

The MOST Microsatellite Mission: One Year In Orbit

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ABSTRACT: The MOST (Microvariability and Oscillations of Stars) microsatellite, launched from the Plesetsk Cosmodrome in Russia on June 30, 2003, has had a very successful first year in orbit. MOST is an astronomical science mission designed to measure brightness variations as small as a few parts per million in bright nearby stars. This application demands a pointing accuracy that is not normally associated with microsatellites. One requirement for the MOST mission was that the spacecraft point the boresight of the science instrument (a 15-cm optical telescope feeding a CCD camera/photometer) to an accuracy of 25 arcseconds. In practice, the MOST attitude control system (ACS) far exceeds expectations, achieving a pointing accuracy of between 3 and 5 arcseconds on a regular basis. The instrument reaches a photometric precision at least 25 times better than anything ever attained, from the Earth or space.

This success did not come easily, but after a commissioning process that lasted about 5 months and had to overcome several unexpected hurdles. The most serious of these included an unexpectedly high level of stray Earthlight leaking into the instrument focal plane, and the corruption of 1 random block of RAM (of 32 in total) in the onboard computer, which was not recognized until well after launch.

In this paper, the post-launch history of MOST will be described, with special emphasis on achieving the unprecedented ACS performance. Some of the exciting early scientific results, which in one case has overturned two decades of previous theory and observation, will also be summarized. The next instrument capable of matching the duty cycle and photometric precision of MOST will be the COROT satellite, a CNES mission due for launch in 2006. COROT represents a more conventional (hence, more costly) approach to this type of space science mission, and direct comparisons between COROT and MOST will be made.

OVERVIEW

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 is 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 and using it to determine the composition of their atmospheres.

The objective of this paper is twofold. The first is to describe the team's experience in commissioning the MOST satellite. The second is to compare the MOST

satellite mission to a larger, non-microsatellite mission with similar objectives.

The paper begins with a description of the commissioning of the satellite. An overview of the planned commissioning process is presented followed by a description of what actually happened.

Following this, some of the initial science results from the prime astronomical target of the MOST mission, Procyon, are presented. These results demonstrate the tremendous success of the MOST mission to deliver top quality scientific discoveries.

The Procyon results are profoundly different from what was expected. These differences are having a ripple effect across the science community and forcing other missions, including the COROT mission, to reanalyze their capabilities in the context of the MOST results.

This demonstrates a very useful role of the microsatellite as forerunner or pathfinder for larger more expensive missions, not merely to demonstrate technology that might be required for such missions, but to perform scientific investigation as well.

SATELLITE DESIGN OVERVIEW

The satellite design has been described in Grocott *et al* (2003). However, for ease of understanding a brief description of the functionality will be provided. This is meant as an aide to understanding the commissioning activities that will be described shortly.

Figure 1 shows the MOST electronic architecture. This shows the major functional units that make up the MOST satellite. The housekeeping computer, which is central to the design and the figure, is an off-the-shelf product that has been modified to meet MOST requirements. Based on a V53 processor, the computer's crystal frequency has been increased from 9 MHz to 29 MHz to accommodate the processing demands of the mission. It interfaces with the rest of the satellite through a custom interface card that provides power, serial and digital I/O connections. The housekeeping computer's main tasks include receiving, executing, and distributing commands and/or files uploaded from the ground, and collecting and transmitting engineering and science data to the ground.

