

EXPANDING CAPABILITIES OF THE MOST SPACECRAFT

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Abstract

The MOST (Microvariability and Oscillations of Stars) microsatellite launched from Plesetsk Cosmodrome in Russia on June 30, 2003, and has had nearly three enormously successful years in orbit. MOST is a stellar photometry mission designed to measure variations on the order of 1 part per million in intensity of light coming from stars.

Following the completion of satellite commissioning, at which point the spacecraft was meeting all of its performance objectives, the MOST spacecraft has seen a series of upgrades to continually improve the performance of the spacecraft and expand its capabilities. Upgrades include improving pointing accuracy and stability by more than a factor of 5, greatly expanding the range of targets the spacecraft can reach, expanding to multiple target capability, and adding tertiary science data from the on-board star tracker amongst others. These focused improvements have led to greater scientific results from the MOST spacecraft.

Introduction

The MOST (Microvariability and Oscillations of Stars) microsatellite was launched from the Plesetsk Cosmodrome in Russia on June 30, 2003. It was developed under the Canadian Space Agency's Small Payloads Program and was Canada's first space telescope as well as the first Canadian space science satellite in over 30 years. The scientific objective of the mission is to perform asteroseismology, measuring the minute variations in intensity of light coming from stellar targets. The primary science objectives include: measuring light intensity oscillations in solar type stars; determining the age of nearby "metal-poor sub-dwarf" stars, which will in turn allow a lower limit to be set on the age of the Universe; and detecting the first reflected light from orbiting exoplanets.

The launch of MOST was the culmination of a process of design focussed intently on maintaining a small set of clearly defined requirements. Important in maintaining low cost and meeting deadlines was the strict adherence to the original requirements without allowing any creeping scope increases in the program. Commissioning of the MOST spacecraft was completed with the spacecraft fully functional and satisfying all of its original requirements.

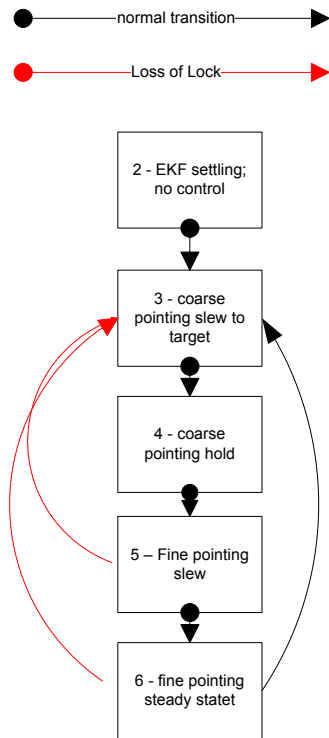
Once fully operational, the on-orbit performance of the spacecraft was analyzed and wherever it made sense scientifically, the boundaries were pushed to get the full capability of the spacecraft. The purpose of this paper is to demonstrate the areas of MOST Operations that were expanded post-commissioning. The focus will be on some key areas that made a substantial contribution to the scientific mission; the pointing accuracy and stability of the spacecraft were improved, an entirely new stream of science data was extracted from star tracker data; expanding the range of targeting capabilities for the spacecraft, and performing pathfinding operations for the NEOSSat mission being jointly developed by DRDC and CSA. Throughout, the process of improving and expanding the capabilities of the spacecraft, the goal has been to improve the quality and quantity of scientific data delivered by the spacecraft. Most importantly, these

improvements to the spacecraft performance have been achieved economically because the effort has been focussed tackling the real issues based on on-orbit experience rather than a considerably larger set of perceived issues that would need to be addressed had the improvements been attempted prior to launch of the spacecraft.

The paper begins by describing key aspects of the MOST spacecraft performance and capabilities as originally designed and achieved at the end of the commissioning period. This sets the context for the improvements that are subsequently described.

Baseline MOST Operations and Performance

The attitude control system for MOST has three primary operation modes. In safehold mode, there is no attitude control. The spacecraft was designed to generate sufficient power for essential loads in all attitudes. Detumble mode, uses magnetometers to sense and magnetorquers to actuate a B-dot control law that can rapidly despin the satellite. This mode was developed primarily to reduce spacecraft angular momentum as a result of tip off from the launch vehicle. Third, and the focus of this section are the pointing control modes. In coarse pointing, the spacecraft attitude is determined using coarse attitude sensors; the magnetometer, coarse sun sensor, fine sun sensor, and rate sensors. In fine pointing mode, the spacecraft attitude is determined using the star tracker and rate sensors. Control in both of these pointing modes uses the reaction wheels.



The pointing control mode consists of five states and is shown in Figure 1. Pointing states 0 and 1 correspond to idle (no control) and detumble mode respectively and for clarity are not shown in the figure. Pointing state 2 is used on initialization of pointing control. In this state, the attitude determination Extended Kalman Filter (EKF) is initialized and settles. Attitude determination takes place, however there is no active actuation. On transition to pointing state 3, the spacecraft autonomously begins a coarse pointing slew from its existing orientation, to the commanded target orientation. On reaching the target, pointing transitions to pointing state 4, which is a hold in coarse pointing. Coarse pointing mode provides pointing accuracy of approximately 2 degrees. When a fine pointing command is issued, the star tracker begins a lost-in-space calculation. From this, the star tracker determines the actual pointing orientation. The spacecraft then autonomously enters pointing state 5 and slews from the orientation determined by the lost-in-space calculation to the target orientation. Lost-in-space and fine slew states use a coarse map in the star tracker that is low resolution but provides for a fast readout of the star tracker image. When the slew is completed, the star tracker autonomously switches to the fine map for better resolution and accuracy and the spacecraft enters pointing state 6. This pointing state represents steady state fine pointing.

