FROM OBSERVATIONAL GEOMETRY TO PRACTICAL SATELLITE DESIGN: ASTEROIDFINDER/SSB

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INTRODUCTION

A small solar system body (SSSB) is presently classified as a Near-Earth Object (NEO) if it approaches the Sun to 1.3 Astronomical Units (AU) or less. Most of these objects are difficult to observe due to their minute size, their highly variable apparent motion relative to the background of stars, and their location in the sky relative to the Sun. Objects that cross the Earth's orbit at ~1 AU, when seen from the Earth and moving in its vicinity, are increasingly backlit as they approach the Sun. The closer they approach the Sun's position in the sky, the more the visible part of their sunlit side is by geometry reduced to an ever slimmer tiny crescent. This applies to all Earth-crossing asteroids, certainly to the Aten class of asteroids which orbit the Sun in less than one year but still have the most distant parts of their orbit outside the Earth's, and in particular to the Inner Earth Objects which orbit the Sun completely Interior to Earth's Orbit (IEO). Only ten mostly Aten-like IEOs have been found so far, of which two are classified as Potentially Hazardous Asteroids (PHA). A third IEO's orbit comes closer to the Earth's orbit than required for PHA status; although it does not quite have the size to be classified as a PHA, it still is similar in scale to the Tunguska object. Presently, only one 'deep' or 'real' IEO is known, 2008 EA_{32}, which orbits the Sun in a fairly inclined and eccentric orbit at distances similar to the planets Venus and Mercury.

Ground-based observations of Atens and IEOs are severely constrained by the presence of the Earth's body and atmosphere between the target object and an observatory situated on the Earth's night side within the circle of astronomical dusk and dawn. An Earth-orbiting survey telescope can in principle evade these constraints with ease, to become an efficient and cost-effective tool for the eventual discovery and follow-up of these objects. The scientific goal of the AsteroidFinder instrument payload is to better observe and characterize IEOs and Aten NEOs. Following an invitation to a DLR-internal competition, AsteroidFinder has been selected as the first primary instrument payload to be flown in the frame of the Kompaktsatellit line of developments within the Research & Development Programme of DLR, the German Aerospace Center. It will be flown on a satellite platform based on the Standard Satellite Bus kit, /SSB. This set of satellite bus components, structures, and concepts is based on the evolved heritage of DLR satellite bus technology. The foundation was laid by the highly successful infrared Earth observation satellite, BIRD. It has been built upon by the technology demonstrator platform, TET, developed within the On-Orbit Verification (OOV) programme of DLR Space Agency. TET is in production and testing, and further missions are on the horizon. New components for mission-specific needs and services are being added to the /SSB kit on a mission-by-mission basis. [1]

The mission-oriented step-by-step expansion strategy of the /SSB kit serves two intentions: Maximize the return on investment through the reuse of flight-proven technology - minimize the overhead associated with conventional standard bus concepts developed in a blank sheet, one-serves-all approach. Any hardware, software, operational or conceptual design is developed to fully serve one specific mission, first. Only on a secondary level, but right from the start, design decisions are made with the individual component's potential for wider use in mind. Beginning with BIRD, a small satellite platform fit for full copy-build reuse has been realized, and is now, within the /SSB kit concept, serialized in production. It has the flight-proven capability to serve one full-scale scientific instrument payload, represented by BIRD's camera platform for pixel-aligned bi-spectral infrared and near infrared image taking. TET is a version to support well over a dozen engineering experiments at a time.

