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NESS: A Dual-Use Microsatellite for Asteroid Detection/Tracking, and Satellite Tracking R&D

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Abstract. The Near Earth Space Surveillance (NESS) mission is being developed by Dynacon and a team of asteroid scientists, supported by the Canadian Space Agency (CSA) and Defence R&D Canada (DRDC). NESS uses a single satellite to perform a dual mission: searching for and tracking Earth-approaching asteroids, and tracking satellites in Earth orbit. There are aspects of both of these activities that are best accomplished using an orbiting observatory. The concept presented here is to implement NESS using a small imaging telescope mounted on a low-cost microsatellite-class platform, based on the design developed for the MOST stellar photometry microsatellite mission.

Introduction

The capabilities of microsatellites continue to grow more sophisticated with each passing year, allowing them to be used to carry out types of missions that once required much larger satellite platforms. In the early 1990s, miniaturization of digital electronics enabled microsats to demonstrate orbiting store-and-forward packet radio communications. Miniaturization of optical sensors then allowed optical remote sensing to be carried out from this class of platform.

Up until recently, imaging space science missions still relied on larger, more expensive satellites. However, the development of miniaturized attitude control system components such as reaction wheels and star trackers, has allowed a team led by Dynacon to develop the MOST mission[1] for the CSA, in which a microsatellite-based space telescope employs an attitude control system[2] similar to that of the Hubble space telescope.

These new capabilities also enable other types of missions to take advantage of the benefits of using the microsatellite approach—such as shorter development times, and much lower costs than for larger satellites—while achieving high levels of performance and capability. This paper summarizes one such, the Near Earth Space Surveillance (NESS) mission.

The NESS mission concept is to use a microsatellite platform to place a small optical telescope in low Earth orbit. This telescope will be used to search for and track two types of objects that are resident in space: asteroids, and Earth-orbiting satellites.

NESS serves the purposes of two separate space-tracking communities:

- Asteroid tracking is done for several reasons. Astronomers search to discover new asteroids, and use knowledge of their orbits to help develop models of solar system evolution and planetary formation. Follow-up tracking of asteroids is done in order to refine the accuracy of their orbit estimates, to allow future close approaches with the Earth (i.e., good observing opportunities) to be predicted; additional tracking allows a precise estimate to be made of the likelihood of a collision between an asteroid and the Earth. Looking ahead to future asteroid rendezvous and sample-return exploration missions, each new asteroid catalogued represents an additional potential mission target, and accurate orbit estimates are needed to allow exploration spacecraft to be navigated to their targets.
- Satellite locations are tracked for a variety of purposes. These include provision of ephemeris information in support of mission operation functions, such as pointing of high-gain ground-station antennas, and on-board estimation of magnetic field strength/direction for attitude estimation purposes. They also include support of the "space traffic control" function: predicting

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14. ABSTRACT

The Near Earth Space Surveillance (NESS) mission is being developed by Dynacon and a team of asteroid scientists, supported by the Canadian Space Agency (CSA) and Defence R&D Canada (DRDC). NESS uses a single satellite to perform a dual mission: searching for and tracking Earth-approaching asteroids, and tracking satellites in Earth orbit. There are aspects of both of these activities that are best accomplished using an orbiting observatory. The concept presented here is to implement NESS using a small imaging telescope mounted on a low-cost microsatellite-class platform, based on the design developed for the MOST stellar photometry microsatellite mission.

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> potential satellite collisions. NORAD uses satellite tracking data to distinguish satellites from ballistic missiles approaching North America. Because of the importance of the latter application, the U.S. Department of Defense's Space Command is tasked with maintaining an accurate catalog of all trackable objects in Earth orbit. While satellites in low Earth orbit are efficiently tracked using ground-based radars, optical tracking has advantages for satellites in higher orbits (e.g., in geostationary orbit, or Molniya orbits). The Canadian Department of National Defence (DND), as part of Canada's contribution to NORAD, plans to develop SAPPHIRE, an operational space-based satellite tracking system; there are numerous design alternatives and operating modes to choose from, and the R&D branch of DND (Defence R&D Canada, DRDC) is actively researching these to help guide the development effort for SAPPHIRE and potential follow-on systems.

Optical search and tracking for both asteroids and satellites is done routinely using ground-based observatories, by comparing sequential star-field images to look for faint, moving objects. Performing these observations from a space-based observatory offers important operational advantages, such as 24-hour-per-day operations, and avoidance of the cloud-cover, and performance-enhancing advantages such as the lack of scattered light from the Moon and the Sun. The design of the MOST microsatellite, being developed by Dynacon for the Canadian Space Agency, provides NESS with a small—thus inexpensive to launch—platform with an agile and very accurate attitude control system, and a photometrically very sensitive imaging telescope, two key requirements for this mission. The NESS mission will serve both communities, by carrying out R&D in support of the DND's space-based satellite tracking program, as well as carrying out search and follow-up tracking for Earth-approaching asteroids.

We begin by explaining the rationale for the two objectives of the NESS mission, and for achieving them with a single satellite. The driving requirements for the mission are set out. A system design to achieve those requirements, based on the MOST design, is summarized. Key elements of the plan for developing this system are outlined.

