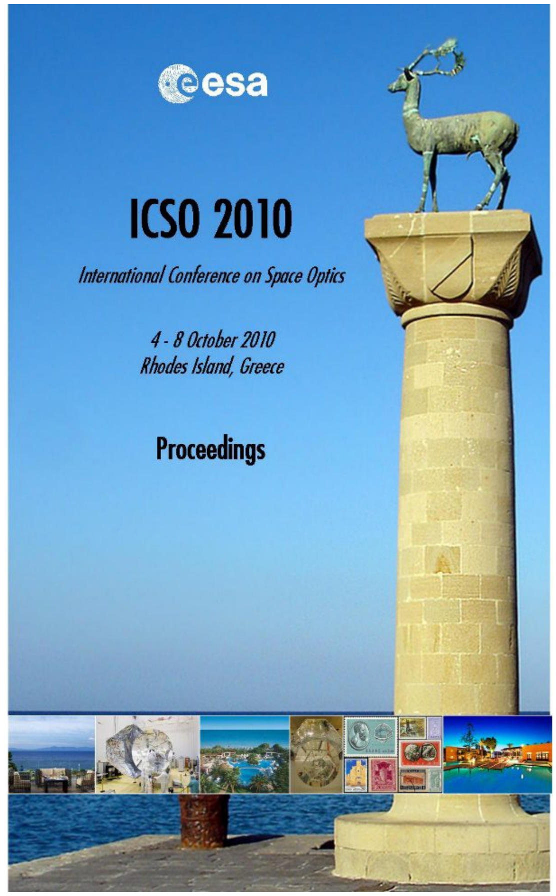
International Conference on Space Optics—ICSO 2010

Rhodes Island, Greece

4–8 October 2010

Edited by Errico Armandillo, Bruno Cugny, and Nikos Karafolas



AsteroidFinder – the space-borne telescope to search for NEO Asteroids

M. Hartl, H. Mosebach, J. Schubert, H. Michaelis, et al.

International Conference on Space Optics — ICSO 2010, edited by Errico Armandillo, Bruno Cugny, Nikos Karafolas, Proc. of SPIE Vol. 10565, 105650D · © 2010 ESA and CNES
CCC code: 0277-786X/17/$18 · doi: 10.1117/12.2309201

ASTEROIDFINDER – THE SPACE-BORNE TELESCOPE TO SEARCH FOR NEO ASTEROIDS

M. Hartl[1*], H. Mosebach[1], J. Schubert[1], H. Michaelis[2], S. Mottola[2], E. Kührt[2], K. Schindler[2]
[1]Erwin Kayser-Threde GmbH, GERMANY, [2]DLR Institute of Planetary Research, GERMANY.

ABSTRACT

This paper presents the mission profile as well as the optical configuration of the space-borne AsteroidFinder telescope. Its main objective is to retrieve asteroids with orbits interior to the earth's orbit. The instrument requires high sensitivity to detect asteroids with a limiting magnitude of equal or larger than 18.5mag (V-Band) and astrometric accuracy of 1arcsec (1σ). This requires a telescope aperture greater than 400cm^2, high image stability, detector with high quantum efficiency (peak > 90%) and very low noise, which is only limited by zodiacal background. The telescope will observe the sky between 30° and 60° in solar elongation. The telescope optics is based on a Cook type TMA. An effective 2°×2° field of view (FOV) is achieved by a fast F/3.4 telescope with near diffraction-limited performance. The absence of centre obscuration or spiders in combination with an accessible intermediate field plane and exit pupil allow for efficient stray light mitigation. Design drivers for the telescope are the required point spread function (PSF) values, an extremely efficient stray light suppression (due to the magnitude requirement mentioned above), the detector performance, and the overall optical and mechanical stability for all orientations of the satellite. To accommodate the passive thermal stabilization scheme and the necessary structural stability, the materials selection for the telescope main structure and the mirrors are of vital importance. A focal plane with four EMCCD detectors is envisaged. The EMCCD technology features shorter integration times, which is in favor regarding the pointing performance of the satellite. The launch of the mission is foreseen for the year 2013 with a subsequent mission lifetime of at least 1 year.