The Phase 0 study of the top three out of nine payload candidates for the first Kompaktsatellit flight has confirmed that the science-driven requirements of instrument payloads addressing current topics of research can converge with the capability-driven requirements of a small satellite platform, obviating in many cases the need for one-off custom-designed scientific satellites. Small satellites using the /SSB structural layout can be launched as secondary payloads, and in principle on almost all presently advertised and available launch vehicles, due to their small size and mass, and robust mechanical design. [12]

As of late-April 2009, AsteroidFinder/SSB has successfully passed and concluded the project's Phase 0 1-out-of-3 competition, Phase A, and an extended scope Δ Phase A. This most recent phase was solely focused on a thorough and rigorous shakedown of the final Phase A design status. The objective was to demonstrate the robustness of the primary scientific mission, the primary instrument payload design, and the related critical bus functions, regarding all parameters related to high secondary payload launch opportunity selection flexibility and possible late changes in the selected launch opportunity in terms of orbit parameters or launch vehicle. For this purpose, the final Phase A design was temporarily frozen as-is, and analyzed without regard to possible secondary instrument payloads and improvements from lessons learned that were nevertheless collected continuously but separately during Δ Phase A, and are now being incorporated. Project planning preparations for Phase B of AsteroidFinder/SSB are presently under way, while ground verification testing of key technologies and other studies related to time-critical items are continued on the fly. AsteroidFinder/SSB is planned to be launched by 2013, for a one-year baseline mission.

PRIMARY SCIENTIFIC INSTRUMENT PAYLOAD AND MISSION

Instrument Features and Capabilities

The AsteroidFinder instrument payload was designed to fit the /SSB stowed satellite envelope as defined by precursor missions, $592 \cdot 656 \cdot 892$ mm^3 ($23.3 \cdot 25.8 \cdot 35.1$ cu.in.) overall. The telescope, focal plane array, and sensor proximity electronics were fitted to the resulting payload compartment volume of $460 \cdot 580 \cdot 550$ mm^3 ($18.1 \cdot 22.8 \cdot 21.7$ cu.in.). The primary goal of telescope accommodation was to maximize the telescope aperture. Two basic configurations of telescope optics, CCD sensor type, and motion compensation were studied in detail. The selected telescope design is an all-reflective $f/3.4$ Three-Mirror Anastigmat (Cook) with Schmidt corrector plate, feeding a 2-by-2 array of 1K^2 electron-multiplied backside illuminated silicon CCD sensors passively cooled to a semiconductor temperature below -80°C. Motion compensation is achieved by fast read-out of the CCDs at 5 frames per second and chip. 300 frames are then registered and stacked on board as an image of an effective exposure time of one minute, to drastically reduce the data volume to be transmitted. A rectangular aperture of $230 \cdot 228$ mm^2 ($9.1 \cdot 9.0$ sq.in.) is used for maximum volume efficiency, achieving an effective aperture of 430 to 474 cm^2 (66.7 to 73.5 sq.in.) within the field. The field of view has a diameter of 2.8°, with approximately $2° \cdot 2°$ of the sky being covered by the sensor chips. This places the instrument in the same league as CoRoT (Convection Rotation and planetary Transits), although at a raw and on-board processed data rate higher by almost two orders of magnitude.

Each sensor chip feeds its own independent string of proximity and data processing electronics, thereby providing full four-fold hot functional redundancy, although the loss of one channel would cause the loss of one quarter in area coverage. A common interface module and the four front-end electronics modules for CCD control and read-out are located within the dedicated payload bay volume provided by the /SSB, in the gaps left over by the telescope, focal plane array, and associated structures. The data processing units and a power supply unit are mounted as standard Eurocard-sized printed circuit boards in payload-assigned slots within the /SSB electronics segment.

The instrument is designed to achieve within an exposure time of one minute a limiting magnitude of at least 18.5 mag in the Johnson-V band for a solar-coloured object. This limiting magnitude is defined as a 5-σ detection of such an object with an astrometric accuracy of one arc-second at 1-σ RMS deviation, under the worst-case sky background conditions to be expected within the Region of Interest (ROI) described below, 20.3 mag/arcsec^2.
The instrument design is presented in detail in a separate poster. [2]