Mission Rationale

Mission #1: Asteroid Science

NESS proposes to use a space-based telescope to observe asteroids, in order to extract scientific knowledge from those observations. This is, of course, an activity that can be (and is) carried out using ground-based telescopes. Being located on the ground, however, imposes some limitations that interfere with the ability of scientists to make some very important types of observations; by being in orbit, NESS is able to fill these observational gaps. The overall context of existing ground-based asteroid observational astronomy is described below, as a prelude to describing the potential science contributions that can be made by NESS.

Science Context

Asteroids, the smallest planetary objects in the Solar System, are studied for several important reasons. Until recently, they could only be studied from afar by astronomers, who have discovered them one by one, and measured their orbits, their brightness and their reflectance spectra.

With the advent of planetary exploration space missions, such as NASA's current Near Earth Asteroid Rendezvous (NEAR Shoemaker) mission (http://near.jhuapl.edu/), spacecraft are underway to inspect some asteroids directly, collect from them and analyze samples, and eventually return samples to Earth for detailed study. This science has already resulted in an improved understanding of the evolution of the solar system, and of the genesis of Earth and the other major planets, and much more remains to be discovered; for example, asteroid and comet collisions may have played an important role in the genesis of life on Earth (http://neo.jpl.nasa.gov/neo.html).

In addition to their scientific value, some asteroids represent a threat to the Earth; there are many Near Earth Asteroids (NEAs) which follow orbits that bring them close to the Earth, and there is ample evidence that asteroids of all sizes have collided with the Earth throughout history, causing damage and climatic disruptions ranging up to the level of world-wide mass extinctions (e.g., see http://wwwdsa.uqac.uquebec.ca/~mhiggins/MIAC/chicxulub.htm). Recent international efforts have greatly improved the ability to predict far in advance how closely large asteroids will approach the Earth, potentially providing enough advance warning to allow action to be taken to avoid damage from such collisions, making this area of science potentially of the greatest possible practical importance to the entire population of the Earth.

The international NEA effort is carried out by a community of researchers who perform three broad tasks.

The first is performing search programs in order to discover new NEAs. The second is carrying out astrometric and photometric data processing on these discovery observations, followed by computation of orbital elements and rapid dissemination of these elements to many follow-up observers. This enables the third task, rapid astrometric confirmation and follow-up of the discoveries, in the absence of which newly-discovered NEAs would promptly be "lost" again. In addition to these NEA-focused tasks, some astronomers also perform photometric, spectrographic and polarimetric observations of asteroids of all types, from which information on asteroid size, albedo, spin rate and composition can be deduced.

There are now several major NEA discovery programs in operation, using CCD detectors on large-aperture telescopes, principally the Spacewatch program (University of Arizona), NEAT (NASA-JPL), LINEAR (MIT Lincoln Laboratory), LONEOS (Lowell Observatory), the Catalina Sky Survey (University of Arizona) and BAO-SCAP (Beijing Astronomical Observatory). NEAT, LINEAR, LONEOS and Catalina are robotic telescopes that generate massive amounts of astrometric data; they are currently discovering 15-20 new NEAs per month. As a side-benefit, they are also discovering enormous numbers (tens of thousands per month!) of "main-belt" asteroids and comets. Processing of the massive amounts of astrometric and photometric data and calculation of orbital elements and ephemerides, as well as the dissemination of that data to the observational teams, is handled in an efficient and timely fashion by the Minor Planet Center of the IAU. The Spaceguard Central Node (Italy) and NASA-JPL use this orbital data to determine future (and past) close planetary encounters of all PHA's. Follow-up is done by a relatively small number of professional astronomers, and a much larger number of skilled amateurs.

NEAs come in different types, and NESS is most useful in making observations of some (not all) of these. In particular, NESS will be able to out-perform ground-based observatories in observing "Aten-class" asteroids, Earth-orbit-crossing asteroids (with potential for colliding with the Earth) whose semi-major axis is smaller than that of Earth's orbit, and "Inner-Earth-Objects"(IEOs)whose orbits are entirely inside of Earth's orbit.

Potential NESS asteroid science opportunities include:

- Searching for Aten-class asteroids and IEOs
- NEA rapid astrometric confirmation and Follow-up
- Compositional studies

Further details on these asteroid science objectives may be found in an earlier NESS paper[3].

Mission #2: Satellite Tracking

Canada and the United States are partners in NORAD, the North American Aerospace Defense Command. NORAD historically has used the satellite-tracking services that are now provided by the U.S. Space Command, to distinguish between ballistic missiles approaching North America, and the >8,000 detectable man-made objects currently orbiting the Earth. This satellite tracking function is fed by data collected by the radar and optical sensors of the Space Surveillance Network (SSN), which continually measure the distance and/or direction from each sensor to satellites passing overhead.

In the past, Canada contributed sensors to this data-collection activity—a set of Baker-Nunn optical film cameras located in Canada. With the advent of electronic imaging sensors, the Baker-Nunn instruments have been decommissioned, replaced by new instruments such as GEODSS. Canada's Department of National Defence has recently initiated a Surveillance of Space (SOS) program, in order to contribute new Canadian sensors to the SSN.