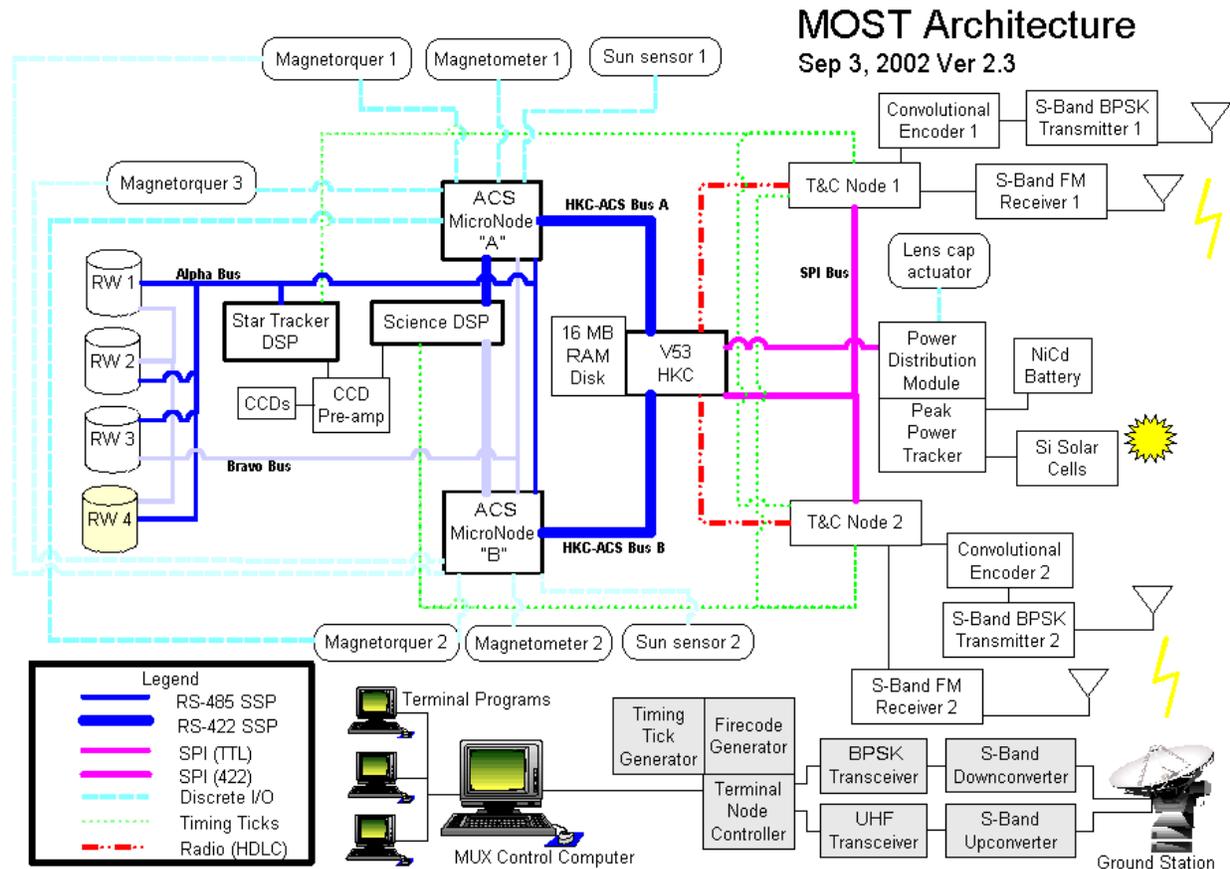


Figure 1 MOST Electronic Architecture

In the figure, roughly from the V53 to the right, the satellite design is typical of AMSAT based designs. It consists of the main housekeeping computer (V53), two radio transmitters and receivers including support electronics, and the power system for the satellite.

The V53 computer forms the major functional unit of this portion of the satellite as it is through software on the V53 and direct command to the V53 that this portion of the satellite is controlled. Note that the power system contains electronics that control a door that covers the aperture of the telescope to protect the telescope from direct sunlight. The command interface for this door is through the V53.

In this portion of the satellite, telemetry sensing consisting primarily of temperatures and power system information (battery voltages and currents, solar panel voltages and currents, and power switch states and currents), is distributed but controlled through SPI commands from the V53.

The V53 software consists of three layers. On boot-up the V53 executes a Bootloader that has minimal functionality primarily allowing the upload of software. Pre-positioned on the V53 is a SCOS (Spacecraft Operating System) kernel and a task called PHT. This task enables limited functionality of the V53 computer that permits real-time command and response from the V53. Finally the third layer of software which provides full functionality of the V53 is uploaded from the ground.

To the left of the V53 computer in Figure 1 is the equipment that makes the MOST satellite unique for a microsatellite in the scientific contribution that it can make. These are the electronics to support the telescope, and the attitude control system (ACS) hardware and electronics. The ACS equipment consists of magnetometers, sun sensors, and a star tracker for sensing, and magnetorquers and reaction wheels for actuation. The design includes redundant ACS computers, sun sensors, magnetometers, magnetorquers and reaction wheels (a 3-axis prime and redundant skew reaction wheel configuration).

Science and star tracker images are taken on dual 1024x1024 CCD arrays that share the focal plane of the telescope. Each CCD is connected to a pre-amplifier, and to analog and digital electronics boards. These units each form separate functional units in the satellite. However, the star tracker is grouped together as part of the ACS system.

The ACS computer, Star Tracker DSP and Science DSP contain two stages of software. Similar to the V53, the first stage is a bootloader that has some limited functionality and allows upload of new software. The second stage is the fully functional software and is pre-positioned in FLASH memory in each computer. Therefore on boot-up, these units can be loaded with to their full software load without requiring upload of software from the ground.

There are four attitude control modes for the satellite:

Safe-Hold: . The satellite is essentially power positive in all practical orientations. This is an uncontrolled state in which there is no active attitude control. In this mode, the focus is nominally on commissioning or recovery operations.

Detumble: This mode involves using the magnetometers and magnetorquers to implement B-dot control to slow the tumble rate of the satellite so that coarse pointing control can be executed. Normally this is used after kick-off from the launch vehicle.

Coarse Pointing: After the satellite is detumbled, the ACS uses sun sensors and magnetometers to determine the spacecraft attitude, while using reaction wheels to control the attitude to orient the main solar array towards the Sun and to roughly point in the direction of science interest. The magnetorquers are used to desaturate the reaction wheels.

Fine Pointing: The ACS utilizes the star tracker to determine spacecraft attitude. The reaction wheels are used to control attitude. Again, the magnetorquers are used to desaturate the reaction wheels.

Three ground stations in Toronto, Vancouver and Vienna are used to communicate with the satellite by sending commands and receiving data. The primary control station is located in Toronto, while the secondary stations (Vancouver and Vienna) are controlled and coordinated over the Internet.

There are four major data flows for this satellite. Real-time command and response is the first. The system architecture enables real time command and response from any unit on the satellite. In this mode, the V53 acts as the primary conduit for command and response messages. Commands not destined for the V53 itself are forwarded to the active ACS computer. The ACS computer acts as the secondary conduit forwarding all messages not destined for it to the remaining units. Responses are passed back to the unit from which the command was received and are relayed to the ground

from the V53. Note that this is the primary form of communication during active satellite passes.

The second major data flow is whole orbit telemetry. Throughout all orbits, the V53 software is designed to collect and store telemetry on the health and status of the entire satellite.