Figure 1 Nominal MOST pointing control states

Normal exit from pointing state 6 is on command to coarse point to a new target. At any point when the star tracker is used for attitude determination, loss of lock on the star tracker will lead to a return to coarse pointing state 3.

Operationally, MOST points to a single inertial target for extended periods originally planned to be from 14 – 45 days. Thus, the spacecraft spends most of its time in pointing state 6, steady state fine pointing. To switch to a new target, the spacecraft is coarse pointed to a new target, a new set of coarse and fine star maps is uploaded to the star tracker, and a fine pointing command is sent. This culminates with the spacecraft in pointing state 6 once again on the new target.

Figure 2 shows the fine pointing performance of MOST that was typical following commissioning. The red circle indicates the 25 arcsecond (2σ) pointing requirement. The blue line indicates the boresight pointing error in pitch and yaw. The pointing error obtained had a 1σ value of 4.6 arcsec in pitch and 4.2 arcsec in yaw. This pointing performance is approximately $2\frac{1}{2}$ times better than the requirement.

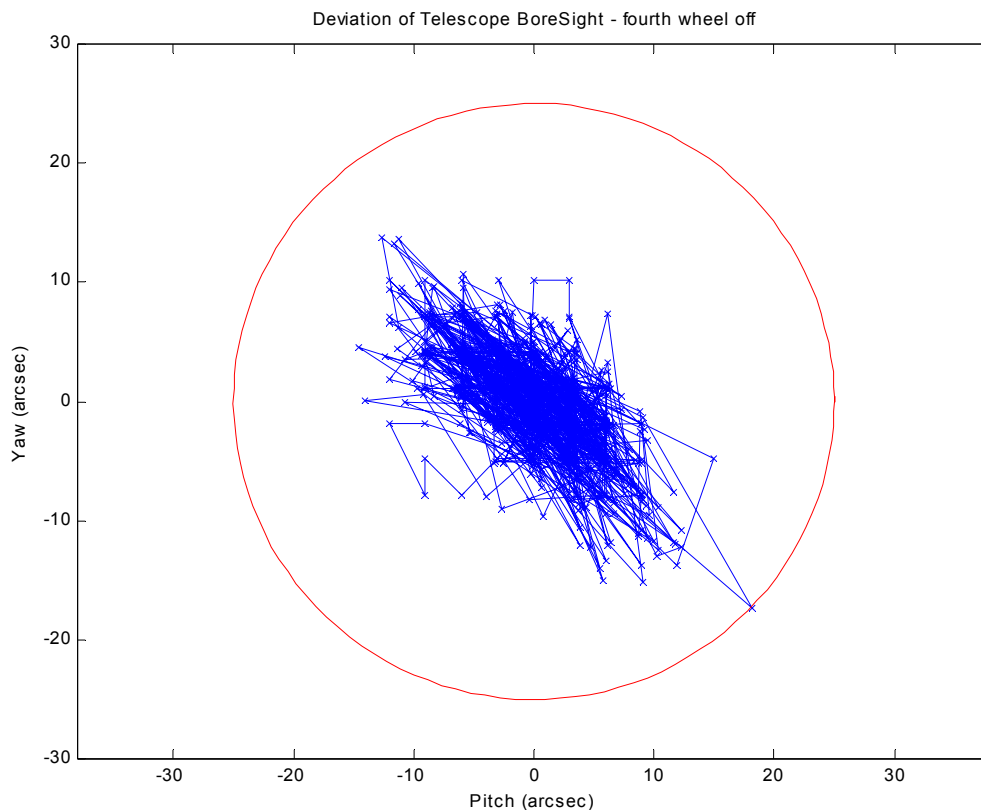


Figure 2 Typical MOST boresight pointing error immediately following commissioning

The primary science objectives of MOST require continuous pointing at a target without any interruptions. In order to avoid the Earth itself occulting the target, MOST looks in a direction called its continuous viewing zone. The continuous viewing zone (CVZ) is a cone with half angle of approximately 26 degrees (at orbital altitude of 820 km, taking into account atmospheric distortion as well) centered on the orbit normal direction. If the spacecraft points within this CVZ, it is guaranteed that the Earth or the Earth's atmosphere will not interfere with viewing of a star as the spacecraft orbits the Earth. Because the orbit precesses slowly (synchronous with the sun at approximately 1 degree per day), the CVZ precesses and maps out a band of accessible targets in the sky

Figure 3 shows the nominal range of targets for the MOST spacecraft. The shaded gray area indicates targets with a Right Ascension (RA) and Declination (dec) within the bounds of where MOST can point. The figure clearly shows the upper and lower bounds of the CVZ which are skewed from the equatorial plane because the MOST orbit is inclined 98.7 degrees. In addition, the front panel of the MOST spacecraft must point within 30 degrees of the sun for the sun sensor (SS) to provide a valid reading. While the sun sensor is not used in the attitude solution in fine pointing, it is necessary that the sun sensor reading be valid for the spacecraft to have sufficient pointing accuracy that the star tracker lost-in-space calculation will yield a result. This effectively limits the spacecraft to point within 30 degrees of the ecliptic plane. Combining these two constraints yields the gray area shown in Figure 3 and shows that there is a seasonal variation with the greatest limitation on available targets in the summer.

