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# MESSENGER SPACECRAFT POINTING PERFORMANCE DURING THE MISSION'S MERCURY ORBITAL PHASE

**Robin M. Vaughan**[*], **Daniel J. O'Shaughnessy**[†], **and Sarah H. Flanigan**[‡]

A number of attitude changes are executed daily by the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft in orbit about Mercury to collect and return science measurements to Earth. Prior to orbit insertion in March 2011, several analyses verified that the guidance and control system is capable of executing the orbital attitude profiles within the required accuracy. This paper compares the desired attitude profiles with profiles obtained from ground simulations and with attitude telemetry from a selected week in orbit in May 2011. The ground software tools are shown to match each other and actual spacecraft attitude to within a few tenths of a degree, which is sufficient for science planning purposes. Attitude changes introduced by spacecraft ephemeris model updates and time biasing of attitude and instrument commands in each sequence load are shown to maintain the intended planet-relative geometry without introducing large deviations in turn durations or causing violations of attitude constraints. These analyses provide confidence that the ground simulations performed throughout the orbit sequence development process are adequate to ensure safe execution of the sequences by the spacecraft.

## INTRODUCTION

The MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft was launched from Kennedy Space Center on August 3, 2004. As part of NASA's Discovery program, the spacecraft began its study of the planet Mercury with three flybys conducted in 2008 and 2009. The spacecraft is now conducting a one-year survey of the planet after its insertion into orbit about Mercury in March 2011.[1] The MESSENGER spacecraft configuration and the locations of some of the main engineering components and science instruments are shown in Figure 1. MESSENGER carries a diverse suite of miniaturized science instruments to globally characterize the planet.[1] Four of the science instruments are co-boresighted and mounted inside the launch vehicle adapter ring: two imaging cameras (Mercury Dual Imaging System – MDIS), a laser altimeter (Mercury Laser Altimeter – MLA), ultraviolet to near-infrared spectrometers (Mercury Atmospheric and Surface Composition Spectrometer - MASCS), and an X-Ray Spectrometer (XRS). MDIS consists of a narrow-angle camera (NAC) and a wide-angle camera

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[*] Principal Professional Staff, The Johns Hopkins University Applied Physics Laboratory, 11100 Johns Hopkins Road, Laurel, MD, 20723.

[†] Guidance and Control Lead Engineer and Principal Professional Staff, The Johns Hopkins University Applied Physics Laboratory, 11100 Johns Hopkins Road, Laurel, MD, 20723.

[‡] Associate Professional Staff, The Johns Hopkins University Applied Physics Laboratory, 11100 Johns Hopkins Road, Laurel, MD, 20723.

(WAC) that are both mounted on a pivoted platform that extends their observing range in orbit. Other instruments located outside the adapter ring are a Gamma-Ray and Neutron Spectrometer (GRNS), an Energetic Particle and Plasma Spectrometer (EPPS), and a Magnetometer (MAG). Several antennas are used to communicate with Earth and for radio science. The seven instruments plus radio science each require different planet-relative viewing conditions to obtain the measurements that collectively are meeting the primary mission science requirements. Returning these measurements requires daily periods when the phased-array antennas are pointed at Earth.

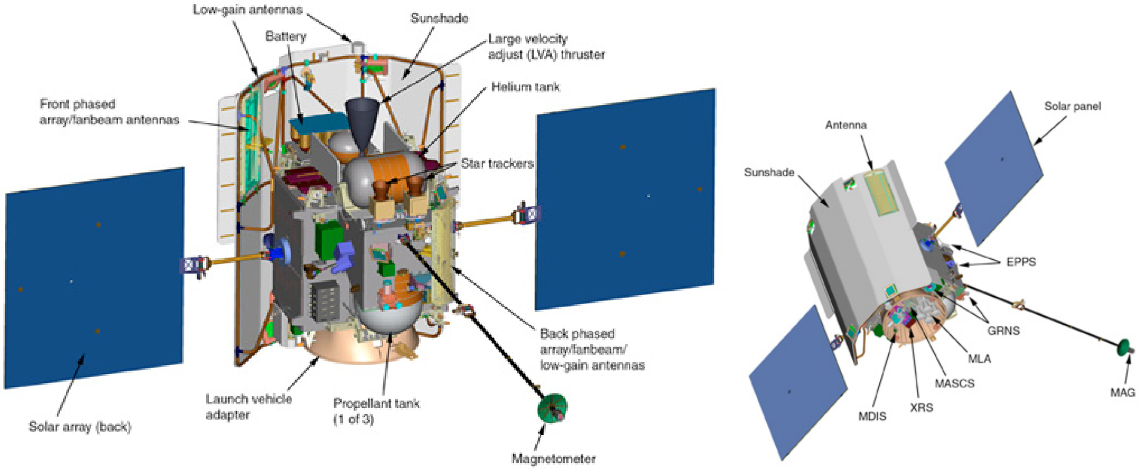

**Figure 1. MESSENGER Spacecraft Components and Science Instruments.**

The attitude profiles for science observations at the three Mercury flybys were designed by a small team of guidance and control (G&C) analysts working closely with the science teams.[2] The highest density and complexity of attitude commanding generally occurred within 24 hours centered on the time of closest approach to the planet. Although these designs served as a starting point for orbital observations, the manual development process was clearly not sustainable given that the same intense level of activity is needed continuously for the entire year. A software tool called SciBox[3] has been developed to generate the coordinated sets of spacecraft attitude and instrument commands that implement the diverse geometries required for the orbital science observations while satisfying the attitude constraints for spacecraft thermal safety. Modeling of spacecraft attitude dynamics in SciBox has been limited to approximate formulas in order to minimize the amount of computer time needed to generate the observation schedule over the full year in orbit. Results are presented for a set of analyses and tests that have been conducted to verify that the SciBox modeling is sufficient and that the spacecraft's G&C system is capable of executing the attitude profiles designed by SciBox within the required accuracy. Comparisons are made between predicted spacecraft attitude profiles from high-fidelity simulations or from flight telemetry and the profiles generated by SciBox. The operation of the spacecraft's G&C system is first summarized to provide the background necessary to better interpret these comparisons. The summary places emphasis on the guidance functions that interface with pointing commands generated by SciBox to compute the desired spacecraft attitude.

## MESSENGER GUIDANCE AND CONTROL SYSTEM OVERVIEW

The MESSENGER G&C system maintains a three-axis-stabilized spacecraft using reaction wheels as the primary actuators for attitude control.[4] MESSENGER also carries 16 monopropellant thrusters and one large bi-propellant main engine for trajectory corrections, attitude control (nominally during burns only), and momentum offloads. Star trackers and an inertial measurement unit containing four gyros provide knowledge of inertial attitude and rotation rates. Sun sensors are used to provide Sun-relative attitude knowledge as a backup to the inertial sensors for spacecraft safety. Software algorithms run in the main processor to coordinate data processing and commanding of sensors and actuators. The software also controls the orientation of the two solar panels, electronic steering for the two high-gain phased-array antennas, and, optionally, pivot positioning for the MDIS cameras. An additional interface with the MLA provides the range and slant angle to the planet's surface used to configure the instrument but does not involve any active mechanical or electronic steering.

## Coordinate Systems, Angle Conventions, and Attitude Constraints

The two primary coordinate systems used by the G&C system are the Earth mean equator and equinox of J2000 (EME2000) inertial reference frame and the MESSENGER spacecraft body frame illustrated in Figure 2. Spacecraft attitude is specified as the orientation of the body frame relative to the inertial reference frame. Azimuth and elevation angles relative to the body frame axes are also shown in Figure 2 and can be used to define directions to celestial objects as seen from the spacecraft. The –Y axis points out away from the large sunshade that shields the spacecraft components from direct exposure to the Sun. The shade has been sized to allow small deviations from direct Sun pointing when needed for science observations or engineering activities. The region of allowable deviation from direct Sun pointing is called the Sun keep-in (SKI) zone. The SKI bounds are given as minimum and maximum azimuth and elevation angles, placing the –Y axis at the center of the SKI zone. The default SKI bounds used by the guidance software are ±10º in azimuth and ±12º in elevation. This area is called the "inner" SKI zone and is the zone enforced when computing commanded attitude. The –Z axis points out from the top deck of the spacecraft where the battery, star trackers, and smaller propulsion tanks are located. When the spacecraft is over the sunlit northern hemisphere of Mercury, around its orbital periapse, the top deck must point away from the surface of Mercury to protect the battery and other components from radiation reflected off the planet's surface. This second attitude constraint, called the "hot pole" keep-out (HPKO) zone, is satisfied by keeping the angle between the –Z axis and the direction to the center of Mercury (nadir) greater than 90º. The boresights of the two MASCS spectrometers, MLA, XRS, and the two MDIS cameras at the 0º pivot position are all nearly aligned with the +Z axis. Therefore, the pointing for most science observations can be viewed as aligning the +Z axis with some target feature of interest either on the surface or around the limb of Mercury. All pointing commands must be designed such that spacecraft attitude remains within the bounds of the SKI and HPKO constraint zones at all times. The SKI constraint is generally the more restrictive, and it is often the case that the commanded attitude will be on the boundary of the SKI zone to obtain the best possible orientation for the science measurements.