Ground-based optical sensors are essentially optical telescopes, which take images of patches of the sky, which are analyzed to find the moving star-like images of satellites. There are several limitations that constrain the operations of any such sensor:

- They cannot operate during day-time, or too close to sunrise or sunset, due to sky-glow caused by the Sun obscuring the faint images of the satellites being tracked.
- Their effectiveness can be diminished at times when the Moon is in the sky, again due to sky-glow.
- Their effectiveness is diminished by cloudy or misty weather, frequently to the point of zero effectiveness.
- Less than half of the sky is visible to the sensor at any one time, due to obscuration by the Earth.

For these reasons, the amount of useful operational time from any one optical sensor can be very low, depending somewhat on geographic placement. Another significant geographic factor is that sensors located outside of Canada's borders would be difficult to maintain and operate, for logistical reasons.

It is notable that several of these limitations are not applicable to a space-based optical sensor, and the constraints imposed by the remaining limitations are significantly reduced. An orbiting optical sensor could be much more productive than a ground-based one, as well has having a much more reliable and rapid response time.

One question that arises naturally relates to telescope aperture size: can a telescope with sufficient photometric sensitivity to carry out a useful satellite-tracking mission, be built and flown within the small size constraints of an affordably-small satellite? The answer is "yes," as has been demonstrated by the Space Based Visible (SBV) experimental telescope[4], flown as a payload aboard the BMDO's Midcourse Space Experiment (MSX) satellite in 1996. This telescope has a 15-cm aperture—interestingly, the same aperture size as for MOST's telescope—and is routinely detecting satellites as faint as M=15. The sensor's performance is good enough that, after its experimental phase concluded successfully, the Space Surveillance Network began using it as a Contributing Sensor.

For these reasons, the DND's SAPPHIRE program will involve Canada launching a satellite system to be used to track other satellites. This system will likely be used primarily to do routine tracking of communications satellites in geostationary orbit, and other high-orbit Earth satellites (which in NORAD parlance are called "Deep Space Objects").

The schedule for this program involves placing one or more tracking satellites into orbit around 2005. Research is currently being carried out by Defence R&D Canada in support of this program, in order to improve the program's understanding of the mission requirements and design issues.

Based on the MOST satellite's precise photometry and imaging capabilities, DRDC has developed an interest in the use of microsatellites to conduct some of this research in a rapid, low-cost way. The feasibility of doing this has been reinforced by the striking similarities between the MOST and SBV instruments, and the similarity in attitude control performance between MOST and the MSX satellite.

This has led to the concept of DRDC participating in the NESS mission, to carry out research in support of the development of SOS system requirements. To pick just one of many examples, fundamental design decisions such as the question of how much image processing for target detection should be done on the ground versus on the satellite, depend critically on difficult-to-predict details of pixel-level imager noise characteristics. Flying an engineering model imager in the relevant environment, i.e. in orbit, would be a powerful way to validate analytical models of this type of effect.

Mission Requirements

Asteroid Science Requirements

A notional set of requirements has been established for NESS, based on the asteroid science objectives that are being examined in the current mission concept study. These have assumed that NESS will employ a satellite whose design is similar to that of MOST, which will be equipped with detectors similar to those used in ground-based asteroid tracking observatories, and whose operations will be based on the techniques used currently in ground-based asteroid tracking.

- The NESS science payload will consist of a telescope, 3 CCD detectors (one for tracking science observations, the second for colorimetry science observations, and the third for attitude control star-tracker measurements) and a data system.
- In order to achieve sufficient astrometric precision, the telescope must have a point spread function of FWHM ~ 1 arcsec.
- In order to be sufficiently productive in performing follow-up tracking, it must have throughput sufficient to detect asteroids of $m_R = 18 - 19$ with $S/N = 2$ in a 600 second (combined) exposure in tracking mode.
- The requirements for colorimetry include the ability to record $m_R = 18$ targets with $S/N = 20$ in a 1 hour (combined) exposure.
- The telescope must have an unvignetted field of about 1 degree.
- The optical surfaces must be sufficiently smooth that they do not produce unacceptable scattering and the instrument must be baffled in such a way as to allow observation within 20 to 45 degrees of the Sun.
- The detectors must be compatible with the above. Astrometric reduction requires that the image scale be 3.5 arcsec/pixel or better. The tracking detector must be approximately 1000 x 1000 pixels to cover the required area. It must be capable of exposure times ranging from 1 second to 3600 seconds (combined).
- Spectral bandpasses: the tracking detector need only be sensitive in the visual to red regions (500 – 750 nm). The colorimetry detector must have sensitivity in the spectral range 400 – 1100 nm in order to cover the range of the ECAS filter scheme.
- The data system must be able to acquire targets in accordance with an uploaded file of target search coordinates or pre-planned search area.
- Positioning of the system requires a tolerance of approximately 20 arcsec. It also requires the ability to record the time of the beginning of each integration to within 1 second of time.
- It must be able to store a minimum of 20 MBytes of

data on board and transmit it to a ground station on command

Satellite Tracking Requirements

The notional requirements for the satellite tracking element of NESS's mission are driven by a basic requirement to be able to detect the majority of the Deep Space Objects in Space Command's catalog of Resident Space Objects, while achieving a astrometric accuracy compatible with catalog-maintenance requirements.