Mission Goals and Needs

The basic goal of AsteroidFinder is to detect and characterize a statistically significant number of IEOs. AsteroidFinder will prevalently observe a ROI of the sky in the sun-referenced ecliptic longitude ranges –60° ; –30° and +30° ; +60° and in the ±40° sun-referenced ecliptic latitude range. Asteroids will be recognizable through their apparent motion against the fixed star background on subsequent images. The first detection observations enable the determination of short-arc orbits of adequate accuracy to recover the detected objects within one month, from ground-based follow-up observations or from AsteroidFinder itself.
With respect to SSSBs, the innermost solar system still is largely uncharted territory. Information on the orbital parameters and approximate size of previously unknown IEOs and other objects passing through this region is critical for the evaluation of SSSB distribution models. These models are used primarily for two important purposes: In the planetary defence context, they serve to determine the overall risk and frequency of impacts on the Earth and other terrestrial planets, and the size-frequency and relative velocity distribution of the impactors. In the wider scientific context, many of these models are based on the orbital evolution of the solar system as a whole, and modelled SSSB populations serve as sets of test particles that as a whole record and statistically image the integrated influence of various gravitational and non-gravitational effects over time. To determine the relative strength of these effects and their variation over time, observed and modelled populations can be compared at varied parameter settings, and before and after correction for observational biases which may also be determined in the process. The energy-frequency distribution of impactors is also used to determine the age of solid surfaces in the solar system, expanding the relative dating of planetary surfaces from the size-frequency distribution of craters alone. For absolute dating, a reference is required which can only be provided by returned samples that are dated by isotope clocks, such as the Apollo and Luna Moon rocks. The orbital and size-frequency distribution of impactors varies across the solar system. For example, IEOs can presently not reach objects beyond the Earth-Moon-system, and Aten asteroids can not reach the surfaces of main belt asteroids, although both may well migrate over time due to long-term perturbations to hit or become part of either group of solar system bodies. These localized SSSB population differences have to be modelled to determine the absolute age of planetary surfaces outside the Earth-Moon system as long as local surface samples remain unavailable.
The high number of observed and modelled bodies enables sound statistical results. Each body adds seven or more parameters to the database; its orbit parameters, estimated size, and occasionally its shape and other physical properties. For example, the model population by Bottke and Morbidelli used in the evaluation of the AsteroidFinder's performance contains 57649 virtual objects, including 1190 virtual IEOs, down to a limiting absolute magnitude $H = 23.0$, corresponding to a diameter of about 100 m at an albedo of 0.15. [3]
The mission of AsteroidFinder is presented in detail in a separate presentation. [4]

Observation Strategy

The observation strategy of all small solar system body surveys has been evolved operationally from initial concepts through the lessons that can only be learned in the operational phase. Often, dramatic improvements in efficiency have been achieved over time. It is expected that AsteroidFinder/SSB will not be an exception to this rule. A first operational observation strategy will be developed in the project's Phase B which is to be kicked off, soon.
In general, objects are to be observed in the ROI which continues sunward from the parts of the sky covered by ground-based surveys down to 30° solar elongation in the plane of the ecliptic. Moving object identification is accomplished through apparent motion and parallax, requiring repeated observations of the same field which the satellite has to provide at certain intervals. The natural quantization of the interval for periodic revisits is the satellite's orbital period of approximately 100 minutes. Shorter revisit intervals are possible down to the time of exposure, but the range of possible intervals depends strongly on the location of the field of interest within the ROI.
AsteroidFinder/SSB is to be launched as a secondary payload into a Sun-synchronous orbit (SSO), and will have to accept a fixed orbit that is determined by the primary payload of the selected launch. It is well possible that a launcher switch may have to be accepted very late in the programme, as it happened for BIRD. For the evaluation of the influence of the whole parameter space of commonly used SSOs on the scientific yield of the mission, a detailed mission analysis of 36 reference orbits has been conducted during Δ Phase A. Four seasonal subsets at epochs from 2012 JUL 01 to 2013 APR 01 were studied, each of nine different local times of ascending node (LTAN) from 06:00 to 21:30. A worst-case altitude of 600 km has been assumed for all reference orbits. A number of known yield-degrading factors such as lunar phases and planet transits of the ROI have been neglected to ensure that only orbit-induced effects influence the results. The same automatic pointing strategy has been applied to each of these reference orbits, and the resulting coverage of the ROI has been evaluated. As expected from the basic observational geometry which is determined only by the relative apparent positions of the target field, the Sun, and the Earth seen from the position of the satellite in low Earth orbit (LEO), dawn-dusk SSOs perform best, while a noon-midnight orientation of the orbital