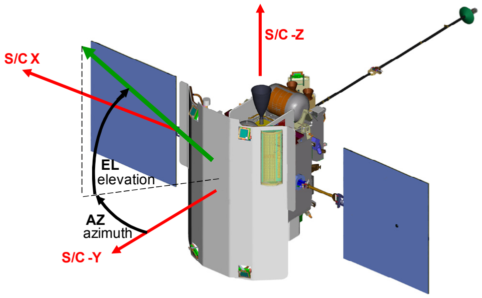

**Figure 2. MESSENGER Spacecraft (S/C) Body Frame and Azimuth and Elevation Angle Conventions.**

## Guidance Functions

The MESSENGER spacecraft guidance functions include computation of the desired (or commanded) spacecraft attitude, maintaining knowledge of spacecraft and celestial body positions and velocities, and applying attitude constraints. The desired attitude and rotation rate for each science or engineering activity is specified by setting a basic pointing command and, optionally, superimposing a scan pattern command. These two commands specify the unconstrained pointing, and additional commands determine whether to apply the SKI and HPKO constraints. Desired (or commanded) spacecraft attitude and rate are computed using a set of parameter values specified for the pointing option and scan pattern. All of the pointing options share a common framework in which four vectors are used to define the desired attitude. Two of these vectors are specified in the spacecraft body frame, and two must lie in an external frame and are used as the targets for the body axes. For an unconstrained attitude, the primary body and external target vectors are aligned exactly and the secondary external target vector is placed in the plane containing the primary and secondary body vectors. The secondary vectors essentially define a "roll" about the primary target direction that completes the attitude specification relative to the inertial reference frame. The SKI and HPKO constraints are always applied during the orbital phase including during eclipse periods. The guidance software checks whether the unconstrained commanded attitude is within the constraint limits and adjusts that attitude to lie on the closest point on the SKI or HPKO boundaries if it violates the constraint.

Ten pointing options are available to point antennas at the Earth, point instruments at or near various celestial bodies, or align thrusters with a target direction for velocity change ($\Delta V$).[5] Pointing targets include directions in the EME2000 inertial frame specified as vectors or right ascension and declination angles; directions from the spacecraft to the Sun, Earth, or a target planet; directions in the target planet body-fixed frame specified as vectors or as latitudes, longitudes, and heights; directions in a local vertical, local horizontal (LVLH) frame given as azimuth and elevation angles; or points on the target planet that optimize illumination geometry. The target planet is obviously set to Mercury now that the spacecraft is in orbit. Scan patterns combining periods of fixed-rate rotations about specified axes with pauses can be added to the base pointing option. These patterns are used to design mosaics or continuous scans that enable target motion in an instrument field of view (FOV). Motions can be rotations about axes in the spacecraft body frame, the inertial frame, or the LVLH frame or translations along inertial axes. Each axis may have a different combination of rates, pauses, and motion reversals. The guidance software enforces certain compatibility restrictions between the scan frame and the base pointing option.

Ephemeris models and models for the shape, size, and rotation of a target planet are available to the guidance system when needed to formulate the commanded attitude. The guidance block continuously interpolates on-board ephemeris models to obtain the position and velocity of the Sun, Earth, Mercury (the target planet), and the spacecraft, all referenced to the solar system barycenter. The precise ephemeris models used for science pointing are expressed as Chebyshev polynomials. A simple linear conversion of spacecraft time to terrestrial dynamic time (TDT) is performed to extract the necessary positions and velocities for the spacecraft or the celestial body. The precise spacecraft ephemeris spans are updated weekly by the operations team using the most recent trajectory solution delivered by the navigation team. These spacecraft ephemeris fits are constructed to provide the accuracy necessary for science pointing over the entire orbit. Additional G&C flight software parameters define the Mercury body-fixed frame orientation relative to the inertial frame and a triaxial ellipsoid approximation of Mercury's shape and size. The values for these parameters are specified by the science team.

In addition to applying the SKI and HPKO constraints to the commanded attitude, the guidance software monitors estimated spacecraft attitude for violations of either constraint. The guidance constraint monitor checks whether the estimated attitude is within a "middle" SKI zone whose bounds are 1–2° outside those of the inner zone or within the HPKO zone. If a violation is detected, the system automatically overrides the commanded attitude and performs a turn back to a safe attitude. The autonomy software is requested to perform a demotion to a safe mode. A third "outer" SKI zone with bounds at ±15° in azimuth and elevation is used by spacecraft autonomy software.* If the spacecraft attitude places the direction to the Sun outside this outer SKI zone for longer than a specified duration, the flight processor is rebooted and demotion to a safe mode is performed. The sequence command load then current is terminated when the spacecraft is placed in one of its safe modes.

## SCIBOX POINTING SCENARIOS FOR ORBIT SEQUENCE LOADS

SciBox is a sophisticated tool designed to automate the steps of mapping the mission science objectives for types of measurements and coverage of the planet surface and surrounding environment into the series of distinct observations to be made during each weekly sequence load. SciBox includes algorithms developed in collaboration with the science teams that optimize the set of future observations based on knowledge of the required and achievable geometries, prioritization of measurement types, knowledge of previously obtained measurements extracted from telemetry received over prior orbital loads, and remaining coverage needed to meet overall mission science requirements. It handles different aspects of resource management such as the amount of data stored on the solid-state recorder (SSR) and allowable instrument power consumption during long eclipse periods. Three weeks before a sequence load will be executed, SciBox is run to generate the preliminary versions of the sequences of instrument and spacecraft attitude commands for that week using the latest available spacecraft trajectory solution. During the remaining weeks before the load is uplinked to the spacecraft and executed, these command sequences are checked (and possibly modified) by the science, engineering, and mission operations teams to ensure appropriate science value and spacecraft health and safety.

Among the many capabilities of SciBox, the primary one of interest for G&C purposes is the determination of the necessary sequence of spacecraft orientations that allows the different science instruments to collect their measurements. The four remote-sensing instruments located inside the adapter ring – MDIS, MLA, MASCS, and XRS – are the ones that make use of the largest variety of orientations to obtain their measurements. The Gamma-Ray Spectrometer (GRS) on the GRNS instrument occasionally also requires a specific spacecraft orientation for its observations. MDIS, MLA, XRS, and the two MASCS spectrometers will point at locations on the planet surface. The Ultraviolet and Visible Spectrometer of MASCS is also pointed to view the exosphere around the planet limb. The fields and particles instruments (EPPS, the GRNS Neutron Spectrometer, and MAG) are generally able to collect useful data at any spacecraft orientation. The only other attitude driver for SciBox is the need to periodically point one of the phased-array antennas at Earth to downlink the science data.

SciBox makes use of the pointing options that are available in the G&C flight software to implement the spacecraft orientation needed for each type of science activity. Of the eight specialized G&C pointing options that utilize pre-specified values for some of the primary and second-

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* For convenience, the inner SKI zone will be referred to simply as the SKI zone in the remainder of the paper. Science observations must be designed such that spacecraft attitude remains within this zone at all times.

ary vector sets, SciBox uses only three as shown in the first rows of Table 1: downlink, nadir, and a generic limb scan. The pointing option used most frequently by SciBox is the generic or "user-defined" option under which the primary and secondary vectors must each be individually specified to define the desired orientation. The 10 SciBox pointing scenarios that are commanded using pointing option 1 along with their reference vectors and the science activities that they support are listed in the bottom rows of Table 1. Scan patterns are explicitly added and the scan capability of the generic limb scan pointing option is activated by SciBox to perform some of the MASCS exosphere observations. SciBox does not make use of the G&C pointing options that compute MDIS pivot angle along with spacecraft attitude. The MDIS pivot position is always commanded separately from the spacecraft attitude although the timing of the pivot and attitude commands is obviously coordinated to ensure that the camera boresight points in the desired direction for each image.