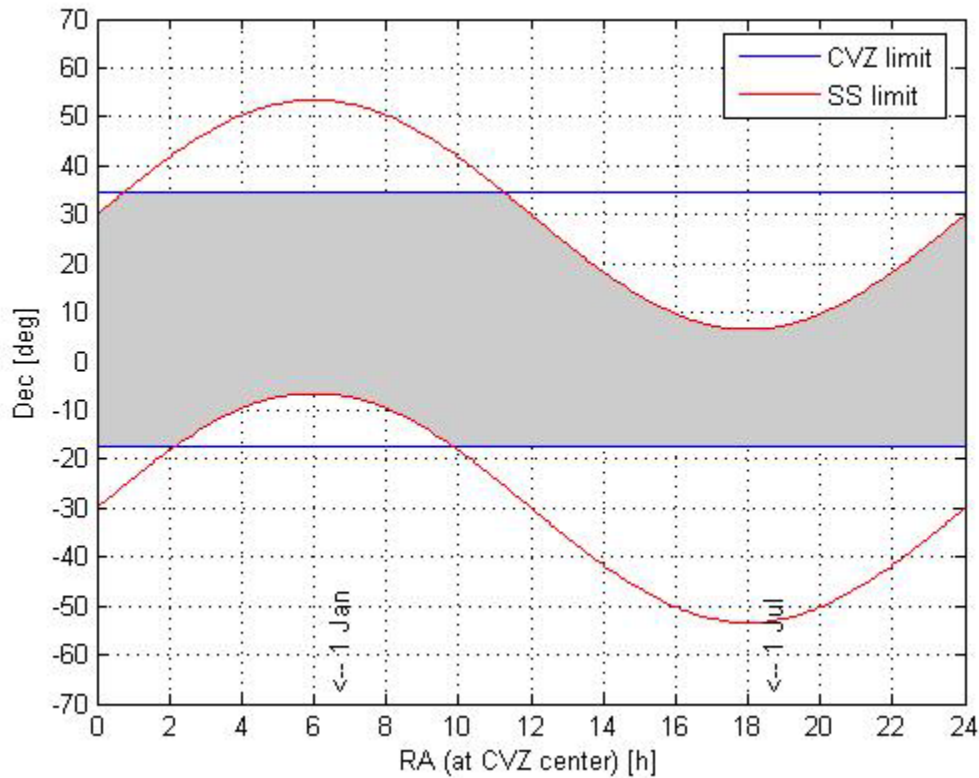


Figure 3 Nominal MOST target range

Pointing Improvement

While the pointing requirement is 25 arcseconds, improvement in the pointing accuracy of the spacecraft leads directly to improved photometric stability and therefore reduced photometric noise in the instrument. And as a result, better science is achievable.

On two separate occasions, major changes have been made to the star tracker algorithms that have dramatically improved the star tracker resolution. This in turn has lead directly to improved pointing accuracy.

The MOST star tracker uses a correlation method to find the best fit of a star image to the star map. The original algorithm that was developed had a resolution of 3 arcseconds, equal to the pixel size on the CCD. The algorithm was modified twice. First the resolution was improved by permitting averaging over many solutions rather than simply taking the best fit at the pixel scale. The second modification was to

adopt a centroiding algorithm to determine the centroids of stars and determine the best fit to the star map. This improved the resolution of the star tracker by enabling sub-pixel interpolation. It has resulted in a factor of 5-10 improvement in resolution of the star tracker.

Figure 4 shows the results of these changes. Similar to Figure 2, the boresight pointing error is shown as pitch error vs. yaw error showing the track mapped out by the boresight of the instrument as the pointing wanders by tiny amounts. The green circle indicates the 25 arcsecond requirement. The red line indicates the pointing performance that was achieved on the target Procyon using the initial algorithm. The result was a 1σ pointing error of 3.8 arcseconds in pitch and 7 arcseconds in yaw. The modified correlation algorithm was implemented on Procyon as well and the results can be shown in the blue line. The star tracker algorithm resulted in a 1σ pointing accuracy of 1.4 arcseconds in pitch and 3.4 arcseconds in yaw. This was a factor of two improvement. Finally, the correlation algorithm shown in yellow resulted in a 1σ pointing accuracy of 0.8 arcsec in pitch and 1.4 arcsec in yaw, a net improvement of a factor of 5 in pointing accuracy. Additionally, the variation in pointing performance from target to target due to differences in the quality and quantity of guide stars has been reduced so that the pointing accuracy varies little from one target to the next.

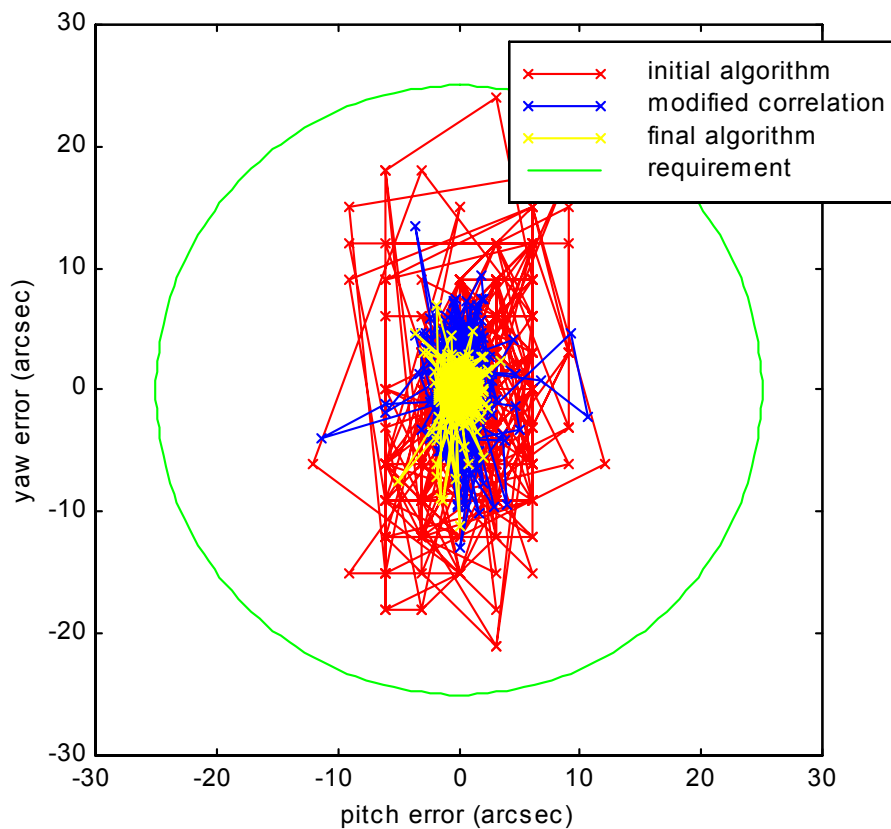


Figure 4 Improvement in MOST pointing accuracy and stability as a result of modifications to star tracker algorithms