plane of the SSO interferes most with the primary mission observations. It is expected that observation strategies and possibly ROI outlines tuned to the orbit ultimately to be used will achieve a significantly higher efficiency than demonstrated in this worst case approach. A survey of past and future launch opportunities has been conducted to support and focus this optimization process early on. It seems possible to avoid some of the yield-degrading factors such as the Moon, bright planets and stars, or the brighter parts of the Milky Way, by evasive pointing manoeuvres within the ROI or temporary excursions to adjacent regions of the sky. Also, orbital eclipses may alleviate straylight concerns for a considerable fraction of the orbit, depending on the LTAN flown and the orbital season.

The design process of a non-optimized exemplary observation strategy for the evaluation of the set of baseline orbits is presented in detail in a separate poster. [5]

SECONDARY MISSIONS AND SECONDARY INSTRUMENT PAYLOADS

Secondary missions are planned for the primary payload, AsteroidFinder, and discussed for dedicated secondary instrument payload candidates. Secondary missions are only to be conducted on a non-interference basis with the primary mission of the primary instrument payload, AsteroidFinder's search for IEOs and other short-period NEOs. Also, although they are basically welcome, dedicated secondary instrument payloads are in addition to non-interference only to be flown on a space-available basis. Candidate instruments have been proposed since Phase 0, and some have been studied in detail already in Phase A. Although the most recent Δ Phase A was with the explicit exclusion of secondary missions and instruments primarily focused on the primary mission and instrument payload, additional candidate instruments have been proposed, and initial studies have been undertaken on a time-available basis. The selection of secondary instrument payloads and study of secondary mission concepts will take place in the first part of the Phase B later in 2009.

Space Debris

The main secondary mission of the primary instrument payload, AsteroidFinder, is to test the space-based observation of space debris and artificial satellites in Earth orbit at different observational attitudes. It is expected from the results of two independent studies, that the instrument will detect approximately 1.4 debris objects per minute in the range from 1 mm to 25 mm (~1 in) in size, and hundreds of decimetre-sized debris objects per week. [6,7] Also, technical spaceflight support observations or synchronized observations with ground-based installations such as space debris radars may be undertaken whenever an event takes place or an object of interest passes through the volume of near-Earth space observable by AsteroidFinder. The events and related objects may, for example, include planned spacecraft manoeuvres and separation events, in-flight failures and fragmentations, or space debris collisions, such as the Chinese ABM test of January 11th, 2007, the kinetic disposal of the failed NRO satellite known as USA-193 on February 20th, 2008, or the Iridium/Strela event of February 10th, 2009.

Astronomy at Low Solar Elongations

Due to the class of its telescope and the extremely sensitive EMCCD sensors with their high dynamic range and selectable gain, AsteroidFinder will provide a unique capability for dark sky astronomy at low solar elongations, beyond the search for IEOs and NEOs. Although it is not envisaged to provide filtered channels, it is in principle possible to observe any object of scientific or planetary defence interest. Objects may be observed in an area of the sky vastly larger than the two windows of the ROI, as long as they are at all detectable and the properties of interest are visible in silicon-spectral black-and-white. Such objects may range from interplanetary dust and serendipitous comets to transiting exoplanets and cataclysmic variables. Also, interplanetary spaceflight support observations or synchronized observations with ground-based installations such as asteroid radars may be undertaken whenever an object transits the area of the sky observable by AsteroidFinder. Objects that leave the parts of the sky observable from the ground may be followed-up when close to the Sun, such as sufficiently bright, newly discovered NEOs or Kuiper Belt Objects.