**Table 1. Science Activities and SciBox Pointing Scenarios for Orbit Loads**

| Science Activities* | SciBox Pointing Scenario | Description (Primary and Secondary Pointing Vectors) | Scan Included? |
|---|---|---|---|
| n/a | Downlink | Unit vector within SKI zone (usually –Y axis) along Sun line<br>Earth line in –X,–Y or +X,+Y quadrant (FOVs of phased-array antennas) | No |
| MLA_NADIR<br>GRS_Nadir<br>MDIS_BASEMAP<br>MDIS_COLOR<br>MDSTargeting<br>XRS_DAYSIDE | Nadir | +Z to nadir (direction to Mercury center)<br>-Y along Sun line | No |
| UVSLimbScan | Radial Limb Stare<br>Radial Limb Scan | +Z at a specified height from Mercury limb along a specified radius out from Mercury center<br>–Y along Sun line | No<br>Move along the radius between two heights |
| UVSExoStare | Nominal | –Y along Sun line<br>+Z to nadir | No |
| MDIS_ThermalCal<br>UVSExoScan | NominalRoll | –Y along Sun line<br>+Z to nadir | Rotate at fixed rate about –Y axis |
| MDIS_LimbImaging<br>MDIS_PIVOTCAL<br>MDIS_STEREO<br>MLA_OFFNADIR | Off-Nadir | Vector in XZ plane to nadir (vector offset from +Z axis toward + or –X axis by specified angle)<br>-Y along Sun line | No |
| XRS_NIGHTSIDE | Specular | +Z at point on Mercury surface that maximizes illumination angles<br>–Y along Sun line | No |

| | | | |
|---|---|---|---|
| MDIS_SouthPole1&2 | LocalTime<br>SurfaceTargeting | +Z to specified latitude and longitude on planet surface<br>–Y along Sun line | No |
| MDIS_PIVOTCAL<br>MDIS_ThermalCal<br>MDSTargeting<br>UVSStarCal | AimControl | +Z to inertial unit vector or surface latitude and longitude<br>UVVS boresight to star (usually Sirius)<br>–Y to Sun or +Z to inertial direction | No |
| UVSPolarScan<br>VIRSStarCal | AimControl<br>Scanning | VIRS boresight to star (usually Sirius) or Mercury pole<br>–Y to Sun | Rotate at fixed rates about X and Y axes |
| MDSTargeting<br>UVSTargeting<br>VIRPhotometry<br>VIRTargeting | SurfaceTracking | UVVS,VIRS or MDIS boresight to specified latitude and longitude on planet surface<br>–Y to Sun | No |
| VIRTargeting | SurfaceDrifting | Body vector at specified offset from +Z to nadir<br>Body vector at specified offset from –Y to Sun | No |
| XRSCasACal | XRSCasACal | +Z to Cassiopeia A<br>–Y to Sun | No |

(*Note: The activity names are shown exactly as they are used in SciBox, including changes in case and use of underscores between words. MDS and MDIS in the activity names indicate that the observations are performed with the MDIS instrument. VIR and VIRS indicate that the observations are performed with the Visual and Infrared Spectrograph and UVS or UVVS indicate that the observations are performed with the Ultraviolet and Visible Spectrometer; both VIRS and UVVS are part of the MASCS instrument.)

The spacecraft completes one orbit about Mercury in approximately 12 hours, with a nominal periapse altitude of 200 km and apoapse altitude of 15,000 km. A typical SciBox orbit profile has the longest periods spent at the nadir, specular, and downlink pointing scenarios. A downlink window of 7–8 hours duration is scheduled every other orbit near, but not centered around, orbital apoapse. When not used for downlink, the time around apoapse is spent at nadir or specular pointing for XRS. The time around periapse when the spacecraft is under 1500 km altitude is set to nadir or off-nadir pointing for MLA ranging. The next longest amount of time is spent at the nominal and nominal roll scenarios for the UVS exosphere observations at intermediate altitudes. Much shorter periods using the other pointing scenarios are interspersed between these longer time windows. The number of pointing commands associated with these shorter periods is typically much larger than the number of commands used for the longer periods. The pointing scenarios with “Targeting” in their names are used to schedule observations of locations of special interest on the planet surface that have been identified by the science teams using observations from Mariner 10 or the three MESSENGER flybys. The UVSStarCal, VIRSStarCal, and XRSCasACal are calibration activities that point the respective instruments at astronomical targets such as the star Sirius and the supernova remnant Cassiopeia A. Instrument boresights in the spacecraft body frame determined from ground and in-flight calibrations are substituted for the +Z axis as the primary body vector to ensure that these surface targets or calibration objects are captured in the instrument FOVs. Although spacecraft attitude is set to optimize just one science activity, it is almost always the case that other instruments besides the one chosen to set the pointing are simultaneously collecting data.

When specifying spacecraft attitude requests for the orbit loads, SciBox calls the specific G&C pointing commands needed for the associated pointing scenario and populates these commands with the required parameter values on the basis of the most recent spacecraft trajectory solution. SciBox uses a simplified algorithm to compute the amount of time required to complete the turn from one science attitude to the next and sets the times for the pointing commands to allow adequate time to arrive at the new attitude before collecting the science measurement. The pointing command parameters are a mix of fixed values for the pointing vectors and flags that indicate how the on-board software is to compute one or more of these vectors. In those few cases where the two external reference vectors are set to fixed inertial vectors, the commanded attitude computed by the flight software must match that computed by SciBox. For other cases where the pointing vector is specified by a flag that indicates directions from the spacecraft to the Sun, Earth, or Mercury, the flight software will use its on-board ephemeris models to determine the inertial reference vectors. The resulting commanded attitude will match the SciBox attitude only if those ephemeris models are sufficiently close to the trajectory solution used to run SciBox. Although the attitude may be different, the intended instrument targeting will still be achieved provided that the on-board ephemeris models are sufficiently close to the actual spacecraft orbit. The amount of time needed to complete turns between two science attitudes can vary with changes in the spacecraft trajectory. The times of the pointing commands are internally set by SciBox relative to the orbital periapses but must be specified as fixed times for the sequencing software. Therefore, the absolute times of the pointing commands should also be adjusted to match the periapse times for the most recent trajectory solution. The comparisons discussed in subsequent sections of this paper first address the case where the same trajectory is used and then consider the effects of using a different trajectory for the SciBox design and the G&C simulations.

SciBox outputs include reports that define the time window for each activity when the spacecraft is assumed to be stabilized at the target attitude and the times when each individual image is taken with either of the MDIS cameras. It is during these time periods that the comparisons between the ideal attitude intended by SciBox and the predicted or actual attitude taken from a G&C simulation or from flight telemetry are most important. Times in between these “steady- state” windows are periods when the spacecraft is turning between two attitudes. The important factor in these time periods is that the turn can be completed in the time allocated by SciBox. The match between the turn profile computed by SciBox and the higher-fidelity G&C simulation is of lesser importance. The G&C simulation is used as the basis for all spacecraft health and safety checks prior to executing a sequence load.

## SCIBOX POINTING DESIGNS VERSUS G&C SIMULATIONS

Comparisons between spacecraft attitude profiles designed by SciBox and the profiles predicted with the G&C high-fidelity simulator using the SciBox attitude commands were performed periodically throughout the SciBox development process. As the instrument teams refined the concepts for how to implement their observations, the set of SciBox pointing scenarios and science activities gradually expanded to the list shown in Table 1. With each new release of SciBox that contained updates to the pointing commands, a set of sample weekly attitude profiles would be run using the G&C simulator. The selected weeks contained at least one, and usually many, instances of each of the different pointing scenarios used over the year in orbit. Particular attention was paid to time windows using any new pointing scenarios that had just been added to the latest version of SciBox. These G&C simulations helped identify any problems in the SciBox interpretation of the G&C pointing commands so that they could be corrected before any actual orbit loads were generated. A secondary purpose of these simulations was to confirm that the G&C system was capable of executing the turns between the different attitudes in the allocated time and that no attitude constraints would be violated while following the SciBox commands. For these initial comparisons, the same spacecraft trajectory was used by SciBox to design the observations and in the simulator. Furthermore, that same trajectory was loaded to the flight code and served as the "true" trajectory in the dynamics model for the simulations.