I. INTRODUCTION

The AsteroidFinder is a scientific mission to detect asteroids in the solar system using a space born optical telescope mounted on the DLR compact satellite bus SSB flying in a Low Earth Orbit (LEO). The instrument requirements that drive the design of the instrument are the limiting magnitude of 18.5mag (V-Band), the astrometric accuracy and the field of view (FOV) of the telescope.

Near-Earth objects (NEO) like asteroids and comets pose a hazard to life on Earth. Among them Apollo- and Aten-type asteroids which cross the Earth's orbit are potentially dangerous for the earth. Ground-based surveys to detect such objects essentially cover regions in dark-sky directions more than 90° from the Sun. However, there is high theoretical evidence that there is a population of asteroids on orbits that lie entirely within the Earth's orbit, the so-called inner-Earth objects (IEO) or Apohele asteroids, remaining virtually undetectable from the Earth's day side for ground telescopes.

A space based telescope like the AsteroidFinder is able to scan sky areas much closer to the sun. The telescope will observe the sky between 30° and 60° in solar elongation. The detection of objects is limited by the light-gathering power of the telescope, the achievable detector sensitivity and, as the lowest limit, by the sky background, which is due to the zodiacal light with its minimum V-band surface brightness of 23.3mag/arcsec^2 around 140° solar elongation, increasing gradually toward the sun and toward the ecliptic plane.

II. MISSION AND OPTICAL PAYLOAD REQUIREMENTS

A. Mission Statements and Requirements

The AsteroidFinder shall scan the sky between 30° and 60° in solar elongation. This guarantees that the normal vector of the solar panels is always within 30° of the solar direction of the Sun (Fig. 1). With an exposure time of 1min from observation data the NEO provisional orbital parameters shall be identified for follow-up observations. The telescope will be fixed body-mounted to the DLR standard satellite bus (SSB) platform. Pointing shall be achieved through rotation of the spacecraft by means of a 3-axis stabilized platform with pointing accuracy of 5arcmin and a stability of 7arcsec/s. A pointing stability like that should be sufficient for an electron multiplying CCD (EM-CCD) sensor with its high read out rate and short integration time of ~100ms.

[*] michael.hartl@kayser-threde.com

The telescope temperature shall be kept at -30°C and the focal plane shall be cooled to -80°C by passive means, only. The temperature gradient tolerance range for the telescope is expected to be 15°C. There shall be no re-focusing mechanism.

The satellite shall be launched into a sun-synchronous terminator orbit with an inclination of 98°, equatorial crossing time 6:00 local time of descending node (LTDN) and an altitude range from 650 km to 850 km optimized for a maximum observation time by avoiding eclipses by the Earth and minimum cosmic ray impact. The satellite envelope shall not exceed 650×550×880 mm^3 in a stowed configuration, the mass (bus and main payload) shall not exceed 130kg and the satellite lifetime shall be 1 year minimum.