The remaining data flows contain science data. Science Data Stream 1 (SDS1) contains critical science data that would permit minimum science goals to be achieved. SDS1 contains approximately 1 MB/day when science observations are underway. Science Data Stream 2 (SDS2) contains additional science data that allows multiple targets to be observed as well as providing increased resolution data for the primary science. These data streams are generated by the Science DSP and pushed to the ACS computer at high data rates where the data is buffered. The V53 computer then collects the data at a steady lower data rate and stores it on the RAM disk. In fact the need for the Science DSP to send out its data very rapidly was the design driver that led to the Science DSP being connected through the ACS computer rather than connected directly to the V53.

COMMISSIONING PLAN

As initially conceived, the commissioning plan consisted roughly of eight steps

1. Health Monitoring
2. Spacecraft software upload
3. ACS equipment checkout
4. Detumble spacecraft
5. Coarse Point
6. Star Tracker checkout
7. Fine Point
8. Science commissioning

The spacecraft begins its life in safe-hold mode. In this mode, there is no attitude control. Solar panels on all sides of the spacecraft ensure that adequate power is available in all attitudes so that the V53 computer, radios and transmitters (when commanded) can be powered. The initial phase of commissioning is health monitoring. This consists of booting the pre-positioned V53 software and collecting real-time telemetry. The telemetry available is primarily the power status of the spacecraft and the units that are powered on as well as temperature data.

The next stage in commissioning is the upload of the full load of V53 software. There are approximately eight SCOS tasks in the full load of V53 software. The upload of these tasks is to occur over at least 4 satellite passes, and therefore take more than a day.

The third stage is the planned checkout of the ACS equipment required to point the spacecraft in the coarse pointing mode, i.e. this does not include the star tracker. This consists of three main activities. First is the checkout of the ACS computer and the magnetometer and sun sensors which are directly connected to the ACS computer. The checkout consists primarily of communication with the ACS computer and sampling the sensors when they were powered on. The second task is a checkout of the magnetorquers that involves commanding the torquers individually to their extreme values and monitoring the power consumed by the ACS computer that contains the drive circuitry. The third task is to check out the reaction wheel and rate sensor (housed within the reaction wheels) functionality. The rate sensors are to be enabled and then each wheel sequentially commanded so that the response of the wheels would be evident in the rate signals.

Following checkout of the ACS equipment, the fourth stage of commissioning is to detumble the spacecraft. On kick-off from the launch vehicle it is expected that the spacecraft would be in an uncontrolled tumble with body rates significantly larger than the momentum storage of the reaction wheels. The objective of Detumble mode is to reduce the spacecraft momentum to a level that can be absorbed by the reaction wheels upon entry into the coarse pointing mode.

The fifth stage in commissioning is to enter coarse pointing mode. The first pointing objective is simply to place the main solar panels directly opposite the sun so that full power generation can be maintained. The intention is that if any anomalies in pointing occurred, that these would be addressed first in Coarse Pointing mode before adding the complexity of interfacing with the Star Tracker.

The sixth stage is to checkout the star tracker and involves fundamentally four steps. First is to simply take images to ensure the proper function of the CCDs. The second step is to identify the attitude of the spacecraft from sample images. Third is to verify the polarity of the star tracker. Fourth is to begin using the star tracker to estimate attitude in a continuous method. Note that this is different from entering fine pointing mode. The star tracker is providing attitude measurement that is not fed back in the control system. The spacecraft is in coarse pointing mode.

The seventh stage is to use the star tracker in fine pointing mode. Entering Fine Pointing Mode consists of three steps. The first is acquiring the spacecraft attitude. Given that Coarse Pointing Mode is expected to be accurate to only 2-3 degrees, the star tracker

performs a lost in space calculation to determine the actual attitude. From there the ACS software generates a slew trajectory to take the spacecraft to the intended position. Finally the star tracker enters a more precise measurement mode when the slew is completed.

Finally Science commissioning rounds out the commissioning activities of the spacecraft. This contains similar steps as the initial star tracker commissioning in testing the functionality of the CCDs. Test images are planned with the aperture door closed to measure the dark current in the CCD (therefore this step actually takes place before most of the star tracker commissioning). The aperture door is opened. This is followed by sample science data to be taken. Finally, preliminary science targets that demonstrate variability are observed to verify the scientific functionality of the instrument.

In total, this commissioning process was expected to take approximately two months.

COMMISSIONING IN PRACTICE

How the satellite was commissioned in practice varied considerably from what was planned, not so much in what the steps were, but the order in which they were carried out. This resulted primarily from five problems, two major and three minor, that were uncovered during the commissioning process.

Launch of MOST took place at 14:15:25.395 UTC on 30 June 2003 from the Plesetsk cosmodrome in northern Russia. Separation from the launch vehicle took place approximately three hours later. Four and a half hours after that MOST made its first pass over the ground station at the University of Toronto Institute for Aerospace Studies (UTIAS). On that pass, communication was established with the spacecraft. The pre-positioned software on the V53 was executed and real-time telemetry was downloaded from the spacecraft. The data showed that the spacecraft was very healthy, with the battery fully charged and the main solar panels receiving power. On the remaining passes on launch day, telemetry was downloaded as planned showing the spacecraft to be healthy and exhibiting a tumble of approximately 3 deg/sec in which the main solar panels regularly crossed the sun. Stage one of the commissioning process was successfully completed.

Stage two of the process proved to be considerably more difficult not truly being completed until five months later. The SCOS software environment coupled with our ground station software made upload of V53 software tasks difficult. Frequent crashes occurred as a

result of improperly loaded software resulting from dropped packets. The dropped packets occurred as a result of minor ground station issues. The most significant of these was an EMI problem between the elevation controller and the BPSK receiver. When elevation control would step, the communications link would be dropped. The ensuing communications packets that were dropped would sometimes result in the V53 not receiving certain critical packets at the correct time resulting in a crash of the V53. The ground station software was developed in an environment in which dropped packets were a rarity and therefore ground testing did not reveal this weakness. The ground station software was made more and the equipment in the ground station rack was shuffled so that the antenna rotator controller was not located near the BPSK receiver. This allowed us to make progress in uploading software to the V53.