Most of the problems that were identified by the G&C checks of SciBox pointing designs were related to enforcement of the attitude constraints. A misunderstanding in how the guidance software chooses the "closest" attitude on the SKI boundary when the unconstrained commanded attitude is outside of the SKI zone was detected by the correlation of the largest differences between SciBox and simulated attitudes with Sun azimuth and elevation angles closest to the SKI limits. The magnitude of the differences was greatly reduced when the SciBox team changed the logic for this situation to match the flight software algorithm. SciBox has not included any checking of the HPKO constraints in its attitude computations. It is reasonable to ignore this constraint because the science pointing is primarily concerned with keeping the +Z axis close to Mercury and the HPKO constraint deals with the –Z axis. However, the G&C simulations have shown that occasionally the SciBox attitudes do violate this constraint. SciBox now produces a report that lists when its attitudes are outside the SKI or HPKO limits, but fixes for any HPKO violations are made by the G&C team after SciBox is run for each sequence load. Another issue that was uncovered by these comparisons was that some pointing commands for periods where the Sun-Mercury nadir direction changed rapidly require rotation rates that cannot be achieved by reaction wheels. For "noon-midnight" orbits, the angle between the spacecraft-to-Sun and spacecraft-to-Mercury directions approaches 0° and 180°, resulting in a large change in commanded attitude in a very short time. The guidance software computes the commanded attitude each second, so the controller sees this rapid change and tries to follow it by issuing large torque commands to the wheels. The actual attitude deviates from the desired attitude because the largest achievable rate is well below what is needed to precisely follow the geometry, and the deviation is often severe enough to violate SKI or HPKO constraints. SciBox now includes logic to detect these time periods and insert a "patch" to maneuver around these times using inertial vectors and a fixed rate that is easily achievable by the wheels.

## Example Orbit Load Attitude Profile for May 9-16, 2011, Day of Year 129–136

One of the sample weeks that included a majority of the SciBox pointing scenarios is May 9-16, 2011. This load is referred to as the 11129 load because it started executing on day of year (DOY) number 129 of 2011 (May 9). This section presents quantitative results for differences between the SciBox attitude profile and the profile from the G&C simulation using a version of SciBox released prior to orbit insertion, version 6.1b. The science activities and pointing scenarios used in that version of the 11129 load are shown columns 3 and 4 of Table 2. The OD 197[*] spacecraft reference trajectory was used by SciBox and for the G&C simulation.

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[*] Spacecraft trajectory solutions delivered by the navigation team are called orbit determination (OD) deliveries and are numbered consecutively from the first solution generated just after launch in 2004.

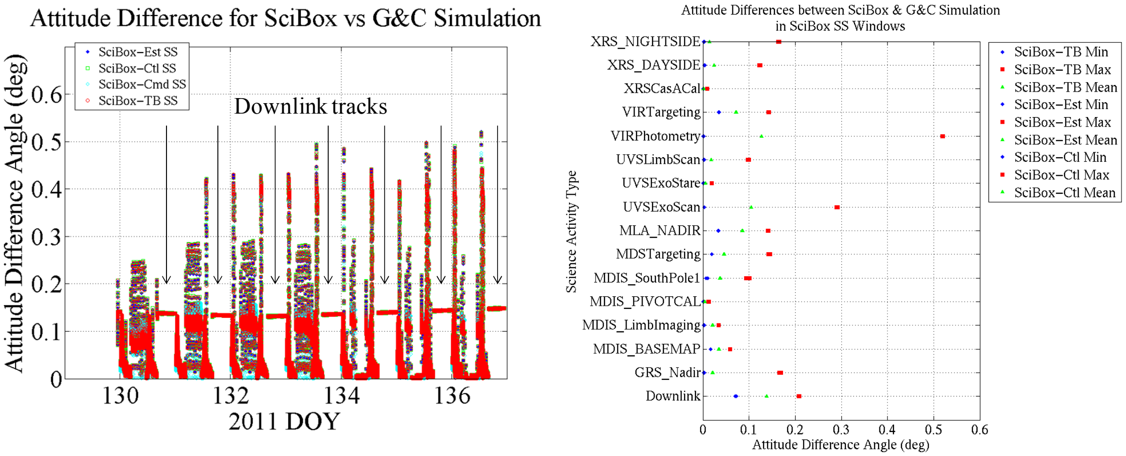
**Table 2. Science Activities and Pointing Scenarios for Orbit Load 11129**

| | | SciBox Version 6.1b (released before orbit insertion) | | SciBox Version 6.2.3 (as run) | |
|---|---|---|---|---|---|
| Science Activities | SciBox Pointing Scenario | # of Pointing Windows | Average Duration of Each Window | # of Pointing Windows | Average Duration of Each Window |
| n/a | Downlink | 7 | 8 hr | 7 | 7.7 hr |
| GRS_Nadir<br>MDIS_BASEMAP<br>MDSTargeting<br>MLA_NADIR<br>XRS_DAYSIDE | Nadir | 17<br>22<br>2<br>19<br>22 | 17.4 min<br>2.6 s<br>19.5 s<br>32.1 min<br>29.2 min | 22<br>23<br>2<br>22<br>21 | 14 min<br>2.5 s<br>19.5 s<br>27.8 min<br>28.2 min |
| UVSLimbScan | Radial Limb Stare<br>Radial Limb Scan | 14 | 9.2 min | 15 | 9.2 min |
| UVSExoStare | Nominal | 10 | 14.1 min | 12 | 16.6 min |
| UVS_ExoScan | NominalRoll | 11 | 186 min | 14 | 2.7 hr |
| XRS_NIGHTSIDE | Specular | 15 | 88.5 min | 15 | 94.6 min |
| MDIS_LimbImaging<br>MDIS_PIVOTCAL | Off-Nadir | 4<br>1 | 4 s<br>4 min | 6<br>1 | 4 s<br>4 min |
| MDSTargeting<br>VIRPhotometry<br>VIRTargeting | SurfaceTracking | 2<br>93<br>4 | 6 s<br>47 s<br>44 s | 6<br>75<br>4 | 8 s<br>47 s<br>44 s |
| MDIS_SouthPole1 | LocalTime<br>SurfaceTargeting | 4 | 4 s | 4 | 4 s |
| MDSTargeting | AimControl | 1 | 6 s | 1 | 6 s |
| XRSCasACal | XRSCasACal | 3 | 4 hr | 2 | 4 hr |
| VIRTargeting | SurfaceDrifting | 7 | 33.1 s | 9 | 33 s |
| | Total # of Pointing Changes | 259 | | 262 | |

SciBox produces a single attitude that combines its algorithms for computing the desired attitude with its limited modeling of spacecraft turns. The G&C simulation produces four separate attitude profiles that represent different aspects of the on-board attitude computations and rotational dynamics modeling. The attitude output from the dynamics model represents the best estimate of the true spacecraft attitude (TB) in response to controller actions and environmental disturbances. The other three attitudes are output from the flight code running in the simulation and represent *(i)* the commanded attitude (Cmd) computed by the guidance functions in response to the pointing commands, *(ii)* the best estimate of the current attitude (Est) generated from star tracker and gyro data by the attitude determination filter, and *(iii)* a propagation of the estimated attitude (Ctl) used by the control functions that run at a higher rate than the filter. The labels "TB," "Cmd," "Est," and "Ctl" are used to distinguish between these attitudes in the plots and tables presented below. The estimator and controller attitudes are nearly always identical because they share the same source, the attitude filter. Large differences between the controller and commanded attitudes occur each time a new pointing command is received. These differences are driven to small values by controller commands to the reaction wheels to turn the spacecraft. In the SciBox steady-state windows, the commanded attitude should be very close to the estimated and controller attitudes. The true attitude should also match the estimated and controller attitude fairly closely.

The difference between the attitude predicted by SciBox and any one of the four attitudes from the G&C simulation can be represented by a time history of a rotation axis and angle. These differences were computed for each of the four attitudes sampled once per second over the course of the simulation. Figure 3a shows the time history of the rotation angle in the SciBox steady-state pointing windows. The seven periods where the rotation angle is approximately constant at 0.15° are the downlink tracks. The near-constant difference is due to a bias between the G&C and SciBox downlink attitudes that results from use of the measured phased-array antenna alignments by the flight software. In SciBox the two antenna FOVs are taken to coincide with the spacecraft XY plane. All of the other periods are windows when one of the 15 science activities is being performed. Figure 3b shows the maximum, minimum, and mean attitude difference angles for each of the individual activity types. The best match is obtained for the XRSCasACal activity which uses inertial vectors to define the spacecraft attitude. Most of the other activities have differences of less than 0.3°, with many less than 0.1°. The science teams have indicated that SciBox attitude predictions should be within 0.1° of the actual attitude for high-precision activities such as MDIS images and the VIRS targeted observations. For other activities, a match between 0.5° and 1° is sufficient to meet science goals. The mean differences are generally within these limits, showing that the SciBox modeling is adequate for design and planning purposes. The relatively small difference values in the steady-state windows also shows that the SciBox calculation for turn durations is a good approximation of actual spacecraft performance.