This is the first example of how a focussed effort to analyze the on-orbit results pointed towards relatively simple modifications that could result in tremendously improved performance. The key point however is that it was much simpler, much more cost effective to make these changes after launch of the spacecraft rather than before launch. Rather than having to analyze and deal with a host of potential issues associated

with the change to the algorithms prior to launch, post-launch there was much more experience with what the actual issues and actual limitations were.

Guide Star Photometry

A direct result of the modifications to the star tracker algorithms was the ability to provide scientifically relevant data on the photometric stability of all of the stars in the fine star map. Photometric data on these guide stars provided an entirely new stream of science data for the mission. In addition to the primary and secondary targets which are imaged on the science imager, the guide stars represent tertiary scientific targets.

The initial correlation algorithm used only a single bit of information on the brightness of a potential star. This was not important for science purposes. However, when the centroiding algorithm was introduced, full 14 bit information on the guide stars was available. To make guide star photometry even more effective, guide star signals for each relatively short guide star exposure were stacked for the full duration of science exposures and passed to the science computer for incorporation in science data collection.

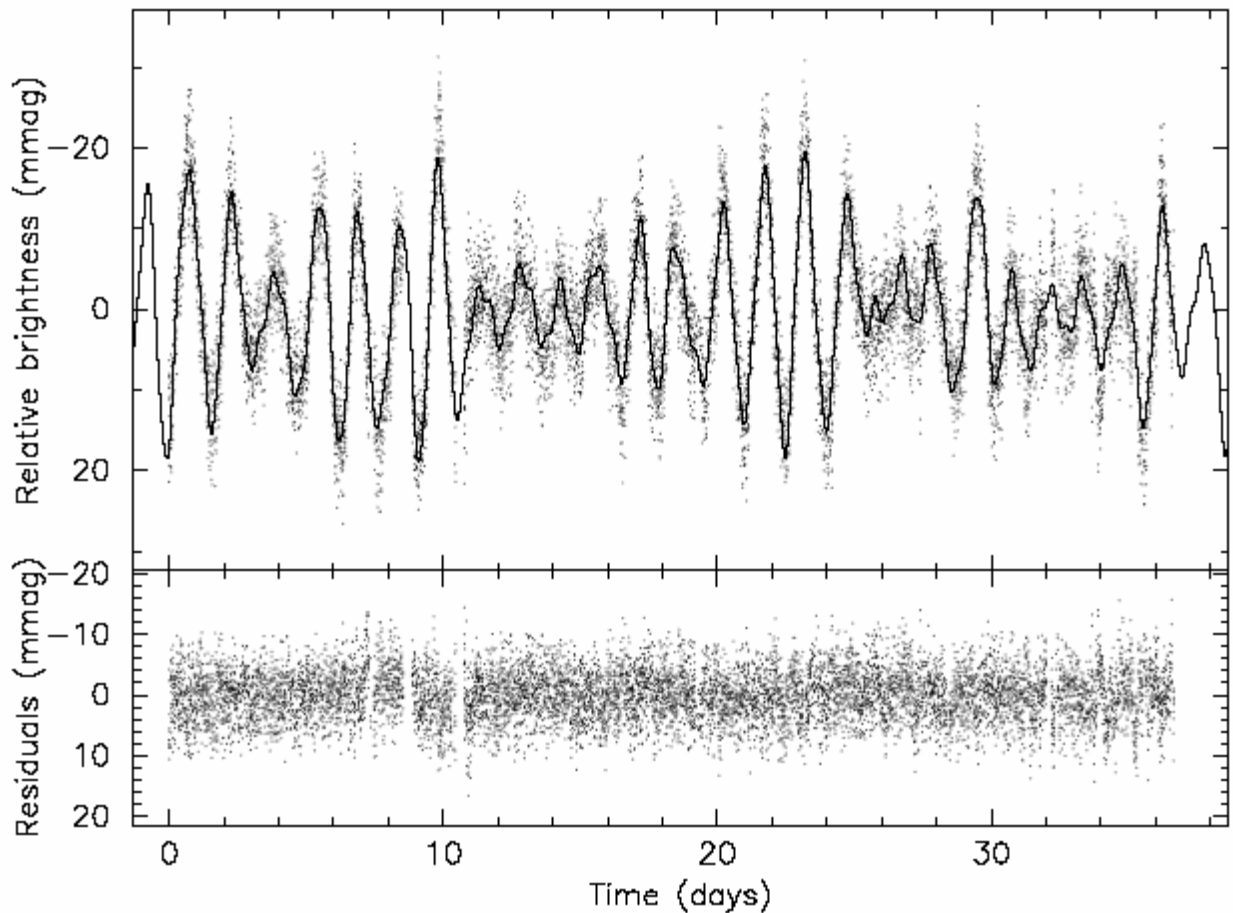


Figure 5 Top: the observed light curve of HD 163830 (dots) is compared with the final fit of a model of 20 oscillation frequencies. Bottom: residuals after subtraction of the final fit

The consequences of adding guide star photometry capability to the mission have been significant. While MOST was designed to have a single primary target and up to 3-4 secondary targets in each field, the

addition of guide star photometry has led to between 3 and 20 additional targets with every field. These targets can be observed with photometric accuracy of down to 15 μmag compared with primary science photometric accuracy of 1 μmag . Of 174 guide stars that have been observed since guide star photometry was introduced, 40 have exhibited detectable photometric variation. Figure 5 shows the results of observation of HD 163830 [1]. This star is a newly detected slowly pulsating B star with the largest number of detected frequencies for this class of star by more than a factor of three.