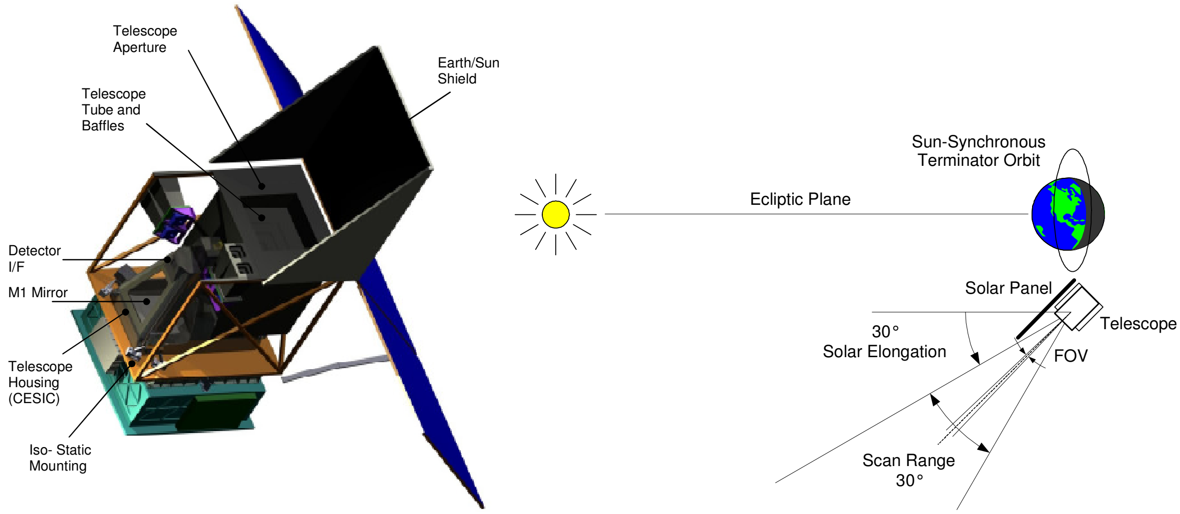


Fig. 1. AsteroidFinder model, orbit and proposed scan configuration**.**

B. Optical Payload Requirements

Tab. 1 shows the main requirements for the AsteroidFinder telescope. Design drivers are in particular the requirements for the point spread function (PSF), the large field of view (FOV) and the distortion requirement.

Tab. 1. Optical payload requirements**.**

Parameters	**Values**
Effective aperture	≥ 400 cm^2
Number of pixels	2048×2048
Pixel Size	13µm×13µm
Corrected FOV	2°×2°
Incremental FOV (IFOV)	0.001° (= 3.5arcsec)
PSF (FWHM)	0.5 pixel
Radial distortion	< 1%
Optical transmission	> 80% @ 450 – 850 nm
Operational temperature range	-60 °C, +10 °C
Non-operational temperature range	-60 °C, +40 °C
Focal Plane Temperature	-80 °C
Overall Payload Envelope	460×580×550 mm^3
Max. Weight	20kg

C. Limiting Sensitivity

The limiting sensitivity of the AsteroidFinder telescope is defined by the zodiacal light background. Within the 30° to 60° angular range with respect to the sun the brightness of the zodiacal light, I_{ZL} lies in the range of $120S_{10} < I_{ZL} < 1000S_{10}$, while at the ecliptic pole it is $I_{ZL} = 60S_{10}$. In the V band $1S_{10}$ corresponds to 27.7mag/$arcsec^2$. A pixel size of 13µm×13µm, equal to 12.4$arcsec^2$, leads to a limiting sensitivity of 19.8mag for $I_{ZL} = 120S_{10}$ and 20.5mag for $I_{ZL} = 60S_{10}$.

Fig. 2 shows the effective flux/pixel, calculated for different celestial stray light sources as a function of their respective V band magnitude. The effective flux/pixel is calculated within a band pass of 400nm to 1000nm, assuming a mean quantum efficiency of QE = 0.5, a mean transmission of T = 0.83 (4 reflections with a reflectivity of 0.95) and an ensquared energy per pixel of EE = 0.8. The typical ranges for those stray light sources which can be regarded as in field or off-axis are indicated. These sources have to be compared with the limiting detection sensitivity of 18.5mag for an asteroid and the 23.3mag/arcsec^2 (at 140° solar elongation) for the zodiacal light. For a limiting magnitude of 18.5mag, the required off-axis stray light rejection, defined as the limiting flux at the detector divided by the input flux from the source on axis is $1 \cdot 10^{-18}$ for the sun and $3.5 \cdot 10^{-18}$ for the light originating from the Earth.