In so doing, software to enable communication with all units on the spacecraft was uploaded and shown to be working well. However, difficulty arose shortly afterward in attempts to store and download whole orbit telemetry. Attempts to download significant amounts of stored data resulted in a situation where the communication was lost with the spacecraft. Resetting the V53 through a firecode would restore communication. It was eventually found that the V53 could get into a state in which it would not receive commands from the receivers. As a result, the transmitters would not be turned on and no communication would occur. It took nearly 4 months to identify the root cause of the problem and to create software that could work around the problem. This eventually led to a complete rewrite of the V53 software to enable a reset of the devices that would lock up. In the meantime, the spacecraft went without continuous whole orbit telemetry data, but the remaining stages of commissioning occurred in parallel. Whole orbit data could be available for short periods of time as it was found that the V53 would remain in communication for up to 12 hours before the communication problem would develop. However there were significant periods of time in which the spacecraft had no whole orbit telemetry as the debugging process required considerable time to isolate which software tasks tickled the receiver problem.

Throughout the debugging process, the ground “flatsat” consisting of flight spares of most of the equipment on the satellite was used to test the hardware and software, but the communications problems were not repeatable in our setup. It was hypothesized that there was significantly more noise entering the satellite receivers creating substantially more V53 interrupts than occurred during “flatsat” testing prior to launch. The

V53 was not capable of handling these interrupts. This hypothesis would later prove critical to establishing operation science data gathering.

Stage three of commissioning involved checkout of all of the ACS components. This proceeded in parallel with the V53 commissioning as soon as the software task to allow communication with the ACS node was uploaded. The ACS equipment commissioning went smoothly. All of the sensors and actuators were functioning normally. Real-time telemetry download during ground station passes showed that the spacecraft attitude remained essentially unchanged, a 3 degree/sec tumble that rotated the main solar panels across the sun each revolution. As a result the power situation was very stable, and there was no need to rush into detumble or coarse pointing mode. The decision was made to hold off on these stages of commissioning until whole orbit data was retrievable since debugging of these would be difficult without it should it be needed.

When whole orbit telemetry was stable for short periods of time, the decision was made to proceed with detumble mode and coarse pointing. On 24 July 2003, the spacecraft was commanded into detumble mode. Figure 2 shows the magnetic field measured by the spacecraft prior to and during this maneuver plotted versus time where the detumble command was sent at Time 0. Prior to initiation of the detumble command, the spacecraft is tumbling at a rate of approximately 3 deg/sec. This can be seen by the roughly 120 second period of oscillation of the magnetic field as measured by the spacecraft. Upon entering the detumble mode the spacecraft was rapidly detumbled. Within one orbit or approximately 6000 seconds, the spacecraft body rate was reduced to less than 0.1 deg/sec. Stage four of commissioning was successfully completed.

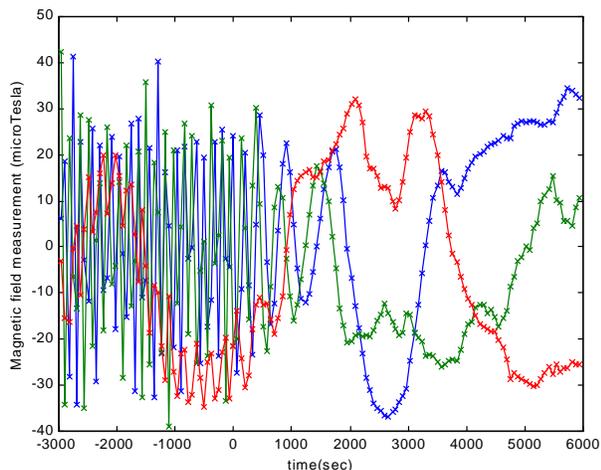


Figure 2 MOST spacecraft detumble whole orbit telemetry

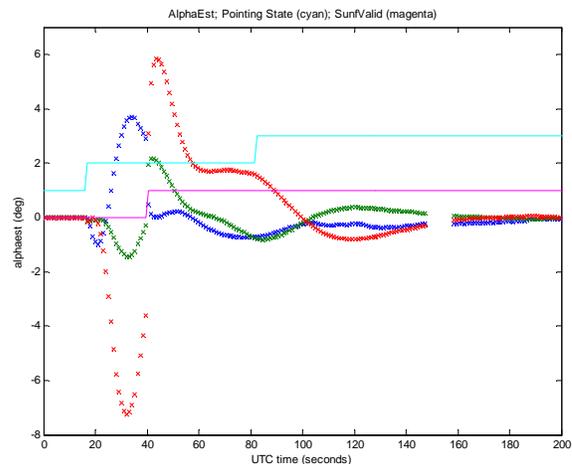


Figure 3 MOST pointing error during initial coarse pointing command

With the spacecraft detumbled (rotating at less than 0.1 deg/sec), it was now in its most vulnerable attitude concerning power. It could now have the main solar panels point away from the sun for several thousand seconds rather than less than 100 seconds when it was rotating at 3 deg/sec. Commissioning therefore proceeded to stage five, coarse pointing.