Photometric Sensitivity: Statistics can be gleaned from the Space Command satellite catalog on Deep Space Object sizes and magnitudes. Assuming that NESS, like MOST, will be in a low Earth orbit, these statistics can be analysed to determine the brightness of these objects as seen from this orbit. The bulk of these targets will have a brightness as seen by NESS ranging from M=11 to M=14.

Target Proper Motion: Both NESS and the target objects will be moving in their own orbits around the Earth, creating a relative velocity between them. This will result in an apparent motion of the target across the sky, as seen by NESS's instrument, of up to 50 arc-seconds per second for a target in geostationary orbit. This will limit the amount of time that the target's image will dwell on any one pixel in the instrument's camera, setting a limit on the amount of signal achievable at the pixel level.

Astrometric Accuracy: NESS should be able to collect images of satellites with a resolution high enough to be compatible with the accuracy needed for the Space Command catalog-maintenance activity, about 1 km. At the ~40,000 km distance between LEO and GEO, this translates to an image resolution of better than 5 arc-seconds.

NESS System Description

The NESS mission requirements appear to be achievable using a microsatellite whose design is closely based on the design for the MOST satellite: the same bus with some new software, and the same instrument with some small changes to the layout of the focal-plane of the camera. That being said, there are some improvements in performance for this mission that could be achieved via additional design changes. These are currently being studied by the NESS team, to see which (if any) changes have sufficiently large incremental benefits in terms of performance, to justify the costs of additional re-engineering of the existing MOST design.

For this reason, the best way to describe NESS is to begin by summarizing the MOST satellite design, which is done below; further details can be found in a recent MOST paper[1], and at http://www.dynacon.ca/most.html. This is followed by a summary of NESS issues that are being studied, with discussion of the potential design changes that they could motivate.

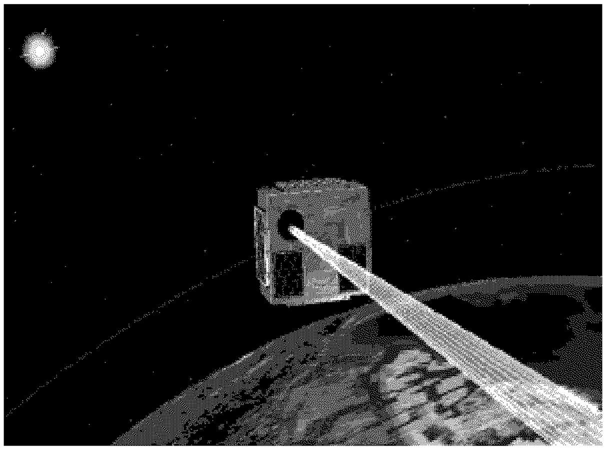

Figure 1: The MOST Microsatellite

MOST System Description

Mission Overview

The science mission for MOST is to conduct very precise, long-duration (several weeks per data record) photometric measurements of stars. The science team, led by P.I. Jaymie Matthews of UBC, will analyze those data to detect stellar oscillations, from which a primary science outcome could be an independent determination of the core composition and ages of stars, and thus a lower limit on the age of the Universe. (There are also numerous secondary science objectives, which are described at http://www.astro.ubc.ca/MOST/index.html.)

Primary funding for MOST is provided by the Space Science Branch ofthe Canadian Space Agency. Dynacon is prime contractor for the mission, and is providing the ACS and power subsystems. UBC is providing the science instrument. The satellite is being integrated at the Space Flight Laboratory at the University of Toronto, which is also developing the bus structure, thermal, OBC and T&C subsystems and the ground stations. The Critical Design Review for MOST was completed in the spring of 2000, and the satellite is now being built.

As illustrated in Figure 1, this mission is being implemented using a visible-light telescope instrument on a microsatellite platform, which will be controlled via a pair of ground stations in Canada. The bus size is about 60 by 60 by 20 cm, and the satellite mass is 57 kg.

MOST will be launched as a secondary payload. A launch opportunity in early 2003 has been confirmed (on a Boeing Delta II launcher, with Radarsat 2), with an early-2002 launch option also being studied. To accomplish the science objectives, MOST needs to be in a "dawn/dusk" sun-synchronous orbit (whose plane crosses the equator at 6 Am and 6 PM local time).

Instrument

The heart of MOST is an astronomical science instrument, shown in Figure 2, that is capable both of astrometrically precise imaging, and of ultra-precise photometry. It consists of:

- A 15-cm aperture, f5.88 Maksutov-optics ***telescope*** with an unvignetted field of view of about 0.7 degrees, and a vignetted FOV of about 2 degrees.
- A ***periscope mirror***, to orient the instrument's line of sight correctly with respect to the satellite's frame.
- A ***camera*** that includes a pair of identical, 1024x1024 pixel (0.86"x0.86") frame-transfer CCD detectors, one of which will be used for photometry science, and the other for collection navigational star-tracking images. It also includes the amplifiers for the CCDs.
- For each CCD, a DSP-based ***CCD controller electronics board***. One of these boards is used to operate one of the CCDs to carry out photometry observations; the other one implements ACS star tracker software
- A set of ***Fabry lenslets*** covering a portion of the photometry CCD, which reduce photometric sensitivity to line-of-sight errors. The focal plane arrangement is shown in Figure 3; the inner and outer circles are the unvignetted and vignetted fields of view.