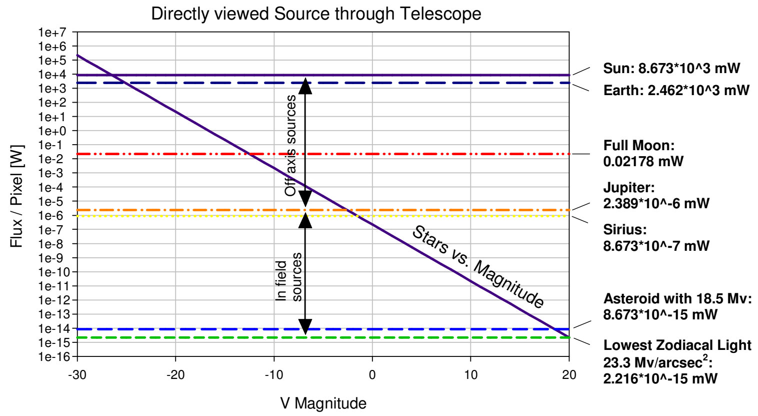


Fig. 2. Effective flux/pixel for different celestial stray light sources.

III. ORBITAL STRAY LIGHT ANALYSIS

A. Geometrical Considerations

The prevention of direct straylight intrusion from sun or earth into the telescope entrance aperture is one of the main objectives in the design of the space craft (S/C). Direct sun light is blocked by a large earth/sun shield. In addition, precautions against intrusion of straylight originating from the Earth out of a 150° solid angle cone need to be taken. Fig. 3 shows the situation for a worst-case orbital height of 650km.

B. ESARAD® Radiative Analysis

The ESARAD® thermal-radiative analysis produced quantitative results for the illumination conditions under the various observational, orbital and seasonal situations. The orbital views with its solar illumination are shown in Fig. 3.

In no situation a direct illumination of the aperture through earth or sun light could be detected, but only light scattered in first or higher order from structures in the vicinity of the telescope entrance aperture. During most of the orbital time and for most observation angles the mean stray light level at the telescope aperture is between 10^{-6}W and 10^{-7}W. Within the earth eclipse (solar declination of -23.5°, around the North Pole) the stray light level falls below 10^{-12}W. The worst case appears above the South Pole at a solar declination of -23.5° in winter time, where the straylight level reaches a maximum of $2 \cdot 10^{-3}$W for an observation angle of 60°. For that worst-case scenario Fig. 4 shows the straylight flux through the telescope aperture within a spectral range of 0.2µm < λ < 2.8µm.