On 25 July 2003, the spacecraft was commanded to point the telescope directly opposite the sun, which would result in the main solar panels pointing directly toward the sun. The results are shown in Figure 3. The figure shows the estimated pointing error in three axes (the blue, green and red x's indicating roll, pitch and yaw respectively), the pointing state (cyan) and the fine sun sensor validity flag (magenta). The spacecraft begins in Pointing State 1 which is EKF acquisition. In this state, the spacecraft attitude is not controlled. It is only estimated. This is the period of convergence for the Extended Kalman filter (EKF). Only the last 20 seconds of the 100 seconds period is shown in the figure. At the end of this period, the estimated attitude is compared with the desired pointing direction and a trajectory is autonomously calculated which will take the spacecraft from its initial attitude to the desired attitude. During Pointing State 2 from (20 to 80 seconds in the figure), the spacecraft is slewing at a maximum speed of 1 deg/sec along the trajectory that was calculated. Finally, in Pointing State 3, the spacecraft is holding attitude at the desired target. The slew begins outside the range of the fine sun sensor as evidenced fine sun sensor validity at 0. There are moderate pointing errors during the slew of up to 7 deg. At approximately 40 seconds, the fine sun sensor becomes valid indicating that the main solar panels of

the spacecraft are within 30 degrees of the sun. At this point, the pointing error makes a step change as the attitude information available from the fine sun sensor enters the EKF, and the information provided by the coarse sun sensor (gathered from solar panel currents) is dropped. The step change is approximately two degrees in roll and yaw and six degrees in pitch. The estimated pointing errors are diminishing as time progresses. When the slew finishes, the pointing error is less than two degrees as measured by the magnetometer and sun sensor, and settles within 100 seconds to less than 0.1 deg. Note that these errors are estimated, not actual. The actual errors are expected to be within about 2-3 degrees and will vary with orientation due to the accuracy of the sun sensor and magnetometer. The step change in estimated attitude when the fine sun sensor becomes valid indicates that the measurement error due to the coarse sun sensor is on the order of 7-8 degrees in this particular orientation. The expectation was that it would be valid to within approximately 10 degrees.

After coarse pointing was entered, commissioning of the star tracker and the science instrument began in parallel. One of the main reasons that science instrument commissioning was performed at this stage was because it was possible. The SDS1 data stream was buffered on the ACS computer. In real-time, ground station software could retrieve data from the buffer, thus bypassing the data storage and retrieval problem that was being solved in parallel on the V53. The buffer was limited in size, but it did permit size data to be collected over an entire orbit if the frequency of science exposures was not too high.

Initial dark images taken when the aperture door was closed showed some unsettling signs of light leakage into telescope. The amount of light getting in appeared to be small, however it was an indicator of a bigger problem that would be encountered.

On 29 July 2003, the door that covers the aperture of the telescope was opened and the telescope saw first light. Figure 4 shows (on the left) the star as it illuminates six pixels on the CCD. The right hand side of the figure shows a 3D contour of the pixel intensity. First light showed that the CCD was performing very well and that the point spread function (PSF) of the telescope was within the expected range.

However, whole orbit data showed a more disturbing image. With the aperture door open, there was considerably more stray light than had been expected. Further investigation showed that the amount of stray light differed as a function of roll angle of the spacecraft about the boresight of the instrument. Figure 5 shows mean signal level collected on the science

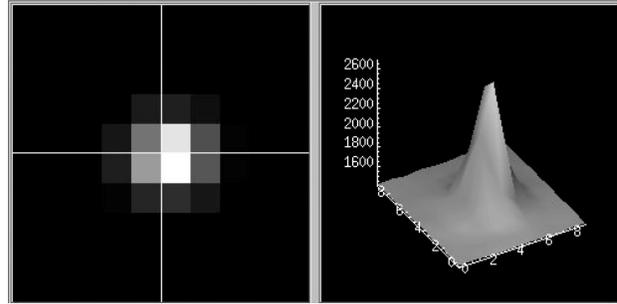


Figure 4 First light, a faint star in the constellation Capricorn

CCD with the spacecraft at three different roll angles as a function of orbital phase. Two effects can be seen that have been categorized as diffuse and specular stray light effects. The diffuse stray light can be seen in the rounded hump that appears in the signal level from orbital phase 0.7 to 1.0 and again from 0.0 to 0.2. This is stray light reflected from the Earth that is entering the telescope aperture and is likely the result of insufficient baffling in the instrument. The general shape of the light curve is quite smooth for the roll angle of 90 degrees, however at roll angles of 0 and 180 degrees, superimposed on top of this light curve are sharp peaks that occur at particular phases of the orbit. For a roll angle of 0 degrees it peaks at a phase of 0.8. For a roll angle of 180 degrees it peaks at an orbital phase of 0.1. This corresponds to Earth light arriving from particular directions being more troublesome and has been called specular stray light. It was named this because it is expected to be caused either by specular reflection from some portion of the spacecraft, likely a portion of the aperture door mechanism, or enters directly through openings in the spacecraft such as vent holes.

The stray light forced a rethink of how the star tracker identifies stars. Significant background light removal

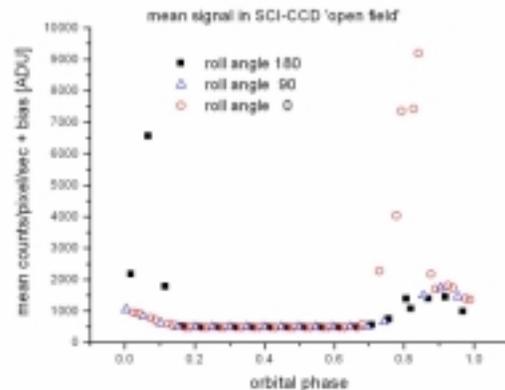


Figure 5 Stray light reaching the focal plane of the telescope

was required to allow the star tracker to identify stars above the background light. The star tracker software was modified to allow for dynamic background removal. Once this was completed and tested, the commissioning proceeded to stage seven, fine pointing.