Engineering and Technology Experiments

Beginning with Phase A, two technology experiments have been proposed as secondary instrument payloads for AsteroidFinder/SSB. These experiments are intended to generate engineering and operational experience with, and provide early flight testing of technologies that may serve as the foundation of future /SSB mission payloads and bus components.

AoS

AoS is a technology experiment that intends to monitor regular civilian Air traffic radio emissions over Satellite, with the goal to map air traffic over remote regions and to help develop technologies that may support future air traffic control beyond ground-based radar range. Ground-based precursor experiments have successfully proven the concept in regions of dense traffic that offer a similar signal density as may be expected for the much wider field of view from orbital altitudes.

The experiment is proposed by the Orbital and Security Systems department of the DLR Institute of Space Systems in Bremen, Germany, and industrial partners.

OSIRIS-SSB

The OSIRIS-SSB Optical High Speed Infrared Link System is a laser communications terminal that supports self-contained technology tests as well as a supplementary data downlink path. The increased use of S-band and X-band communication channels leads to more and more non-interference-based approval of the use of these radio bands. Command uplinks require relatively low data rates and radio bandwidth, and it is comparatively easy to provide pencil-beam transmitters with large antennae on the ground to avoid main lobe interference with other satellites. High data rates and bandwidths are required for downlinks which can not as easily be directed within the constraints of orbiting satellites, with the side-lobes of smaller and less focused antennae being visible over continental distances. The OSIRIS technology is capable of precisely aimed point-to-point communication at data rates of up to 1.25 Gbit/s. The data rate can be reduced arbitrarily to allow for a wider laser beam of given power adjusted by slight defocusing to the absolute ground station pointing capability of the satellite. The technology has been demonstrated in space with downlinks from the European satellite Artemis to ESA’s optical ground station on Tenerife and downlinks from the Japanese satellite OICETS to DLR’s optical ground station in Oberpfaffenhofen within the KIODO project. The goal of OSIRIS-SSB is to demonstrate that the concepts developed at DLR can be used for inexpensive operational data downlinks in future satellite missions, including small satellites with a high daily downlink volume such as AsteroidFinder/SSB. Specifically for AsteroidFinder, the OSIRIS-terminal might be used as a data downlink in addition to the primary X-band path, to efficiently increase the capacity of the data downlink with the higher data rate on the optical path. The increased downlink capacity can be used to allow for an extension of the primary mission goals or allow for the expansion of some secondary missions. With the absolute pointing accuracy expected for AsteroidFinder/SSB as a result of primary mission pointing requirements, the data rate of an accordingly tuned OSIRIS-SSB would still somewhat exceed that of the high bandwidth X-band downlink envisaged, without becoming a pointing requirements driver.
The experiment is proposed by DLR’s Optical Communications Group in Oberpfaffenhofen, Germany.

Space Situational Awareness Experiments

The primary instrument payload already covers two of the three major topics of the current Space Situational Awareness (SSA) efforts, NEOs and space debris. One of the characteristic strengths of small satellites when compared to conventional scientific spacecraft is their rapid reaction capability, operationally as well as regarding the whole process from inception to operation. With the solar maximum predicted to occur around the expected launch date of AsteroidFinder/SSB and the new focus on SSA, it is logical to complement the instrument payload with secondary instruments that investigate the third major topic of SSA, space weather. Four candidate instruments have been proposed in late Phase A and Δ Phase A.