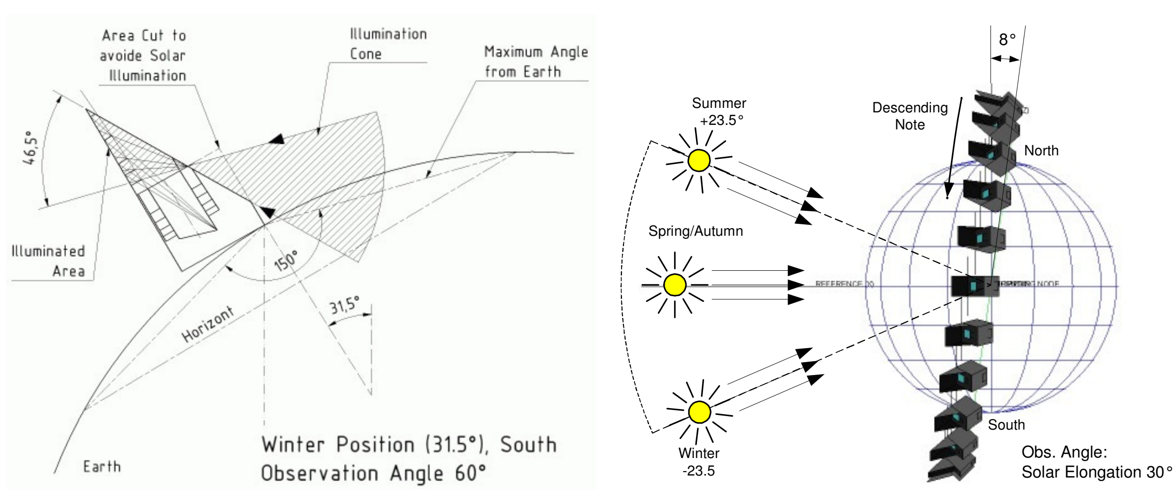


Fig. 3. AsteroidFinder geometrical model; orbit view with solar illumination.

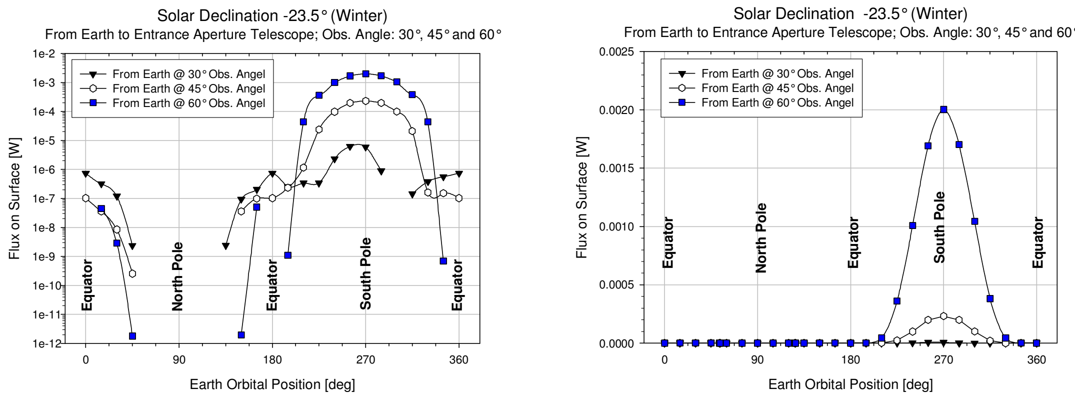


Fig. 4. Straylight originating from Earth illuminating the telescope entrance aperture (log. and lin. scale).

IV. TELESCOPE OPTICAL DESIGN AND ANALYSIS

A. Optical Design

An analysis of a Ritchey-Chretien type telescope showed that it does not seem to be feasible to meet the mission requirements regarding envelope, mass and lifetime and the optical requirements with respect to the limiting sensitivity, i.e. straylight mitigation, with an on-axis or refractive design, an off-axis all-reflective three mirror anastigmat (TMA) has been assumed as baseline, analogous to [1]. More precisely, the telescope is a Cook type F/3.4 system with 2.8 deg radial FOV (Fig. 5) and a focal length of 760mm. The image quality criterion of a PSF with a FWHM of 0.5 pixel requires a not quite diffraction limited system. The image quality has been optimized for a quadratic field with 26.6 mm side length, corresponding to a quadratic FOV of 2°×2°. The wave length range from 450 nm to 850 nm has been weighted according to the quantum efficiency of the e2v CCD201-20 sensor.

The Cook TMA provides for an accessible intermediate image and a real exit pupil, which enables effective baffling the telescope. Unlike the similar Korsch TMA, the tertiary mirror is smaller than the primary mirror [2]. The Cook TMA features an optical axis so the mirror surfaces are rotationally symmetric with an off-axis field (2°) and an off-axis entrance pupil. With the standard Cook TMA design and purely conical surfaces the optical performance had not been satisfactory, so additional aspherical coefficients for the mirrors and an additional Schmidt-type corrector plate (SCP) with a reflection angle of 90° have been applied. Nevertheless the optical design features an optical axis and all surfaces are rotationally symmetric with respect to that. The corrector plate is rotationally symmetric after accounting for the 90° reflection. The axial symmetry of the optical elements simplifies manufacturing and testing and usually makes the system less sensitive to misalignments.