Fine pointing mode was first entered on 16 September 2003. The results were quite good, the pointing accuracy of the spacecraft was maintained within 25 arcsec as required when the star tracker was able to maintain lock. However, at peak stray light and during passes through the South Atlantic Anomaly (SAA) lock was often lost and the spacecraft would drop into coarse pointing mode. It was difficult to determine the reasons why lock was lost primarily because there was no whole orbit data available. The spacecraft communication problems were still unresolved. However through some trial and error, this was rectified by tweaking some parameters, i.e. without changing the software, and steady reliable pointing within the required 25 arcseconds was obtained on 7 Oct 2003.

Figure 6 shows the pointing accuracy obtained at that time. The red circle indicates the 25 arcsecond 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.

Following this, commissioning activities were focussed on the final stage, science commissioning beginning on 9 Oct 2003. Several scientifically interesting targets were chosen in the run up to the prime target Procyon which would be viewable at the end of December 2003. The targets were designed to test the ability of the instrument to view bright objects such as Procyon and to detect variability where it was known to exist. This was accomplished and some scientifically useful results were obtained.

During this period, an operational workaround for downloading scientific data was implemented. The SDS1 and SDS2 data streams were planned to be buffered on the ACS computer and then retrieved by the V53 software. However ground software was capable of directly accessing the ACS computer buffers. Therefore, the ACS computer software was reconfigured to allow for larger buffers of data. This permitted continuous high rate SDS1 data to be stored and downloaded. In addition, approximately 10 minutes per orbit of SDS2 data was available for download. This volume of SDS2 data permitted the science team to verify that the SDS1 data were valid.

The distributed nature of computing on the MOST spacecraft, with many computer performing different

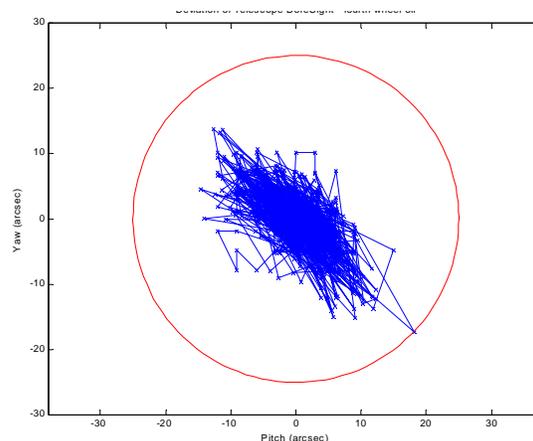


Figure 6 MOST preliminary boresight pointing error

tasks, allowed the operations team to reconfigure the system to provide for the science data to be retrieved. Additionally, difficulty with the V53 did not prevent the spacecraft from maintaining attitude control or performing science tasks. Effectively on 9 October 2003, three months after launch, the system was delivering on the minimum science requirements of the mission.

Throughout the science commissioning activities efforts were still focused on debugging the communication problem with the V53. This finally led to the abandonment of most of the SCOS functionality in the V53 software, and a single task was written to perform all of the required functions of the V53. One of the key additions as already mentioned was to periodically reset the devices in the V53 that connect to the receivers. Following completion of this the last minor problem that was encountered became evident. A great deal of confusion was caused during the debugging of the V53 by the occasional presence of corrupt data files. Having abandoned the SCOS file system, data files were directly stored in known locations in RAM. Once this was done it became evident that the corrupt data files were associated with one of 32 RAM chips on the RAM disk. The software was modified to avoid this area of RAM and commissioning was completed on 11 Dec 2003 a little more than five months after launch.

Overall, the initial problems associated with the ground station and uploading of V53 software were really just teething problems. These were bothersome until they had been resolved, but were easily resolved. Similarly at the end of commissioning the problem with the RAM disk was minor in nature and easy to work around.

V53 communication outages were a major problem that took nearly four months to solve because of the nature of the problem, the fact that it was not repeatable on orbit and not reproducible on the ground. This was a major setback but one that was successfully overcome.

Straylight in the instrument is perhaps the most significant of the problems encountered. It significantly delayed the acquisition of science data because it forced a redesign of star tracker software. This redesign was wholly successful in that the star tracker is now reliable and accurate throughout the stray light period. As far as the science goes, data processing has been affected by the straylight. However, the spacecraft is still able to meet its scientific objectives. All of the other problems were solved. Straylight cannot be solved; merely managed.

POST-COMMISSIONING IMPROVEMENTS

Operations of the MOST satellite involves short bursts of intense activity surrounding the acquisition of a new target, followed by weeks of simple monitoring of data and data flows from the spacecraft. Many of the targets that have been observed have presented challenges; poor guide star fields, close proximity to the bright limb of the Earth and other such things. Often, between targets, software has been modified to address these challenges, or to enhance the capabilities of the spacecraft. One such change has been an increase in the data throughput. The spacecraft is delivering twice the data throughput that was originally planned.

Of particular note are improvements that have been made in the pointing accuracy of the spacecraft. 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.