Expanding Target Capabilities

Over the course of the last almost three years, the capacity to acquire targets originally considered unattainable as grown substantially. The first significant expansion concerned an important scientific target β Virginis. This target had a very poor guide star map. Half of the coarse map, which would be used to acquire pointing on the target, was very sparse while the other half was well populated.

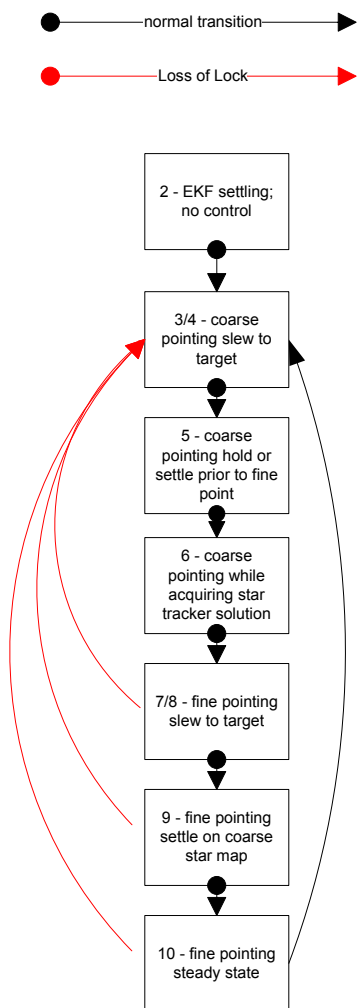


Figure 6 MOST pointing states revised to permit navigation through sparse guide star fields

then upload another command to slew to the target (or another waypoint). In this way, a new class of targets previously considered unreachable, could be targeted.

To make acquisition of targets in sparse guide fields simpler, the structure of the pointing states shown in Figure 1 was revised. What was needed was the ability to navigate through the well populated portions of the star map so that the holes with no guide stars could be avoided. This involved adding three new states.

Figure 6 shows the revised list of pointing states. In both coarse pointing and fine pointing, the ability to hold position once attitude knowledge is acquired was introduced. So for coarse pointing, on exit from pointing state 2 (settling of attitude determination EKF) it is now possible to hold on the initial acquired attitude (pointing state 3) or proceed directly with a slew to the desired target (pointing state 4). Similarly, on exit from pointing state 6 (a newly defined pointing state in which coarse pointing control is maintained while the star tracker is performing the lost-in-space calculation). It is possible to hold (using coarse map star tracker attitude measurement) on the newly acquired position (pointing state 7) or slew directly to the desired target (pointing state 8). Similarly, at the completion of the slew, it was now possible to hold orientation, again using coarse map star tracker measurement, at the end of the slew (pointing state 9). Together, these changes allowed the operators to introduce waypoints on a trajectory that would navigate the spacecraft through the more densely populated regions of the sky. The operators could now command the spacecraft to hold in pointing state 7 following acquisition on a guide star, change the commanded pointing quaternion to a waypoint, proceed with a slew and hold (pointing state 9) at the waypoint,

Over the first two years of operations, the range of acceptable targets was also increased through careful observation and study of the sun sensor limitations. Initially, targets were limited to 30 degrees from the anti-sun direction. However, monitoring of the performance of the sun sensor on-orbit indicated that the valid region for the sun sensor extended to approximately 33 degrees. Therefore, the sun sensor imposed restriction on pointing direction was extended to 33 degrees from the anti-sun region. Secondly, the fine sun sensor is only strictly required to acquire fine pointing, not to hold fine pointing. It is only necessary to provide attitude determination while the star tracker performs its lost in space calculation. Therefore, so long as a target is within 33 degrees of the anti-sun direction when pointing begins, the target can be held until it either leaves the CVZ or reaches 45 degrees from the anti-sun direction. At 45 degrees, temperature, particular of the spacecraft battery, becomes an issue as the side panels that are more exposed to the sun have a greater absorptivity than the front panel that predominantly faces the sun. This increase in target range is shown graphically in Figure 7 which can be compared directly with Figure 3. The dark grey zone in the figure shows a slightly larger target region when the sun sensor limitations were effective. The lighter grey zone represents the area in which targets can be held if acquired at lower sun angles.