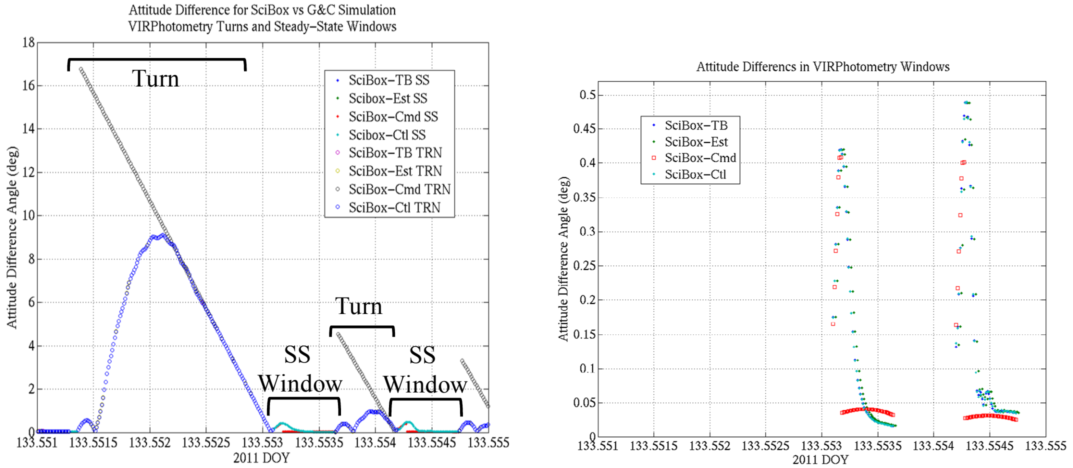
The activity with the largest mean and maximum attitude difference angles is VIRS photometry. Examination of the individual windows shows that the large differences occur at the beginning of the steady-state windows defined by SciBox, indicating that the spacecraft is still completing the turn for part of that window. Figure 4 illustrates how the attitude difference angles evolve during the turns before and within the steady-state windows for two VIRS photometry activities on DOY 133. The turn periods seen in Figure 4a start out with a jump in the commanded attitude to the new target value. The controller attitude angle grows until it meets the commanded angle, and then both decrease to small values as the wheels apply the commanded torques to do the turn. The fact that the attitude differences are larger in the turn periods is an indication of the low-fidelity modeling of spacecraft rotational dynamics in SciBox. There are smaller "humps" in the attitude difference angles at the start of the steady-state windows. These "humps" are more apparent in Figure 4b, which shows an enlargement of the attitude difference angles in the steady-state windows. These humps represent the controller working to "stop" at the desired target attitude. The attitude difference stabilizes to a low value very close to the commanded attitude approximately half way through the steady-state windows.



(a) Differences in SciBox steady-state (SS) pointing windows

(b) Minimum, maximum, and mean differences by science activity type

**Figure 3. Attitude Differences between SciBox Designs and G&C Simulation for 11129 Load.**



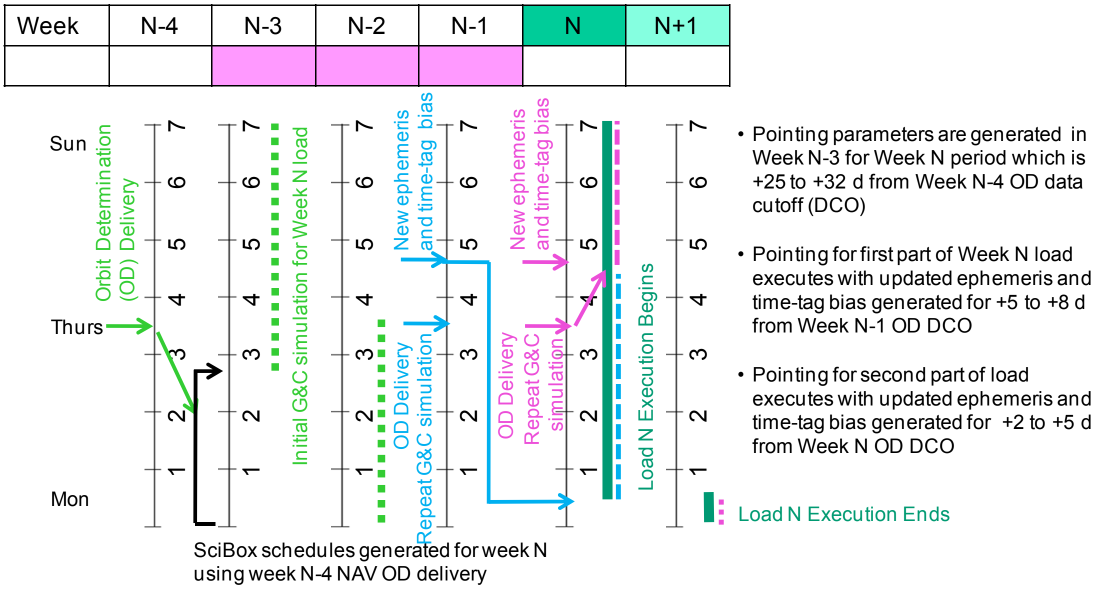
(a) Differences in turn and SciBox steady-state pointing windows

(b) Differences in SciBox steady-state pointing windows

**Figure 4. Attitude Differences between SciBox Designs and G&C Simulation for VIRS Photometry Activities on DOY 133.**

## SCIENCE POINTING SENSITIVITY TO TRAJECTORY KNOWLEDGE UPDATES

The previous section compared attitude modeling between SciBox and G&C simulations using the same spacecraft trajectory solution for both runs. For those cases, both the times of the pointing commands and the values computed for the reference vectors that define the desired attitude should be the same. Although this comparison is an important first step in validating SciBox attitude models, it ignores a key feature of the operational sequence development process. The pointing command times and parameters are generated by SciBox three weeks in advance of execution of the sequence load by the spacecraft. The trajectory solution used by SciBox represents a propagation by the navigation team forward by 25–32 days from its tracking data cutoff (DCO) to predict the spacecraft orbits during the week that the sequence will execute. Errors in the solution itself and also in the models used to propagate the future trajectory will cause the actual orbit to deviate from the one used for the SciBox pointing designs. Errors in the trajectory solution can be kept smaller when the propagation from the DCO is over a shorter time. The navigation team delivers new spacecraft trajectory solutions every week, and these are used to perform two types of updates to minimize pointing deviations resulting from differences in the spacecraft orbit between the SciBox run and load execution. The first update is the weekly replacement of the onboard spacecraft ephemeris model with one fit to the latest navigation solution. The second update is the application of a "time-tag bias" to the times of all the pointing and instrument commands. A fixed bias (positive or negative) is added to the time for all commands in the sequence that will execute after the bias command is received. Biases are applied twice during execution of a sequence load: once at the start of the load (which is chosen to be on a Monday) and once approximately 4.5 days after the start of the load (corresponding to the Friday of the week of load execution). The navigation team delivers new spacecraft trajectory solutions on Thursdays. Ephemeris updates and the time-tag bias for the second part of the currently executing load are uplinked on Friday. The time-tag bias for the first part of the next load is uplinked with the load itself on Friday or Saturday but does not take effect until the load begins on the following Monday. The time-tag bias values are selected by comparing the orbit periapse times from the trajectory solution used in the SciBox run to generate the pointing commands with the new periapse times from the current navigation delivery. Figure 5 illustrates the timing of the navigation OD deliveries, G&C simulations, and uplink of new ephemeris models and time-tag biases for a single sequence load.