SEPS

The Spherical EUV and Plasma Spectrometer (SEPS) is an 8-mode sensor to detect a number of classes of radiation related to space weather and upper atmosphere research. Depending on the polarity and level setting of three electrode voltages, the instrument is sensitive to EUV radiation from 18 to 200 nm; electron energy, temperature, or density; ion density, or composition; and satellite charge. The sensor head can operate in nine modes: as conventional, shielded, or plasma shielded Langmuir probe; RPA electron, plasma, or plasma ion; EUV; and calibration mode. It is expected that a EUV index of solar activity can be established that is better suited to characterize the solar influence on the upper atmosphere than the presently used f10.7 cm index. Such an index would allow better modelling of the energy deposited in the upper atmosphere, especially regarding effects on a short timescale, and also with respect to coronal mass ejections and flares. The resulting changes in upper atmosphere density are relevant for the precise prediction of satellite orbits and the aspects of mission planning related to the maintenance of orbits by on-board propulsion or drag devices. The sensor design has been tested in a simplified cylindrical configuration as well as the intended spherical shape with laser-cut concentric grid electrodes. The laser-cutting process has been demonstrated for complete hemispherical grids down to grid conductor cross-sections of $100 \cdot 120$ µm.
The experiment is proposed by Fraunhofer Institut Physikalische Messtechnik, Freiburg, Germany. [8]

EHF FMCW Space Debris Radar

A millimetre-wave/EHF in-situ space debris radar operating in frequency-modulated continuous wave mode at 94 or 220 GHz is proposed by Fraunhofer Institut Kurzzeitdynamik - Ernst-Mach-Institut (EMI), Freiburg, Germany, and partners IHF and FHR. The space-based use of mm-wave technology would extend the sensitivity down to millimetre-sized particles which could be detected and mapped around the orbital plane of each satellite carrying the instrument. This offers a size range similar to the expected optical detections of space debris by the primary instrument payload, and the potential for synchronous observations campaigns. The short wavelength also enables an extremely compact instrument design well suited for repeated flights as secondary instrument payload. Within the DLR OOV programme, Fraunhofer-EMI also provides the Meteoroid and Debris Detector v3 (MDD3) to be flown later in 2009 aboard the Russian radio telescope satellite Spektr-R in a high inclination, high eccentricity Earth orbit between LEO and near-lunar distances. [9]

MEP-2

Monitor of Energetic Particle-2 (MEP-2) is a low energy particle detector previously flown on Interball and to be flown on Spectrum-Radioastron. MEP-2 can detect electrons from 30 to 350 keV and ions from 30 to 3200 keV. It is a compact, low power, low data rate instrument well suited for use as a secondary instrument payload on a small satellite. Copies of MEP-2 can be manufactured by the Department of Space Physics of the Institute of Experimental Physics of the Slovak Academy of Sciences, Košice, Slovakia. [10]

SREM

The Standard Radiation Environment Monitor (SREM) is a high energy particle detector previously flown on GIOVE B, Rosetta, Integral, and Proba-1. It is sensitive to electrons at > 500 keV and protons at >10 MeV, and is a compact, low power instrument well suited for use as a secondary instrument payload on a small satellite.
Flight models can be provided by the Paul Scherrer Institute, Villigen, Switzerland, via ESA / ESTEC. [10]

DESIGN STEPS

Outlined by Geometry

The relative orientation of all elements interfacing the satellite to its environment is locked by the unique observational geometry which is primarily Sun-referenced: The ROI is defined with respect to the position of the Sun in the sky; the preferred type of orbit is Sun-synchronous; the preferred orientation of the telescope as well as the low temperature radiator is away from the axis linking the centres of the Sun and the Earth; the normal on the solar panels should mostly be pointed towards the Sun; and the room temperature radiators preferably away from it. If the two parts of the ROI were not defined as they are but as two pieces of pie cut along lines of constant elongation and radial angle from the Sun, all elements of the overall observational geometry ultimately to be mapped onto the satellite design would be completely axisymmetric. This is an unusual arrangement that is not common among Earth- or Sun-observation satellites. The only oddball in this geometry is the Earth: It can not be simplified as a point in space because it covers most of one hemisphere when seen from the satellite; and due to its oblateness, the inclination of its axis, and the eccentricity of its orbit, the normal on the plane of the SSO paces through a seasonally cycled set of directions relative to the Sun vector.