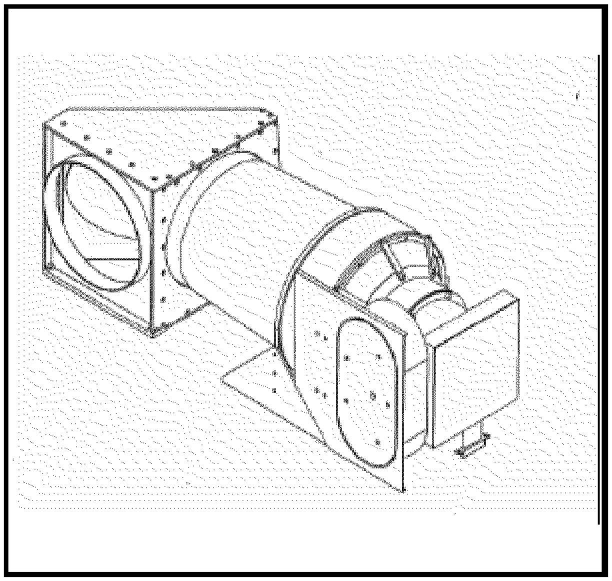

Figure 2: The MOST Instrument

- A focal-plane ***temperature control system***, which includes a passive cryo-cooler to produce focal plane temperatures of ~ -40C, along with an active temperature control system to regulate detector temperatures to much better than 1C.
- An ***aperture door***, which protects the instrument's optics from contamination by dust during launch, and which can be actuated closed to protect the focal plane from heating by the Sun during detumbling and safe-hold modes.

The mass of the instrument is 15.8 kg, and its power consumption is 8W.

Bus

Structure and Thermal Subsystems: The MOST bus structure, shown in Figure 4 in exploded view, comprises a stack of milled-aluminum trays, each containing either electronics boards or attitude control sensors and actuators. The instrument is fastened to one side of this stack. This assembly is then covered over by a set of 6 panels, onto which solar arrays, patch antennas, magnetometers and other external equipment are mounted. A marman-clamp payload attach fitting, also fastened to the tray-stack, provides the interface to the launch vehicle. The thermal control is primarily passive, involving selective use of surface finishes and MLI, but it does include battery heaters for use in safe-hold mode.

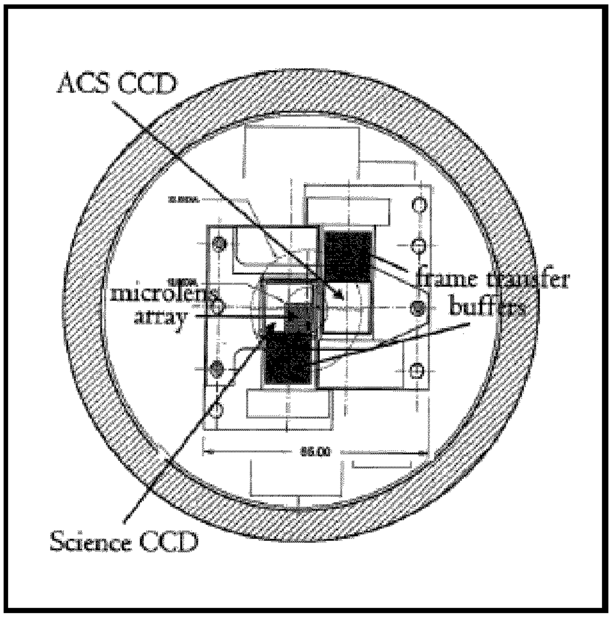

Figure 3: MOST Camera Focal Plane Layout

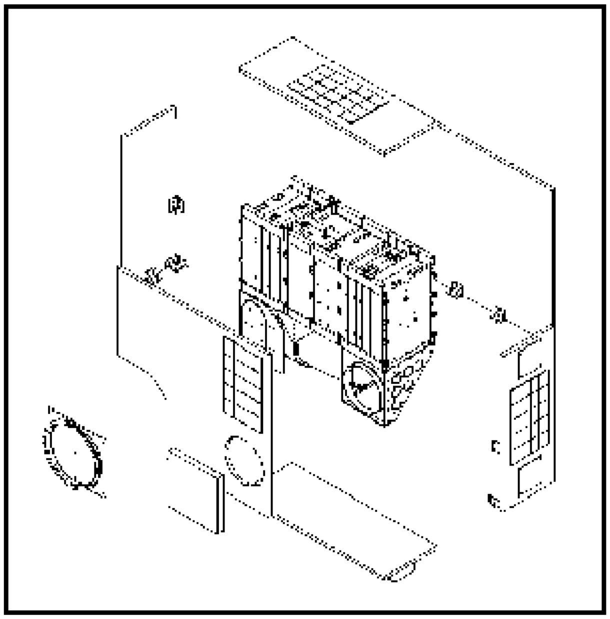

Figure 4: Exploded View of MOST

Attitude Control Subsystem: The ACS for MOST has been designed to the challenging requirement of keeping the instrument pointed towards specified target stars, with an accuracy of better than 25 arc-seconds, for up to 7 weeks at a time. The design and performance of the ACS is described in detail in a recent paper[3]. In summary, it comprises:

- 3 Dynacon MicroWheel reaction wheels.
- 3 solid-state angular rate sensors.
- 2 dual-wound rod magnetorquers.
- 2 sun sensors.
- 2 Dynacon MicroNode DSP-based attitude control computer boards.
- Dynacon-developed star-tracker software, running on one of the instrument's CCD electronics boards.
- ACS software, running on the MicroNodes, based on modules from Dynacon's MicroDirector ACS software library.