- Pointing parameters are generated in Week N-3 for Week N period which is +25 to +32 d from Week N-4 OD data cutoff (DCO)
- Pointing for first part of Week N load executes with updated ephemeris and time-tag bias generated for +5 to +8 d from Week N-1 OD DCO
- Pointing for second part of load executes with updated ephemeris and time-tag bias generated for +2 to +5 d from Week N OD DCO

**Figure 5. Trajectory Knowledge Updates and Sequence Development Schedule for Orbit Loads.**

Two weeks were selected from the year-long orbital phase to investigate the effects of the ephemeris updates and time-tag biasing on spacecraft attitudes: July 19–25, 2011 (DOY 200–206, 11200 load), and January 30–February 6, 2012 (DOY 030–037, 12030 load). These weeks were chosen because they collectively include examples of most of the different SciBox pointing scenarios and reflect the different selection and ordering of these scenarios early and late in the orbital phase. Version 5.3 of SciBox and reference trajectory OD 189 were used to generate the pointing commands. The navigation team generated two sets of perturbed trajectories for each week, one representing the delivery made the Thursday before the load begins execution and one representing the delivery made on the Thursday during load execution. In each set, four different perturbations from the OD 189 reference trajectory were included with different assumed errors in the initial state used to propagate the trajectory from the DCO. Trajectory errors were expressed in the radial, transverse, and normal (RTN) directions where R is the radial direction from Mercury center to the spacecraft, N is normal to the spacecraft orbit plane, and T completes a right-handed system (T= N × R). Errors in T represent changes in the location of the spacecraft along its orbit, or downtrack errors, which can be largely corrected by applying the time-tag bias. The magnitudes for the RTN errors were set at the 3-$\sigma$[*] level of the navigation team's OD covariance analysis that included effects of propulsive momentum dumps and expected uncertainties in other trajectory modeling parameters such as Mercury's gravitational field.

Three different G&C simulations were performed for the first and second parts of each of the two week-long loads. The first simulation, called the "baseline," represented the pointing commands as designed by SciBox and used the OD 189 reference trajectory and the original times of the pointing commands as generated by SciBox. The second simulation, called "No Update," used the OD 189 reference trajectory for the flight code ephemeris model with the original times for the pointing commands but used one of the perturbed trajectories as the spacecraft orbit in the dynamics model. This run represented what would happen to the SciBox designs if no action were taken to incorporate new trajectory knowledge. The third simulation, called "Update," used one of the perturbed trajectories for both the flight code and the dynamics model and applied a bias to the times of the pointing commands. This run represented the planned operational strategy for incorporating new trajectory knowledge. There were four "baseline" simulations – two loads with two parts for each load – and eight different simulations using one of the perturbed trajectories in different parts of the G&C simulation. It is not possible to present a detailed comparison of each of the 32 different simulations in this paper. Instead, selected representative results are discussed in the next sections.

### Attitude Changes in Steady State and Turn Windows Using Perturbed Trajectories

Overall attitude differences were examined in the preceding section by looking at the time history of the rotation angle representing the transformation from SciBox attitude to one of the attitudes output from the G&C simulation. Small angles indicated a close match between SciBox and G&C models. This same comparison can be used in examining the results from the perturbed trajectories, but the rotation angle profiles must be interpreted differently. The fact that the attitudes using the perturbed trajectories do not match the baseline case almost always indicates that the flight software is adjusting to meet the original targeting objective for the instrument observation because there are very few activities that specify constant inertial vectors to set the attitude. This comparison is primarily made to determine whether the new attitudes resulting from improved trajectory knowledge move far enough from the original attitudes to cause health and safety issues. Large angle changes could mean that the new attitude would move closer to or be clipped at the SKI or HPKO constraint bounds. Turns might take longer to complete if the starting or ending attitude was very different from that assumed in the SciBox run.

Figure 6 shows attitude differences as a rotation angle profile versus time for 4 of the 32 simulations. The perturbed trajectory, the time range of the simulation, and the time-tag bias applied for each of the cases are listed below each plot. It was assumed that the baseline simulation was

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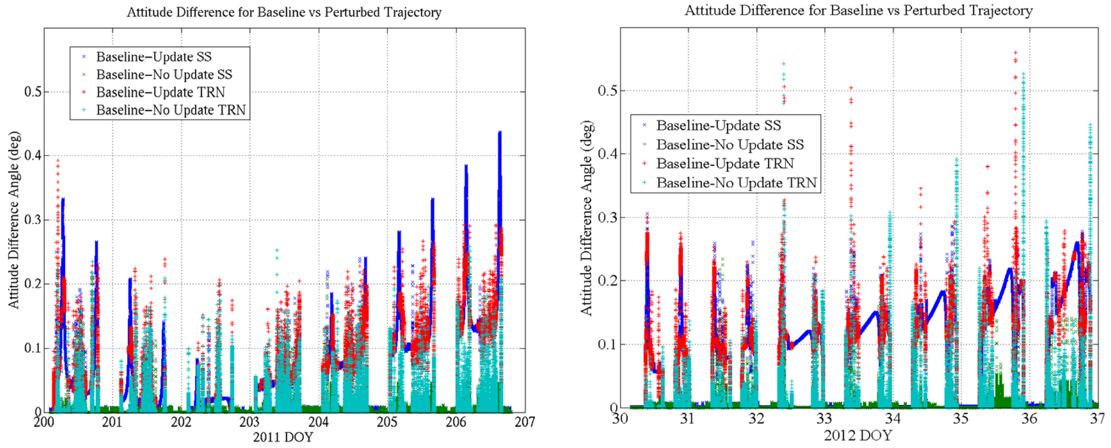
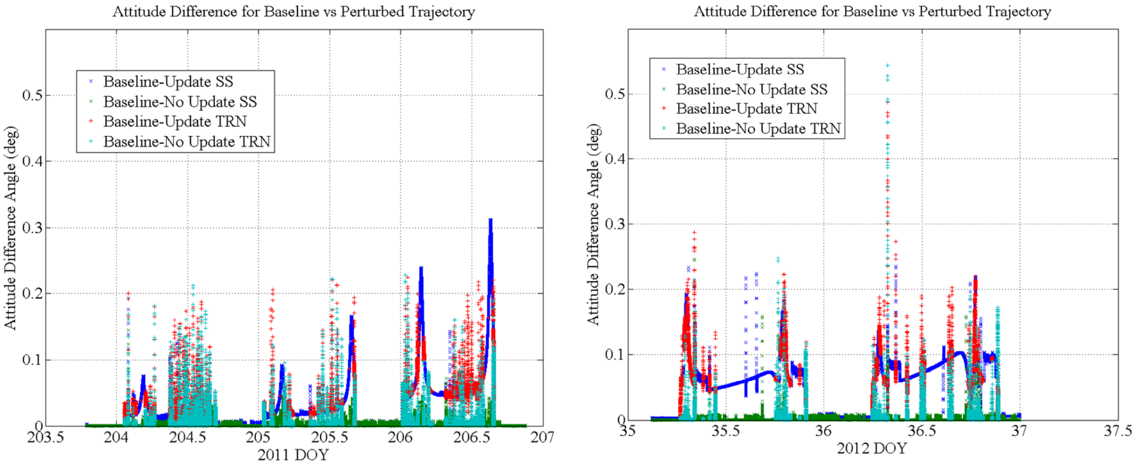
[*] $\sigma$ represents the square root of the diagonal variance entries of the covariance matrix for uncertainties in the R, T, and N position components.

sufficiently close to the SciBox designs to be used as the basis for comparison with the simulations using the perturbed trajectories. The “true” attitude output by the dynamics model for the “Update” and “No Update” simulations were differenced with the “true” attitude from the baseline run. Values were compared at the same times relative to the start time of the simulation even though the absolute start time was different for the “Update” run for which a time-tag bias was applied. Each plot in Figure 6 shows rotation angle values for time periods in the SciBox steady-state pointing windows (SS) and all the turn times in between (TRN) for the “Update” and “No Update” simulations.



Case 1 11200 Part 1
DOY 200-206
RTN errors 3-σ high
Time-tag Bias +22 s

Case 2 12030 Part 1
DOY 030-036
RTN errors 3-σ low
Time-tag Bias -24 s



Case 3 11200 Part 2
DOY 203-206
R & N errors 3-σ low, T error 3-σ high
Time-tag Bias -21 s

Case 4 12030 Part 2
DOY 035-036
R & N errors 3-σ high, T error 3-σ low
Time-tag Bias +33 s

**Figure 6. Attitude Differences for Selected Sample Perturbed Trajectory Simulations.**

The maximum angular difference from the baseline attitude for these cases is less than 0.6°, which is unlikely to cause a constraint violation. As expected, the differences are usually larger for the "Update" run than for the "No Update" run. There is almost no difference in the steady-state pointing windows for the "No Update" case because the same spacecraft trajectory information is used to compute the commanded attitudes for this case and the baseline run. The larger differences seen during the turn periods for the "No Update" case are most likely due to the effects of disturbance torques acting at different times relative to the turn times in the dynamics model, which is using the perturbed trajectory. Turn paths are dependent on starting momentum, and the momentum profile evolves differently for the perturbed trajectory than for the baseline trajectory. The largest differences are seen during steady-state pointing windows around the periapse times for the perturbed trajectory in the "Update" cases. Spacecraft position relative to the planet changes most rapidly around periapse, and the spacecraft attitude computed using the perturbed trajectory deviates more from the baseline attitude. All of the profiles exhibit a "bowed" shape, because differences are larger toward the start and stop times of the simulation, which reflects the way in which the time-tag bias was selected. The average difference in periapse time over all of the orbits in the simulation time period was used for the time-tag bias. The magnitude of the periapse time difference grew or shrunk monotonically over the orbits, so the average value fell closest to the actual value for orbits in the middle of the simulation period.