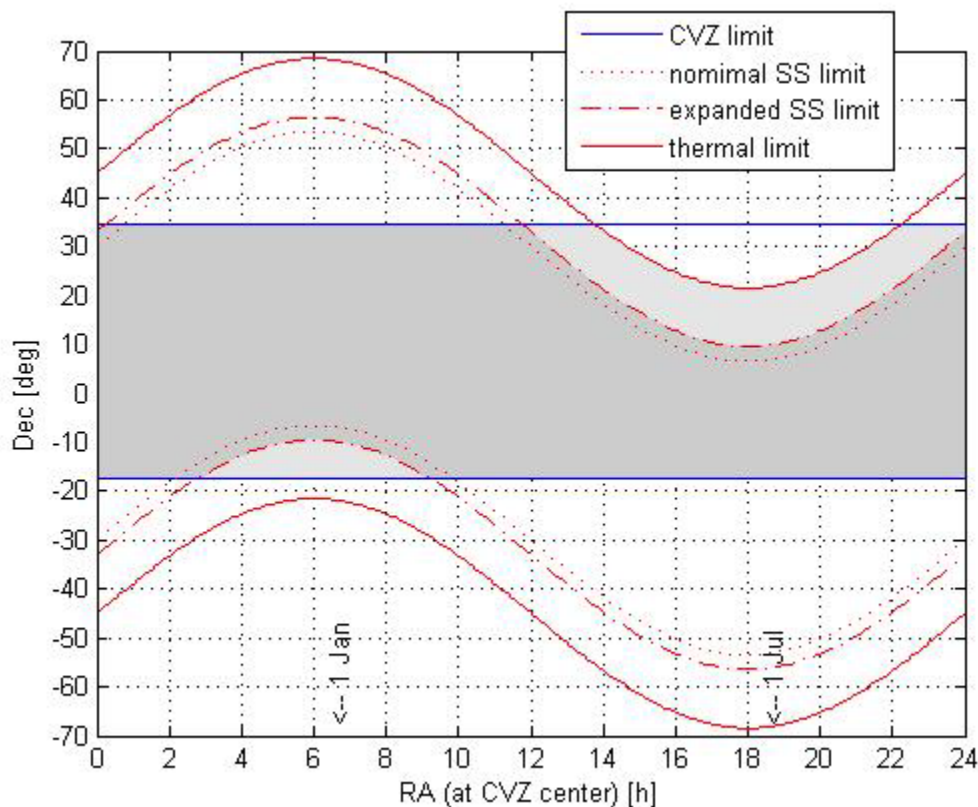
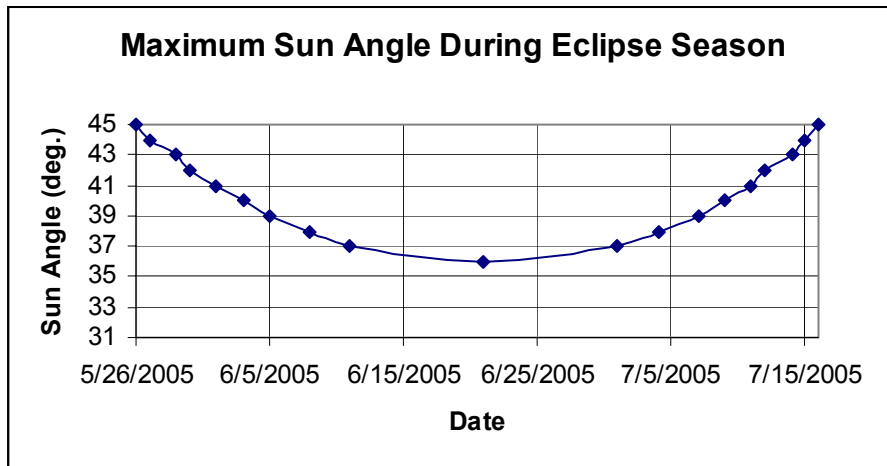


Figure 7 Expansion of MOST target zone based on extending fine sun sensor operation

The MOST spacecraft was launched into a 6pm LTAN sun synchronous orbit at an altitude of 820 km. One characteristic of this orbit is that for most of the year the orbit is eclipse-free. There is a short eclipse season lasting about 12 weeks around the summer solstice. As the MOST spacecraft was originally designed to operate while pointing within 30 degrees of the anti-sun direction, there are also power restrictions on how far from the anti-sun direction the spacecraft can point. However, because the spacecraft was designed to operate at these angles through the longest eclipses in the eclipse season, when eclipses are shorter and outside of the eclipse season, the spacecraft can point at larger angles from the sun. For the first fully operational eclipse season in 2004, MOST launched during the eclipse season and

was in commissioning for half of the 2003 eclipse season, targets were kept within 30 degrees of the anti-sun direction. However, careful analysis of the power generation, power consumption, and battery performance permitted us to expand the acceptable target zone for the 2005 eclipse season.



States 17-20 are identical to 7-10 in that the star tracker is used to determine the spacecraft attitude. The difference between states 17-20 and 7-10 is that in the event of a loss of lock by the star tracker, the spacecraft returns to pointing states 13-16 which rely only on rate sensor information.