The ACS includes software to detumble the satellite after release from the launch vehicle, to carry out coarse (about 2 degrees accuracy) pointing prior to enabling the star tracker function, to slew from one target star to the next, and to carry out fine pointing when conducting science observations.

Power Subsystem: MOST collects power via solar panels mounted on all 6 faces of the satellite. These use high-efficiency silicon photovoltaic cells. Peak-power tracking is done independently for each panel. Power is stored in a NiCd battery, at a bus voltage of 12-14V. Switched bus voltage is distributed to each satellite tray; power conditioning is done in a distributed fashion in each tray. MOST's dawn/dusk sun-synchronous orbit has the desirable property that, for most of the year, the Sun is not eclipsed by the Earth; even during the height of 10-week eclipse season, the maximum eclipse duration is 17% of the orbit period. The power subsystem produces an average of at least 30W when doing science pointing.

On-Board Computer Subsystem: MOST employs a distributed-computing architecture, with digital processors embedded in almost all the subsystems. The OBC provides communications between all of these, coordinated by a central NEC-V53 processor board equipped with a 16 Mbyte RAM-disk. The RAM-disk is used to store science and telemetry data in the intervals between ground station passes, as well as to store the V53's operating software. The V53 communicates with the ACS MicroNodes and the CCD drive electronics boards via several RS-422 and RS-485 serial buses. It also operates the T&C Subsystem's radios.

Telemetry and Telecommand Subsystem: MOST is equipped with 2 S-band receivers and 2 S-band transmitters, each pair covering one hemisphere of the satellite's field of view, and each using its own patch antennas. The receivers are equipped with 9600 baud modems, and the transmitters with modems that can select between 9600 and 38400 baud.

Ground Stations: MOST will communicate with two ground stations in Canada, one in Toronto and one in Vancouver. MOST's orbit is such that it will pass within sight of any point on the ground 2 or 3 times near 6 A.M. every day, and 2 or 3 times near 6 P.M. every day, with an average pass lasting 5 to 10 minutes; the geographic separation between ground stations will increase the total daily contact time somewhat. The two ground stations will be identical. Each employs a 2m-diameter gimballed tracking antenna, driving doppler-corrected S-band transmitters and receivers. These are connected through modems to PC-type computers, which carry out tracking, telemetry and command functions, and which collect and forward to the operations team the science data and engineering telemetry data collected each day.

Performance of the "MOST-As-Is" Design

Initial analysis of the MOST satellite design indicates that, with minor modifications, it would be able to carry out asteroid and satellite tracking operations, at a performance level that approaches the requirements of the NESS mission. These changes are:

- Removal of the Fabry lenslet array in the focal plane of the camera. These lenslets are needed to carry out MOST's photometry mission, but for NESS they merely obscure otherwise-useful CCD area.

- Modify the software in order to carry out some simple image-processing, in order to either send raw camera images to the ground for processing, or to carry out some level of asteroid and satellite tracking processing aboard the satellite.

This would result in a satellite that could take useful satellite tracking images and asteroid tracking images. It would not enable asteroid compositional studies; additional of colour filters and polarizing filters would be needed for that.

The graph in Figure 5 can be used to determine the level of asteroid and satellite tracking performance achievable by the MOST design "as is." It presents the results of an a photometric analysis of the MOST instrument, when operated in a mode compatible with asteroid and satellite tracking operations:

- The satellite is assumed to be pointing in an inertially fixed direction, held by the ACS. The effects of pointing error/jitter are neglected in this analysis.
- A target asteroid or satellite is assumed to be drifting across the field of view of the instrument. The rate of drift, in arc-seconds per second, represents one axis of the graph.
- The faster the target's proper motion, the less time it will spend depositing light energy into any one pixel of the MOST camera's CCD, resulting in a lower signal level.
- The graph shows the brightness that a target must have, expressed in terms of equivalent stellar magnitude, in order to result in a signal to noise ratio of 1 at the pixel level, taking into account the known sources of noise in the MOST instrument.
- An exposure time of 2 seconds was chosen, relatively arbitrarily, for most of the cases analyzed. For proper motion values below 1.5 arc-seconds per second, the exposure length was increased to take advantage of the longer dwell-time of the target in each pixel. The curve in the graph represents an exposure-length optimization in which readout noise is traded against dark-current noise (among many other effects).

The result is that the slower the target's proper motion, the fainter the target can be in order to produce a given S/N. MOST's instrument is capable of achieving an S/N of 1 for target satellites in GEO as faint as M=13 to 15. This S/N level can be achieved for asteroids as faint as M=18 to 19.