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

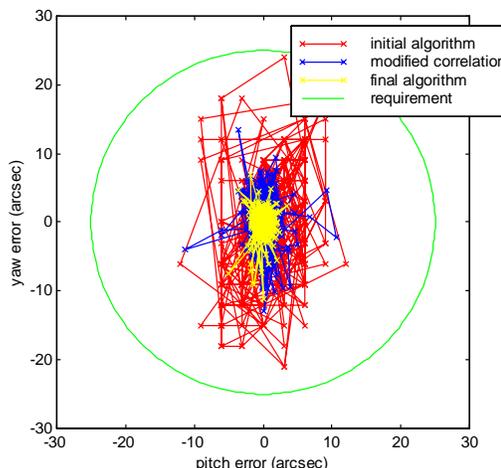


Figure 7 Improvements made to the spacecraft pointing accuracy

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 7 shows the results of these changes. Similar to Figure 6 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.

The star tracker improvements have reached the point where star tracker resolution is no longer the limiting factor in the pointing accuracy of the spacecraft. It is now evident that with the present control system design, external disturbances are now the limiting factor. In particular magnetic disturbances are now the limit on the pointing performance. The dominant terms in the pointing error are second, fourth and higher harmonics of the orbital period corresponding with the

effect of the Earth's magnetic field on the spacecraft residual magnetic dipole.

SCIENTIFIC RESULTS

The primary scientific goals of the MOST mission are: (1) to detect and characterize rapid oscillations in the optical light output of Sun-like stars to seismically probe their internal structures and ages; (1b) in particular, to apply this approach to some of the oldest stars in the solar neighbourhood to set an independent lower limit on the age of the Galaxy and the Universe; (2) to perform seismology of strongly magnetic stars with peculiar atmospheres to explore the exotic physics in these stellar environments which cannot be reproduced in terrestrial laboratories; (3) to measure the rapid light variations in hot massive stellar winds to better understand how gas is injected into the interstellar medium to fuel future star formation; and (4) to detect reflected light from giant close-in exoplanets ("hot Jupiters") orbiting nearby Sun-like stars, to help model the atmospheres of these mysterious worlds.

At the time of writing, MOST has already: detected oscillations in the solar-type star eta Boötis; made a significant null detection in the star Procyon, defying over 20 years of expectations from groundbased spectroscopy and theory; observed differential rotation in a young rapidly-spinning ("pre-teen") version of the Sun; and detected 59 pulsation frequencies in a new delta Scuti variable star. The mission has proven itself a spectacular scientific success, even after only 3 months of commissioning science and 6 months of normal scientific operations. And some of the most exciting science is yet to come, such as observations of the exoplanet system 51 Pegasi for 6 weeks in August – October 2004.

The results on the star Procyon (see Figure 8; Matthews et al. (2004)) (Matthews et al. 2004) are a perfect example of the scientific surprises that await a space mission which forges new territory in observational parameter space (in the case of MOST, unprecedented time coverage and photometric precision.)

Procyon is the eighth brightest star in the night sky, and one of the best studied stars in the Galaxy next to our own Sun. Theoretical work dating back to the early 1980's predicted that this star should show oscillations like those seen in the Sun, but with amplitudes at least ten times larger. Such oscillations could be used to seismically probe the structure and age of this star. Since many of the other properties of Procyon (such as mass and distance) have been determined more accurately than most other stars, this meant that the

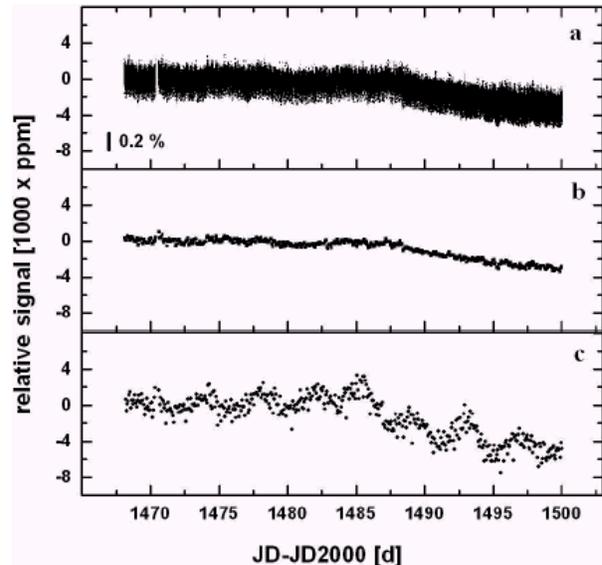


Figure 8 The light curve of star Procyon a) 32 days of photometry for Procyon b) binned at orbital period c) secondary target illustrating significant variation

stellar seismology would permit astrophysicists to test subtler physics in Procyon, and apply the model refinements to the Sun and other stars.

This prompted groundbased observers to look for the signal using precise Doppler measurements, leading to several apparent detections over the last two decades. With this history, Procyon was a natural prime target for MOST. In fact a design constraint on the mission was that the Instrument be capable of observing Procyon, despite the fact that it is about 3 magnitudes (16 times) brighter than the next brightest Primary Science Target in the MOST programme.

MOST monitored Procyon for 32 days, at an average rate of 6 times per minute, with out 7.5 hours of gaps in the data collection (ad uty cycle of 99%). The data reached a noise level of only a few parts per million, the scientific requirement. The data are adequately sensitive to the predicted amplitudes of the expected oscillations, so it was a great surprise to obtain a null result with a high significance level. There are several possible implications, including: (1) our model of Procyon is wrong, and hence models of other stars may need to be modified; (2) previous Doppler measurements of Procyon were seeing true oscillations, and the null photometric detection means the dynamics of such pulsations are dramatically different than they are in the Sun; or (3) previous Doppler measurements were undersampling stochastic turbulence in the atmosphere of Procyon, and the star shows no

detectable oscillations. All of these interpretations require reevaluation of one or more theories in which we have had high confidence for many years.