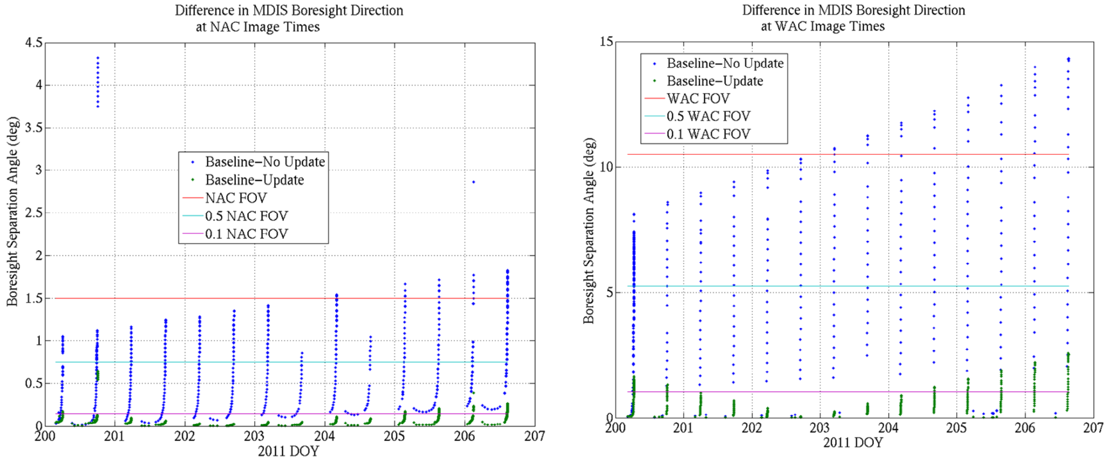
## Instrument Targeting Adjustments using Perturbed Trajectories

Additional checks beyond the overall attitude comparisons were performed as part of the perturbed trajectory analysis. These checks focused on criteria related to achieving the intended instrument targeting for the different types of observations. One of these checks looked at the difference in the angle between the +Z axis and the nadir direction (spacecraft to Mercury center) during periods when the attitude was set for MLA tracking around orbital periapses. Table 3 shows the mean and maximum differences in the +Z-nadir angle for the four sample cases shown in Figure 6 for all instances of MLA_NADIR and MLA_OFFNADIR activities. The mean change is small – less than 0.1° – for the "Update" cases. The maximum changes are larger but still less than 0.5°. Although not apparent from the table, the maximum values tend to occur when Sun elevation is at one of the SKI bounds. There are small changes in the time window when the Sun-spacecraft-Mercury angle allows +Z to be exactly aligned with nadir between the two trajectories used for these cases. The attitude rides the SKI elevation boundary for a different amount of time in the baseline and update cases. Another special check looked at the angular displacement between the MDIS camera boresight directions for the baseline and perturbed trajectory cases. This displacement should be kept to less than 10% of the FOV for each camera to preserve overlap between images that cover the similar locations (although not usually taken close together in time). Figure 7 shows the boresight direction changes for Case 1 of Figure 6. The advantage of using the updated ephemeris model and the time-tag bias is clearly shown by the much larger values for the boresight direction difference for the "No Update" case than for the "Update" case for both NAC and WAC images. Even for the much larger 10.5°-FOV of the WAC, the difference is larger than the FOV for images near the end of the simulation period for the "No Update" case. For the NAC, all of the differences are less than 10% of the 1.5°-FOV for the "Update" case except for one set of observations on DOY 200. This strip of overlapping images is targeted to a particular surface feature and taken at low altitude very close to periapse. It occurs early in the load when the average value for the time-tag bias is not as close to the actual periapse time shift as it is for the orbits in the middle of the load. Even for this "outlier" image set, using the time-tag bias reduces the difference from over 4° to just under 0.75°. Other criteria that were investigated are the distance on the planet surface between the baseline and updated VIRS targeted observations and the tangent height above the lit limb of Mercury for the UVS dayside limb scans. Differences for these criteria were also found to be within the tolerance for successful science data collection.

**Table 3. MLA Nadir and Off-Nadir Comparisons**

| Case | Maximum Change in +Z-Nadir Angle Baseline-No Update (°) | Maximum Change in +Z-Nadir Angle Baseline-Update (°) | Mean Change in +Z-Nadir Angle Baseline-No Update (°) | Mean Change in +Z-Nadir Angle Baseline-Update (°) |
|---|---|---|---|---|
| | MLA_NADIR | | | |
| 1 | 0.054 | 0.437 | 0.000 | 0.001 |
| 2 | 0.203 | 0.306 | 0.002 | 0.124 |
| 3 | 0.046 | 0.312 | 0.003 | 0.115 |
| 4 | 0.133 | 0.209 | 0.003 | 0.093 |
| | MLA_OFFNADIR* | | | |
| 2 | 0.029 | 0.115 | 0.003 | 0.058 |
| 4 | 0.013 | 0.193 | 0.001 | 0.111 |

*There are no MLA_OFFNADIR activities in the 11200 load.



NAC Image Times

WAC Image Times

**Figure 7. MDIS NAC and WAC Boresight Direction Differences for Perturbed Trajectory Example Case 1.**

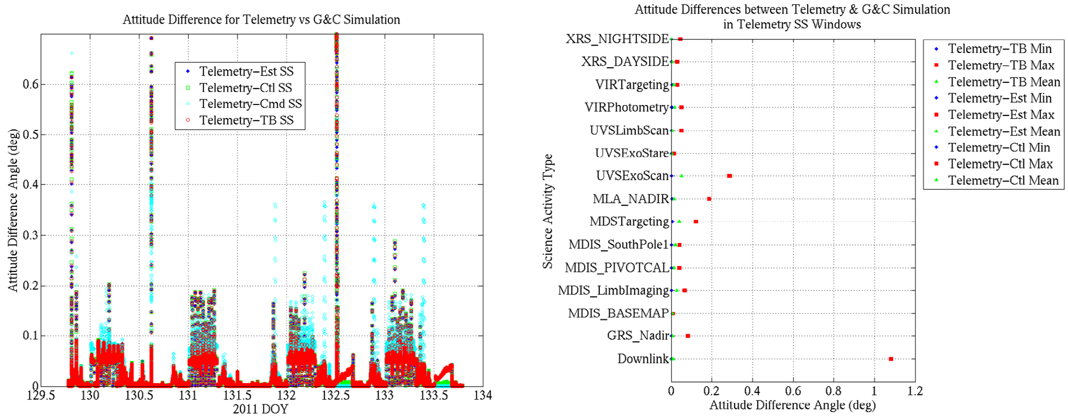
## POST-MOI ORBIT LOAD COMPARISONS

MESSENGER has been executing sequence loads using attitude commands generated by SciBox over the months since orbit insertion in March 2011. This section revisits the sample week of May 9-16, 2011, to compare G&C simulation results with telemetry collected while the load was executing on the spacecraft. The science activities and pointing scenarios used in the "as-run" version of the 11129 load are shown columns 5 and 6 of Table 2. Following the process shown in

Figure 5, the 11129 load was designed using post-MOI version 6.2.3 of SciBox and the OD 209 spacecraft reference trajectory delivered by the navigation team on April 14, 2011. The OD 212 trajectory was delivered on May 5. When part 1 of the 11129 load executed, the G&C flight software was using an ephemeris fit from OD 212 and a time-tag bias of –29 s. While the load was executing, the OD 213 trajectory was delivered on May 12. Part 2 of the load executed using an ephemeris fit from OD 213 and a time-tag bias of –39 s. The change in ephemeris models and time-tag bias value was made during the downlink track on Friday May 13 (DOY 133). The time-tag bias values put the commands for part 1 of the load within 5 s of the predicted orbital periapse times from OD 212 and within 4 s of the periapse times from OD 213.