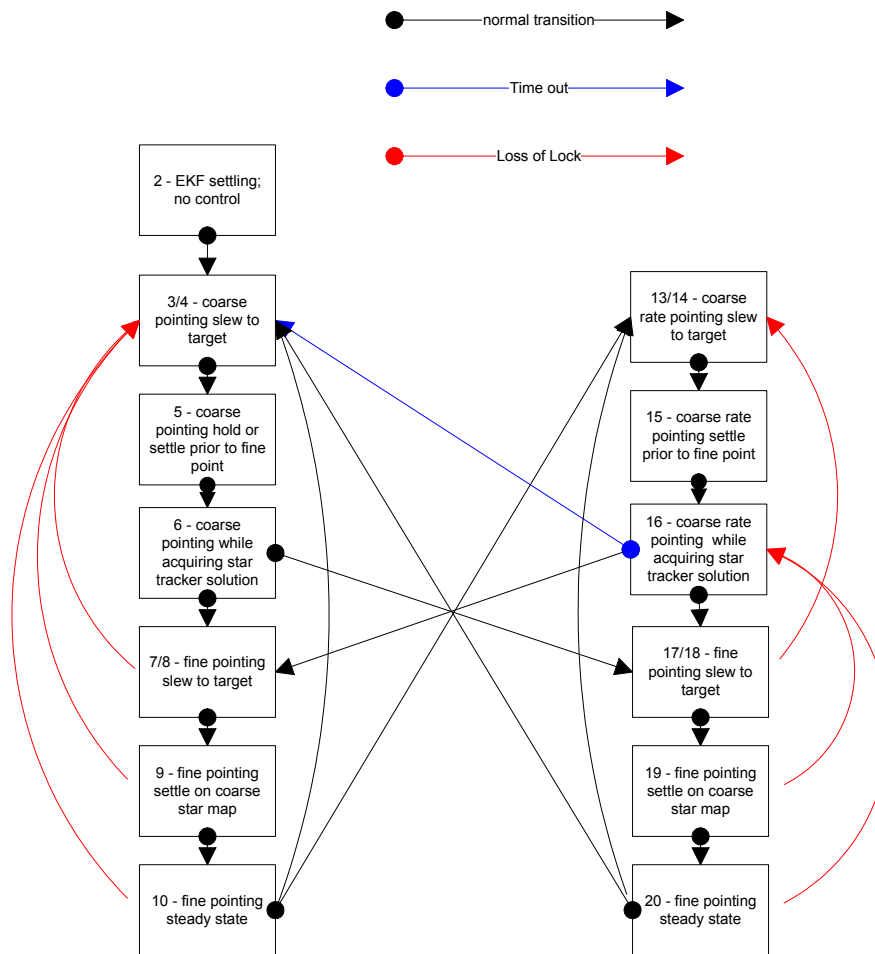


Figure 9 MOST pointing states revised to permit slews using rate sensors only

In addition to the changes in the attitude control software, the software for the science and star tracker computers was modified. Completion of a slew on rate sensors relies on beginning in fine pointing so that the spacecraft attitude is very well known, and ending quickly in fine pointing on the target star. This necessitates have star maps for both the starting and ending points of the slew uploaded on the spacecraft. To smooth the science data collection the science software was augmented to allow multiple sets of science settings so that the science data acquisition can immediately change from one set used for the initial target to another set used for the subsequent target.

These modifications which were initially designed to permit acquisition of targets within the CVZ up to 45 degrees from the anti-sun direction, in fact brought a new degree of operational flexibility. Because it was now straightforward to rapidly slew from one target to another, it became possible to point to more than one target per orbit where it made sense scientifically. As a result, it was no longer strictly necessary to observe only targets that lie within the CVZ. Some science targets require continuous uninterrupted pointing. However, some do not. There are classes of target that can be observed well with interruptions on the order of half an orbit (still much better than is achievable in a ground observation campaign). Therefore, as shown in Figure 10, the only remaining restriction, (and one that cannot be avoided) is the

thermal restriction that limits the spacecraft to point within 45 degrees of the anti-sun direction. This greatly expands the range of targeting capabilities and as a result greatly enhances the scientific capability of the MOST mission.

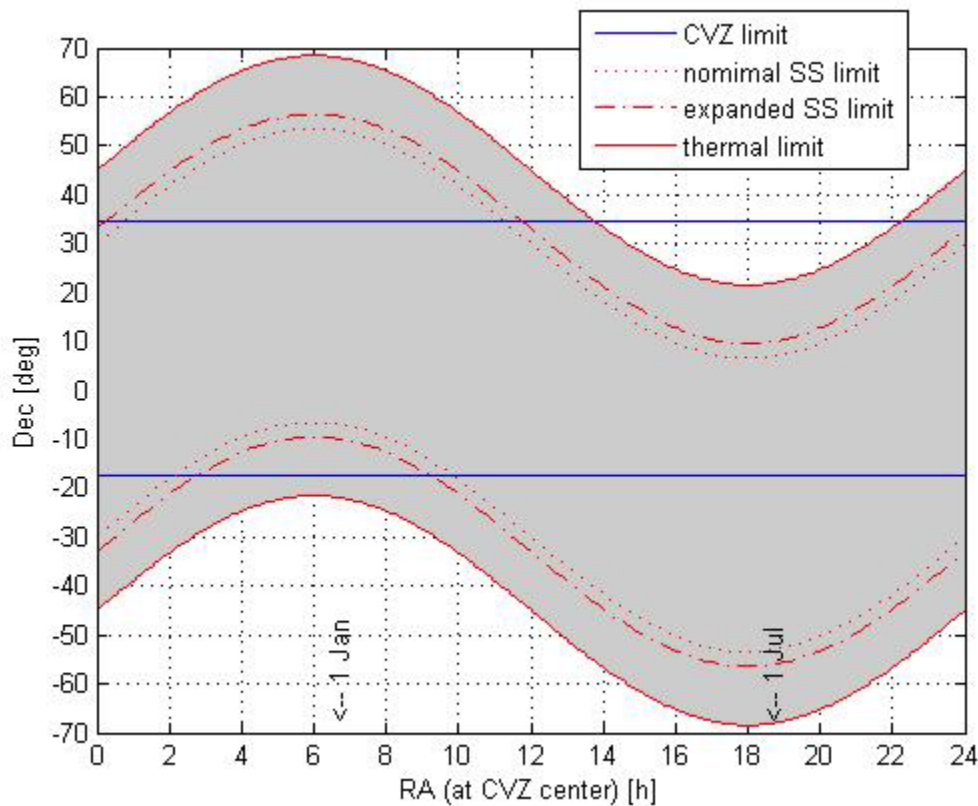


Figure 10 Expansion of MOST target zone based on formalized rate sensor slew capability

NEOSSat Mission Risk Reduction

The NEOSSat mission is the joint development by DRDC and CSA of a microsatellite capable of detecting and tracking Near Earth Asteroids (NEAs) and satellites in orbit around the Earth. The satellite tracking and detection work is R&D in support of the DND Sapphire mission [2].

