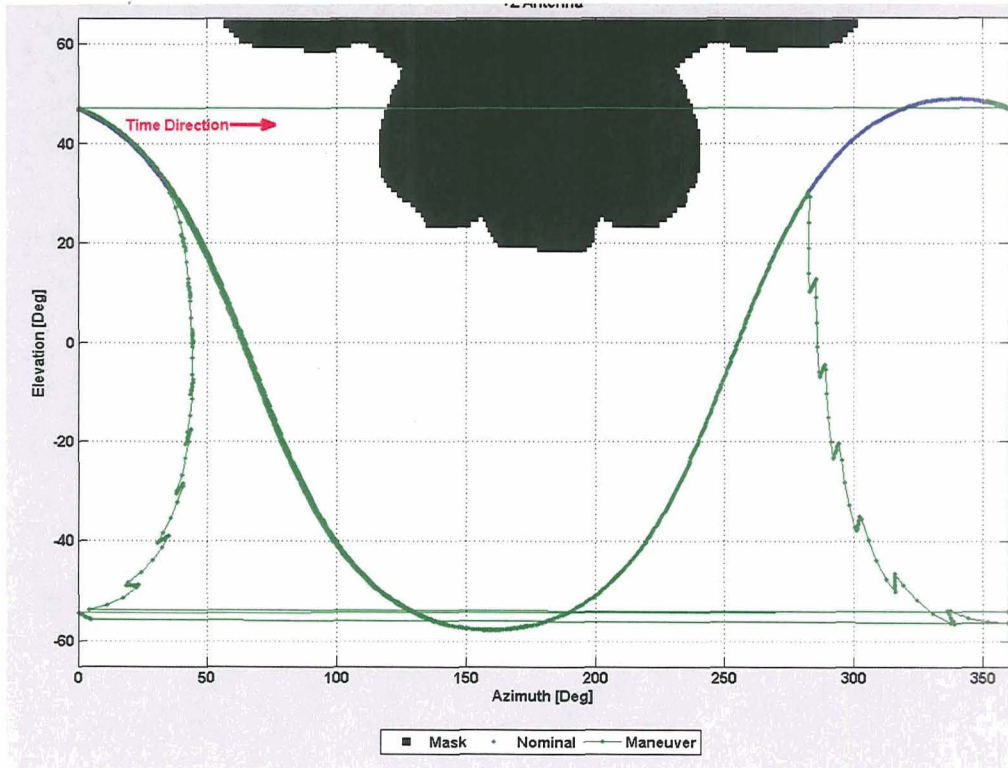


Figure 10. Trajectory for the +Z-antenna Gimbals With and Without an HMI/AIA Roll Calibration Maneuver During Non-Handover Season

## Conclusions

Continuously pointing the SDO High Gain Antennas at the ground station without violating mission constraints is a necessary and non-trivial function. Tools have been designed and implemented to maintain communications in a variety of situations to provide maximum transmission of high quality data. When SDO is commissioned, these tools will be important in ensuring the success of the mission.

## References

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<sup>2</sup> Bourkland, Kristin L., Liu, Kuo-Chia, and Blaurock, Carl “A Jitter-Mitigating High Gain Antenna Pointing Algorithm for the Solar Dynamics Observatory”, 20<sup>th</sup> International Symposium on Spaceflight Dynamics, Annapolis, Maryland, September 2007

<sup>3</sup> Liu, Kuo-Chia, “Jitter Test Program and On-Orbit Mitigation Strategies for Solar Dynamic Observatory, 20<sup>th</sup> International Symposium on Spaceflight Dynamics, Annapolis, Maryland, September 2007