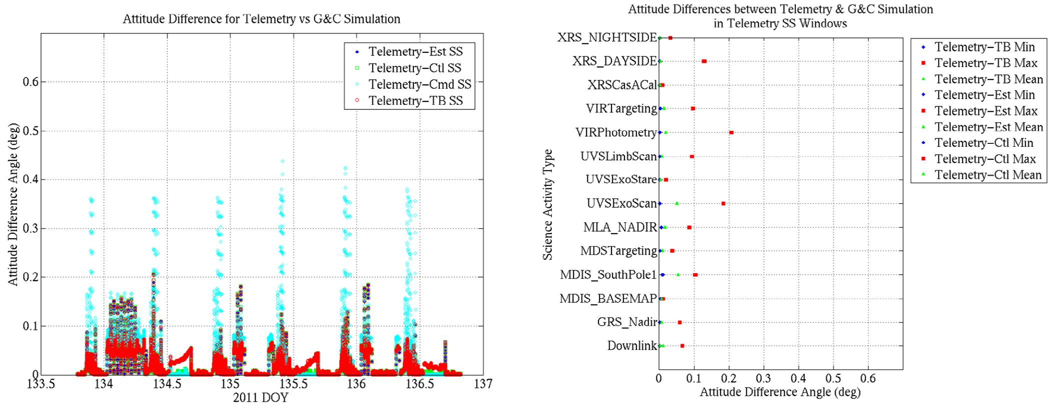
As in previous sections, the difference between the attitudes from the G&C simulation and the estimated attitude from flight telemetry is represented by a time history of a rotation angle. In this case, two separate simulations of part 1 and part 2 of the 11129 load are compared with on-board attitude estimates returned in attitude telemetry packets. Each simulation used the spacecraft ephemeris fit and time-tag bias value given in the previous paragraph. Figures 8a and 8c show the time history of the rotation angle in the SciBox steady-state pointing windows for parts 1 and 2 of the 11129 load. Figures 8b and 8d show the maximum, minimum, and mean attitude difference angles for each of the individual activity types. The three periods in part 1 with the largest differences are all during downlink tracks and reflect operational events that are not related to science data collection.[6] SciBox flags all the downlink tracks as steady-state pointing windows, but spacecraft attitude is sometimes adjusted during the track while still keeping the Earth line in the antenna FOV. During the DOY 129 downlink track, the Sun elevation was -10° to assist with momentum management. Sun elevation was commanded back to 0° before the end of the track. A propulsive momentum dump was performed during the downlink track on DOY 130. The thrusters cannot maintain attitude as tightly as the wheels so the attitude differences are larger during the dump. Sun-spacecraft-Earth geometry dictated a switch from the back to front antennas for the downlink track on DOY 132. Once on the front antennas, the star trackers were turned off for a portion of each downlink track when Mercury would be near or in their FOVs. The difference between the true and telemetered attitude rises over the beginning of each track and then drops sharply at the time that the tracker is turned on after the planet moves away from its FOV. There is a small attitude adjustment as the controller used the updated attitude from the first tracker measurements after turn on.

The attitude differences for the science activities are almost all less than 0.1°. Two exceptions are the UVSExoScans and the VIRPhotometry events. The spacecraft is actually doing slow scans in the UVSExoScan windows, and the largest attitude differences are seen at times when the scan direction is changed. The behavior during the VIRPhotometry events is consistent with the results shown earlier in the paper where the differences end at a smaller value as the controller finishes the turn. The fact that attitude differences are larger during these small “turns” indicates that the G&C simulation is not a perfect match to the actual performance of the spacecraft. Much of the discrepancy may be due to momentum modeling. The simulations were run using predictions for starting momentum state but not repeated using telemetered momentum values. It is difficult to accurately simulate the propulsive momentum dumps, and these simulations are run before any telemetry would be available. The match may also be improved by incorporating a better model for reaction wheel characteristics. However, differences of less than 0.1° for other activities that do not include scans shows that the simulations are a good indicator of the actual attitudes during the most sensitive times when science data are being collected. These differences are consistent with the goal of having actual attitude be within 0.5°–1° of SciBox predictions and match the flight behavior closely enough to ensure spacecraft health and safety when designing the sequence loads.



(a) Differences in SciBox steady-state pointing windows for part 1

(b) Minimum, maximum, and mean differences by science activity type for part 1



(c) Differences in SciBox steady-state pointing windows for part 2

(d) Minimum, maximum, and mean differences by science activity type for part 1

**Figure 8. Attitude Differences between G&C Simulations and Estimated Attitude from Flight Telemetry for Parts 1 and 2 of 11129 Load.**

## CONCLUSION

MESSENGER spacecraft attitude is modeled to varying degrees of fidelity in many ground tools that facilitate routine operations. Two such tools that are critical for orbital operations are the G&C high-fidelity simulation and the SciBox optimization and planning tool for designing science observations. An intensive effort was made to validate the use of these different utilities for different parts of the orbital sequence development process in the years leading up to MOI. Multiple iterations of comparisons of SciBox attitude predictions with results for G&C simulations eventually resulted in differences of less than 0.1° for most observations, well within the accuracy needed for science planning purposes. G&C simulations of the changes to spacecraft attitude resulting from incorporating the best available trajectory knowledge demonstrated that the intended science targeting would be maintained as intended by SciBox. The strategy of applying a time-tag bias to shift start times of the observations so that they remained at the same time relative to orbital periapses was shown to correct most of the geometry differences that could have resulted in large offsets from the intended instrument pointing. Now that the spacecraft is executing sequence loads with attitudes generated using SciBox, comparisons have been made between the G&C simulation results and the attitude estimated by the on-board filter that is returned to the ground in flight telemetry. For time windows where the spacecraft should be stabilized at the intended science pointing, the estimated attitude matches the simulation attitude to a few tenths of a degree. Better matching during turn periods may be achieved with improved modeling of reaction wheel characteristics and greater attention to matching starting momentum state with flight values.

Ground processing of the science data, including mapping images to surface locations, is underway using the telemetered attitude estimates based on star tracker and gyro measurements. The science teams report good correlation between SciBox predictions and the actual data. There have been no anomalies or constraint violations associated with erroneous spacecraft attitude commanding. The G&C simulation has been used to adjust or remove a few of the SciBox attitude requests to avoid potential constraint violations or performance issues when the sequence load is executed by the spacecraft. Both tool sets have greatly reduced the amount of manual checking that would otherwise have been necessary for the MESSENGER flight team to prepare and validate each load.

## REFERENCES

[1] S. C .Solomon, S. C., R. L. McNutt, Jr., R. E. Gold, and D. L. Domingue., "MESSENGER Mission Overview," *Space Sci. Rev.*, 131, 3–39, 2007.

[2] R. M. Vaughan, D. J. O'Shaughnessy, H. K. Kang, and N. Laslo, "Spacecraft Pointing for Science Observations for MESSENGER's Venus Flyby 2 and Mercury Flyby 1", *AIAA Guidance, Navigation, and Control Conference,* paper AIAA-2008-7479, 21 pp., Honolulu, HI, August, 18–21, 2008.

[3] T. H. Choo, B. J. Anderson, P. D. Bedini, E. J. Finnegan, J. P. Skura, and R. J. Steele, "The MESSENGER Science Planning and Commanding System", *Space 2009 Conference and Exposition, American Institute of Aeronautics and Astronautics,* paper AIAA-2009-6462, 11 pp., Pasadena, CA, September 14–17, 2009.

[4] R. M. Vaughan, D. J. O'Shaughnessy, H. S. Shapiro, and D. R. Haley, "The MESSENGER Spacecraft Guidance and Control System," NASA 2005 Flight Mechanics Symposium, 15 pp., Goddard Space Flight Center, Greenbelt, MD, October 18–20, 2005.

[5] D. J. O'Shaughnessy and R. M. Vaughan, "MESSENGER Spacecraft Pointing Options," *Spaceflight Mechanics 2003, Advances in the Astronautical Sciences,* 114, Part II, 747-766, 2003.

[6] S. H. Flanigan, R. M. Vaughan, D. J. O'Shaughnessy, "Guidance and Control of the MESSENGER Spacecraft in the Mercury Orbital Environment," *American Astronautical Society/American Institute of Aeronautics and Astronautics Astrodynamics Specialist Conference*, paper AAS 11-550, 18 pp., Girdwood, AK, July 31-August 4, 2011.