As a risk reduction exercise for the NEOSSat mission, the MOST spacecraft was tasked to test the feasibility of observing asteroids and satellites from a microsat platform in Low Earth Orbit. These extensions to standard MOST operating procedures are similar in nature and approach to the expansion of MOST capabilities that have already been presented. There was no thought on launch of the possibility of demonstrating aspects of the much more challenging NEOSSat mission. NEOSSat calls for pointing stability on the order of 1-2 arcseconds. This was unconscionable with the MOST hardware prior to launch. However, after the pointing improvements discussed earlier, it was achievable. With relatively few other modifications besides specially designing a set of science software settings for the targets, asteroid imaging was achieved. Figure 11 shows a composite photo of the asteroid 2693 Yan'an. This magnitude 14.7 asteroid was imaged from ~1500-2145 UTC on 5 Dec. 2004. The asteroid was imaged with the spacecraft pointing inertially. Proper motion of the asteroid and parallax due to the satellite orbit around the Earth are captured as the asteroid travelled across the CCD image. The results of the experiment provided the science team for NEOSSat with important information on the detectability threshold for an instrument with the characteristics of the MOST telescope.

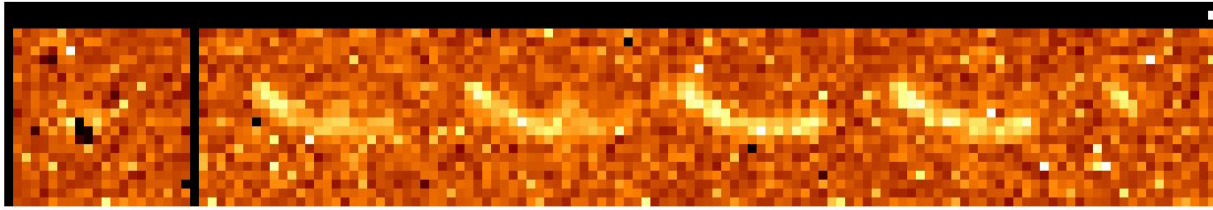


Figure 11 Composite photo of 2693 Yan'an taken 5 Dec 2004 1500-2145 UTC

Satellite imaging proved more challenging because the mode of operations required to capture the satellite images was substantially different from asteroid imaging which by comparison was quite similar to nominal MOST science operations. Two factors required that large CCD images be taken; high relative velocity between MOST and target satellite, and orbital position uncertainty of MOST. Relative velocities on the order of 30-75 arcsec/sec were encountered which would lead to satellite streaks of up to 125 pixels in length. Additionally, MOST uses only NORAD two line elements for orbit determination. The resulting along-track and cross-track errors of both MOST and the target satellites, coupled with using a 30 second window in which to take the image required an image size of approximate 250x750 pixels. These images are considerably larger than any normal MOST science images and in fact required several satellite passes to download. Because the taking of these images did not fall into the form of normal science operations, additional functionality was added to permit a time-tagged image to be taken and stored for later download.



Figure 12 GPS IIR-04 satellite image taken by MOST

Using this added functionality and the already mentioned improved pointing performance that asteroid imaging possible, MOST was able to take images of two satellites. Figure 12 shows a clear satellite streak caused by the GPS IIR-04 satellite traversing the MOST field of view. Figure 13 shows a similar streak caused by the GPS IIR-11 satellite. The results of imaging these satellite streaks are discussed in [2], but with successful capture of these images, the NEOSSat concept has been verified.

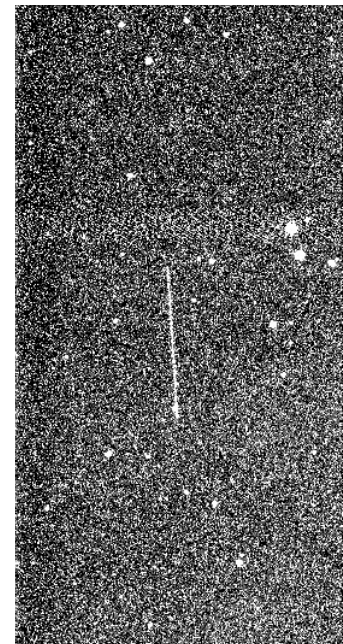


Figure 13 GPS IIR-11 satellite image taken by MOST

Conclusions

Following commissioning, significant improvements have been made to the capabilities of the MOST spacecraft. The purpose of these improvements has been focussed on increasing the scientific output of

MOST. Most importantly, the improvements have been based on the actual on-orbit experience and performance of the MOST spacecraft.

The pointing performance of MOST has been improved by a factor of 5 over the already better than required pointing accuracy that was achieved by the end of the commissioning period. The improvement was important because although the strict requirements were met following commissioning, better performance translated directly to better photometric performance of the instrument. Furthermore, the improvement was achieved by tailoring software modifications to the performance of the star tracker as seen on-orbit.

Guide star photometry was implemented which greatly extended the scientific output of the mission. In the past 2 years 40 of 174 guide stars used has been scientifically interesting and studied with better photometric accuracy than could be achieved from the ground.

Step by step, the target range for MOST was expanded as the actual on-orbit physical limits of the spacecraft were determined. This has led to study of many scientific targets that were not initially considered viable for the MOST mission.

Finally, the MOST spacecraft has been used to demonstrate the feasibility of the NEOSSat microsatellite mission, and serve as a very effective risk reduction exercise for the upcoming mission.

Similar improvements could have been made prior to launch and commissioning. But the key point is that prior to launch and commissioning, the uncertainties in the specific driving factors would mean that the improvements would have been much more labour intensive. Furthermore, any such scope creep before launch should be avoided at all costs precisely because it leads to cost overrun and delay in the program as a whole. By holding strictly to the requirements prior to launch, a cost effective program can be maintained. By then exploring the possibilities of what can be achieved with the satellite, it is possible to expand the capabilities with lower cost and lower risk.

Acknowledgments

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