Forbidden Hemisphere

Silicon-Visible Light

Analysis of the observational geometry and present technological capabilities has shown that straylight from the Sun and the Earth is the most critical performance limiter. Imaged through the telescope, the Sun has 10^{18} times the intensity per pixel of an asteroid of the limiting magnitude as defined above. The sunlit Earth can reach approximately one third of the Sun's per-pixel intensity. This is also the order of magnitude of the minimum required overall stray light rejection. An even higher straylight rejection is desirable since the minimum Zodiacal Light background level may be as low as 22.8 mag/arcsec² within the ROI, only twice the all-sky minimum intensity of 23.3 mag/arcsec². [11] Such extreme levels of straylight rejection can only be achieved with the combination of several methods: The telescope aperture is shielded completely from the Sun at all times, and from the Earth at least during observations. Baffles and stops are used in the optical system to prevent direct illumination of the detectors and indirect illumination by structural parts near the optical path. Diffraction-critical edges must not be illuminated. Primary mirror roughness must be reduced to a minimum to avoid the conversion of out-of-field light to in-field straylight by scattering on surface irregularities. These requirements result in the choice of the Cook TMA system and the definition of a forbidden hemisphere into which the Sun and the Earth must not enter during observations. It forms the basic element of all observational mission analysis [5] and exclusively defines one full face of the satellite shape.

Thermal Radiation

The thermal influences of both sunlight and earthlight become important if the capabilities of state-of-the-art detectors are to be fully exploited at low temperatures. Thus, the optical and thermal behaviour of the satellite as a system beyond the scientific instrument itself is strongly coupled, through the shape and layout of the satellite and the parameters of the satellite's orbit, to the observational geometry of the target area in the sky, the Earth, and the Sun. The most critical part is the low-temperature radiator that radiates the heat generated by the fast read-out scheme of the EMCCD sensors into space, to keep the semiconductor temperature below -80°C. Since the same constraints apply, although moderated by a substantial thermal inertia, its positioning is governed by the same forbidden hemisphere as the telescope. Due to the box shape of the basic /SSB structure and the deep nesting of the telescope aperture within the deployable sunshield related to straylight and its diffraction at the lit edges, there is a relatively large surface available for this radiator that would not exist in a conventional telescope tube satellite design resembling CoRoT or the Hubble Space Telescope. The thermal studies conducted during Δ Phase A have shown that it is possible to keep the sensor temperature below the limit for all but the most noon-midnight-like SSOs. Even in the worst case reference orbit studied, the sensor never warms up beyond -73°C, twice a day, at an average of -77°C which may still be operationally tolerable, even with the inevitable modelling errors included.

Energy - In and Out

The strong coupling of optical and thermal influences forces system-level optimization of the geometrical layout of the satellite in accordance with the outline of the ROI and the survey pointing patterns within it, the orbital plane normal orientation with respect to the Sun, the location of available ground stations, and the field of view of antennae and possibly other directional instruments.

Placing Radiators

The layout of the telescope and the components visible to its aperture is governed by the straylight rejection requirements, only. Although it is directly tied to the location of the FPA, the positioning of the low-temperature radiator happens to arrive within the same geometrical space of constraints as straylight-driven components, and it can be made compatible with straylight rejection.

But there are several other radiators for different temperature levels at higher power ratings, and the related components. The CCD front end electronics (FEE) have to be kept at an intermediate temperature level to reduce heat input to the focal plane array through cabling and other conductors as well as direct thermal radiation. The latter precludes the installation of dedicated FEE mid-temperature radiators within the sunshield containing the low temperature radiator and the telescope aperture, which also serves as its own radiator for the same purpose. The FEE radiators then have to take the second-best place. This place for a radiator also has to be nearly as close to the FPA and telescope as the low temperature radiator itself, and it has to work for all possible SSOs since the satellite has to remain flexible in terms of secondary payload launch opportunity selection. Such a place has been found at the flanks of the payload compartment which are approximately perpendicular to the average Sun and nadir vectors.