These numbers do not translate directly in to target detectability levels. To detect a target, an image consisting of a large array of pixels must be analysed, and compared with other images to detect a moving target. The algorithms for doing this are quite complicated; while they are critically affected by the S/N achieved at the pixel level, they are also subject to other factors. An S/N of 1 reflects a lower limit, below which targets could likely not be detected using pairs of images. However, some noise suppression can be achieved by combining images taken in rapid succession. Thus, an S/N of 1 at the pixel level could, with the right post-processing, be a fair proxy for

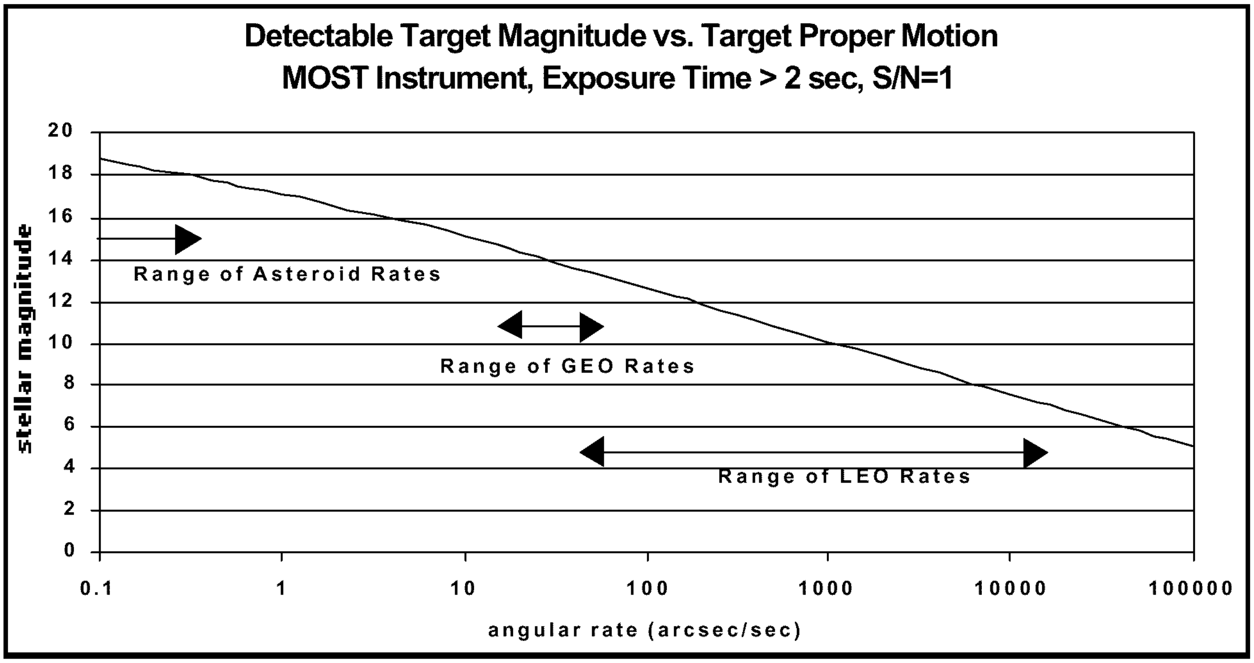

Figure 5: Photometric Performance of MOST Instrument in Tracking Moving Targets

the level at which a target is detectable.

With those caveats, how does the photometric capability of MOST's instrument compare with the two main NESS requirements?

- The DND's SOS mission is expected to be used to track targets in GEO and higher orbits. The great majority of these have a visual magnitude of M=11 to 14. From the graph, it appears that MOST's instrument is suitable for detecting these, with suitable image processing. Thus, the MOST design should be suitable for carrying out SOS-related research in the NESS mission.
- The NESS asteroid-tracking requirement is to be able to detect asteroids of magnitude M=18 to 19, with S/N = 2 in a 600 second (combined) exposure. The MOST instrument comes within about 1 magnitude of being able to achieve that, using single exposures with a typical exposure length of 2 to 40 seconds. The analysis has not yet been done to factor in the effect of combined exposures; this is expected to improve performance.

NESS Design Issues

The above analysis is not intended to argue that the NESS mission should be flown using the MOST design without modifications. While making any modifications to the design would incur some non-recurring engineering costs, it is almost certainly the case that there are modifications that would significantly improve performance, thus increasing the value of the mission, both from the asteroid-science and the satellite-tracking R&D perspectives. Analysis to quantify these costs and benefits is underway done by the NESS team, focusing on several issues with the MOST design, which affect the ability of that design to support some of the NESS mission requirements, or affect the performance achievable using that design. Some of these are discussed in this section, along with design trade-offs that are being investigated.

Camera Photometric Sensitivity: The photometric sensitivity of the MOST instrument appears to be quite adequate for the satellite-tracking R&D mission. The primary figure of merit for asteroid tracking sensitivity is the brightness of the faintest asteroid that can be detected. The potential for improving this, by increasing the diameter of the telescope aperture in order to increase the signal level, has been studied. It would be a relatively expensive modification to make, requiring complete re-engineering of the MOST telescope structure and optics. This also turns out to be of little benefit, because the asteroids to be tracked by NESS are all close to the Sun, where zodiacal light (light scattered from dust particles orbiting the Sun) is particularly bright. The brightness of zodiacal light at 0^{F} ecliptic latitude and 45^{F} solar elongation angle, for example, creates a signal per pixel of the MOST camera as bright as a M=18-19 asteroid. Increasing the aperture size will increase equally both the asteroid "signal" and the zodiacal light "noise": increasing the aperture size in this situation yields no net improvement in S/N ratio, and hence asteroid detectability.