One implication that is unavoidable is that the photometric oscillation signal in Procyon is not as large as had been hoped, so future space photometry missions like COROT and Eddington must reexamine their prime target lists and observing strategies, which were to some extent guided by the previous expectations for Procyon.

MOST vs. COROT: FRIENDLY COMPETITION

MOST and COROT (Bordé et al. (2003)) have a number of scientific parallels in terms of stellar seismology and exoplanet studies. Both MOST and COROT are designed to achieve comparable photometric precision for stellar seismology, down to levels of about 1 part per million (ppm). The difference, partly due to the larger aperture of COROT (30 cm vs. 15 cm), is that COROT will observe fainter stars than MOST. The number of primary targets observed by MOST and COROT are similar while COROT is expected to have a larger number of secondary targets. These secondary targets can be observed to nearly the same photometric level as the primary target due to the larger field of view of the instrument.

However, COROT is also an exoplanet search mission, seeking unknown planets through transits (the dimming of light of a star when a planet passes directly in front of the star's disk, as in the recent transit of Venus in our Solar System). To give a good statistical probability of seeing transits, which require fairly exact alignments with our line-of-sight among planetary systems whose orbital planes are presumably randomly tilted in space, COROT must be able to examine several tens of thousands of stars for many months. MOST, on the other hand, looks at too few stars for too short a time to be an effective search mission. The MOST strategy is to concentrate on known exoplanet systems discovered indirectly through Doppler surveys from the ground, and study the reflected light signature of these systems in detail. MOST is not restricted to exoplanets whose orbits cause transits, given its unique potential to see the reflected light variations, but it will only be sensitive to giant planets in close orbits to their parent stars.

The Sun-synchronous low-Earth orbit (LEO) of MOST was selected to allow its instrument to monitor stars in a Continuous Viewing Zone (CVZ) about 54° wide for up to 2 months, while keeping the bright limb of the Earth as far from the field of view (FOV) as possible

(hence, minimizing scattered light) and putting the satellite in a fairly benign radiation environment. The orbit of COROT has a similar altitude to MOST, but is in an orbit that does not precess with respect to the stars. The scientific advantage of this orbit is that the COROT instrument can monitor selected stars for up to 5 months at a time and therefore will have greater frequency resolution in its photometric results. The cost of this longer time baseline is COROT must spend much of its mission looking over the bright limb of the Earth, so the more severe stray light restricts the CVZ to two small circular fields about 14 degrees in diameter in opposite parts of the sky.

The satellites that carry the MOST and COROT instruments however are very different. As shown in Table 1, MOST is a 53 kg microsatellite while COROT uses the CNES PROTEUS 'mini'-satellite bus and totals 668 kg. In almost all respects, the COROT satellite is a factor of 10 larger than MOST; in mass, size, power consumption, data volume. Yet groundbreaking scientific discoveries are being made with the MOST mission at a cost that is 25 times less expensive.

Table 1 MOST-COROT satellite parameter comparison

	MOST	COROT
Mass	53 kg	668 kg
Dimensions	0.7 x 0.7 x 0.3 m	4.1m x2.0 dia.
Power	35 W	380 W
Pointing accuracy	3 arcsec (3σ)	0.5 arcsec
Data Volume	13 MB/day	110 MB/day
Minimum Mission Duration	1 year	2.5 years
Total Program Cost	US\$ 7.5 M (C\$10M)	US\$ 190M (€160M)

MOST is a pioneer. No other observatory will be able to match its photometric precision and its observational duty cycle until COROT is launched in 2006. It has already made scientific discoveries which are forcing astronomers to reexamine some long-held ideas about stars. MOST is also laying valuable groundwork ("orbitwork"?) for COROT, allowing that mission team to adjust its target list and observing strategy, and learn more about radiation and stray light effects on a CCD photometer in low Earth orbit.

CONCLUSION

The MOST spacecraft has enjoyed enormous success. Though commissioning of the satellite took longer than planned as a result of some unforeseen circumstances, all of the issues encountered during commissioning were solved. This resulted in a satellite that has been able to deliver on its promises.

MOST has not only met the ambitious goals that were set for it, it has greatly exceeded them. It is delivering twice the volume of scientific data than was required. It is pointing to an accuracy of 1 arcsec (1σ) more than five times better than was expected, and better than any other microsatellite.

The MOST science team has made the stunning discovery that there are no detectable stellar p-mode oscillations in the star Procyon, amongst other discoveries. This has had a major impact on the theory of stellar oscillations.

As a direct result of the science results from MOST, the more expensive COROT mission is reassessing its target list and observing strategy. MOST, the microsatellite, is acting as a pathfinder for the more conventional, larger satellite mission that is COROT. However, unlike in the past the microsatellite is not simply a pathfinder for the technology for larger satellites, it is a pathfinder for the science as well.

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REFERENCES

Grocott, S.C.O. "Exploring the Mysteries of the Cosmos on the MOST Microsatellite Mission", Proceedings of the 18th AIAA/USU Conference on Small Satellites, Logan, UT, USA, 11-14 August, 2003.

Matthews, J.M., Kuschnig, R., Guenther, D.B., Walker, G.A.H., Moffat, A.F.J., Rucinski, S.M., Sasselov, D. & Weiss, W.W., "No stellar p-mode oscillations in space-based photometry of Procyon", 2004, Nature 430, pp.51 - 53.

Bordé, P., Rouan, D., Léger, A., "Exoplanet detection capability of the COROT space mission", 2003, Astronomy & Astrophysics 405, pp.1137-1144.