The next-best place for all kinds of SSOs is then required for the room temperature radiators that have to radiate the substantial power consumption of the on-board avionics and image data processing units. The electric energy required is easily provided by modern triple-junction photovoltaic cells, with conversion efficiencies exceeding 25%. Since the angle between the body-mounted telescope and the Sun vector is determined by the average centre elongation of the ROI, approximately 45°, the solar panel is deployed in a two-stage movement in which side-mounted wings are unfolded and then angled with respect to the satellite body together with the central panel between them. Their back side forms the ideally oriented panel radiator for energy conversion losses. Some of the radiated heat hits the satellite body, but the solar panel also provides some shadow for it. After reorientation towards the Sun, the satellite's surfaces are effectively all rotated by the central panel deployment angle, and none of them on average fully faces Earth any longer. Consequently, the launch vehicle adapter side of the satellite and most of the adjacent faces of the satellite body serve as room temperature radiator for the bus electronics segment and service segment.

Communication Signals

The accommodation of antennae for communication, possibly including the OSIRIS laser optics, has to allow Earth pointing according to the directionality of the respective antenna within the constraints of primary payload safety against the Sun, and low temperature thermal control system stability. During Δ Phase A, a placement for nadir-pointed range-compensated antennae has been found that complies with these requirements for all studied SSOs, but is optimal for none. It seems possible to optimize the antenna accommodation if the mounting can be adjusted just before flight around one axis.

Dual Use

The design of a satellite to be launched as a secondary payload has to be light and compact if the chances to hitch a good ride are to remain high. High-density satellite design can be achieved by the use of one component for multiple purposes. The /SSB heritage structure uses fairly massive aluminium panels which seem out of place in the mass budget of a satellite. At a closer look, the same components also serve as thermal conductors from power consumers to the radiators, thermal inertia dampers for temperature stability, and radiation shielding at the same time. This alleviates the need for dedicated components with their own mass and volume requirements, which in turn would increase the size of otherwise unrelated structures.

Similarly, less radiation sensitive components such as batteries, reaction wheels, and payload support structures, are placed around the more sensitive or critical avionics boards. These in turn are oriented such that the sensitive electronic components on them on average offer the smallest cross-section to the directional component of solar high-energy radiation.

To Scale

All this has to be fitted into the limited envelope of a compact class satellite. The stowed envelope and deployed power generation capability of AsteroidFinder/SSB are about the same as the common envelope and power rating of a small fridge for single households. Unlike a common fridge, AsteroidFinder/SSB contains no moving parts but one-time deployables, and no actively controlled temperature regulation systems, but it comes with the computing power of several up-to-date desktop computers, albeit partially hardwired into the dedicated form of FPGAs.

A cliché public relations image of conventional scientific satellites is that with a busy technician in a bunny suit posing next to the behemoth as scale reference. For AsteroidFinder/SSB as it looks today, the only person to pose standing within the stowed satellite envelope for such an image would be a toddler who was born when the project was kicked off, 18 months ago.

LESSONS LEARNED

During the past Phase A and Δ Phase A, many lessons have been learned that will be applied during the coming Phase B of AsteroidFinder/SSB. The envelope might be enlarged slightly to lower the minimum solar elongation which is limited to approximately 33.4° in the Phase A design arbitrarily set as baseline for the studies that comprised Δ Phase A. The use of directional X-band antennae will be studied with respect to the protection of the telescope from sunlight and thermal influences. The primary payload and its low temperature thermal control system will be refined. A large number of improved detail solutions has been found and noted during the time in which the design was temporarily frozen, first for the conclusion of the final Phase A review and then for the Δ Phase A. Secondary missions and instrument payloads will be studied in greater detail to broaden the scope of the overall mission, in rapid response to current themes of interest.

However, the most important lesson learned is that the mission is feasible even with the non-optimized design studied so far, on almost every SSO attained by a civilian satellite as primary payload in the past five years, and for most orbits with good margins.

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