Instrument Field Of View: Zodiacal light noise-per-pixel could be reduced, and hence asteroid detectability increased, by reducing the field of view of the instrument, so that each pixel subtends a smaller patch of sky. The cost of re-engineering the instrument to accomplish this could be more modest, involving changes to optical components but no to structure However, the field of view of the MOST instrument is already a bit narrow for both asteroid-tracking and satellite-tracking applications. For satellites, a wider FOV increases the chance of a targeted satellite appearing in the instrument's FOV, given that the catalog locations of satellites have some uncertainty; also, the high proper motion rates for satellites means that a narrow-FOV instrument has difficulty encompassing a complete satellite track image with an exposure of reasonable length. For asteroids, a narrower FOV would increase the amount of time needed to search a given region of sky, potentially reducing asteroid discovery productivity.

Satellite Layout: In order for NESS to be able to track Aten asteroids it must be able to operate while pointing fairly close to the Sun (from 45 to 90 degrees from the Sun). MOST as currently laid out is designed to have the instrument point almost directly away from the Sun, while its main solar array is pointing almost directly at the Sun. To target NESS towards Aten asteroids while collecting enough solar power will require the satellite's layout to be changed.

Baffling: In order to achieve faint-asteroid detectability while pointing relatively close to the Sun, NESS will need considerably more baffling than MOST, in order to keep stray light levels to an acceptably low level. This will preferably also be designed to control stray light from the Earth's limb, to minimize constraints on satellite attitude during asteroid search and tracking operations.

Filters for Colorimetry and Polarimetry: The MOST instrument is equipped with a single fixed filter, and so cannot be used to carry out any asteroid compositional studies. Various alternatives are being studied for adding color and polarization filters to the NESS instrument, ranging from filter wheels to strips of filter material deposited onto the detector's surface.

On-Board Image Processing: If images from NESS are to be processed using traditional ground-based approaches to detect asteroids and satellites, then the data bandwidth capabilities of the MOST radios will only allow a small number of images per day to be collected. One approach to improving this is to employ higher-bandwidth radios, either by increasing transmit power, or by using a larger antenna on the ground. Another is to employ image-compression software on-board, to reduce the file-size for each image. A challenge in this regard is to be able to detect faint objects in noise clutter; the applicability of several standard ground-based asteroid-detection software approaches is being investigated.

Orbit: The MOST requires being launched into a dawn/dusk sun-synchronous orbit, in order to be able to achieve science requirements. Since few primary payloads fly into this orbit, this has reduced MOST's launch options as a secondary payload. A desirable side-effect is that MOST's power subsystem does not have to accommodate long eclipses, allowing smaller batteries and solar arrays.It currently appears that the NESS mission could be carried out from a much wider range of orbits. For logistical and cost reasons, then, NESS may fly in a different orbit than MOST. However, any other orbit will result in relatively long eclipses, requiring a larger battery and higher-power solar arrays than MOST. The latter could be accomplished either via increasing the size of the solar panels, or by switching from silicon to GaAs solar cells (the latter having a significant cost impact).

Attitude Control Performance

MOST is relatively insensitive to jitter, as long as attitude errors stay within a 25 arc-sec bound. NESS will need more-accurate attitude control. The target requirement is to control attitude to within half a pixel, about 1-2 arc-seconds, in order to achieve an adequate pixel-level S/N for faint asteroids. The pointing accuracy of MOST is limited due to the use of angular rate sensors that have a high drift rate; for NESS, the potential of using Fiber Optic Gyros (FOGs) to replace those sensors is being investigated.

Development Plan

The development team for the NESS satellite will be the same as that for MOST, consistent with the very close similarity between NESS and MOST; indeed, one attractive cost-reducing option is to coordinate the construction of MOST and NESS, so that elements of both satellites are built at the same time, with both programs possibly sharing spares, etc.

A separate science team has been formed for the NESS mission. The team is led by Principal Investigator Alan Hildebrand, who is also leading asteroid compositional study investigations. David Balam is leading asteroid tracking investigations. LCdr Douglas Burrell of the Royal Military College in Kingston will lead satellite tracking R&D. Jaymie Matthews will lead instrument development, and is lading instrument-related design and trade-off studies. During the course of the present concept study, many other asteroid researchers in Canada and abroad have joined the science team.

The Space Science Branch of the Canadian Space Agency is supporting the science team, providing funding via their Concept Studies Program. Dynacon has also been contracted by DRDC, to study how a microsatellite based on the MOST design could be used to conduct experimental satellite-tracking activities.

It is currently expected that NESS could be developed within a schedule as short as 2 years, depending on how closely it can be coordinated with the MOST development schedule. The development cost of NESS will depend on two main factors: the extent to which it is decided to modify the MOST design to increase NESS performance and functionality, and the extent to which NESS's development can be coordinated with the development of MOST. If coordination can be done near-optimally, and a minimal re-design option is selected, the cost could be somewhat less than that of MOST (which will cost the Canadian and Ontario governments approximately CDN$7M, or about US$4.5M). More-extensive re-design, or a development that is not coordinated with that of MOST, would likely cost about the same as MOST.

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