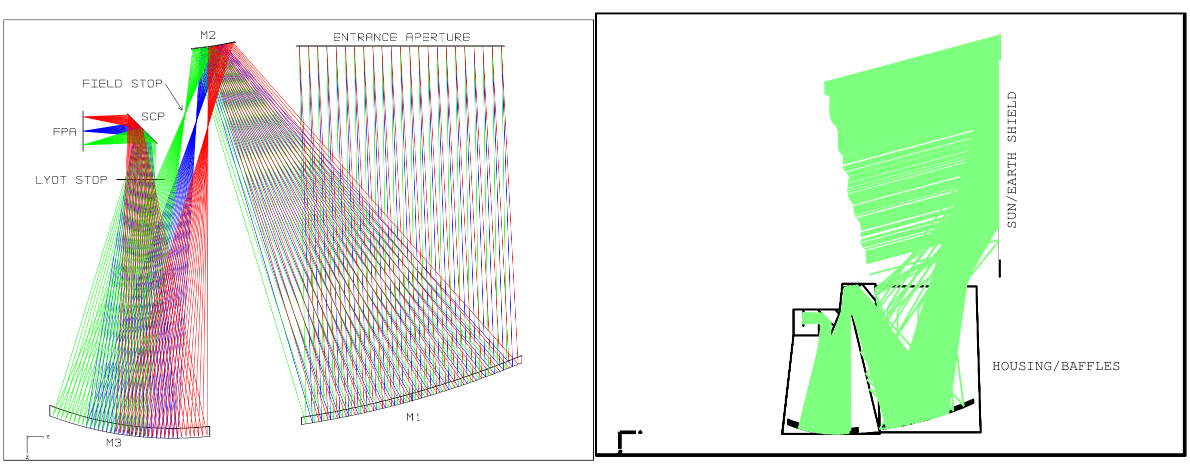


Fig. 5. Layout of the optical design; baffle geometry for the straylight analysis.

Fig. 6 shows the PSF within the area of one pixel (13µm × 13µm). While the image quality is close to the diffraction limit at the field center only, the PSF 0.5 pixel FWHM requirement is met over the full FOV, though.

To utilize the limited available volume in an optimal way, square or rectangular mirrors have been chosen. The size of the entrance aperture is 230mm × 228mm. A Lyot stop is located between tertiary mirror and corrector plate. The effective aperture equals 474cm^2 at the field center and at one field edge and decreases to

430cm^2 at the other field edge due to different viewing factors for different field points and due to pupil aberrations. The maximum distortion is 1.4% and the optical system is almost telecentric at image side.

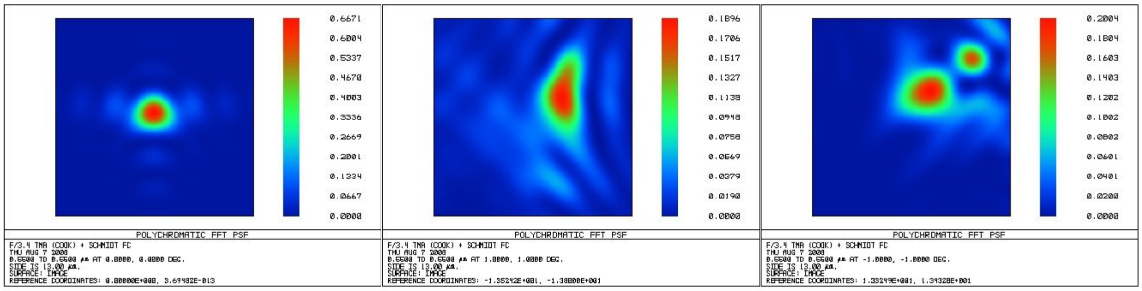


Fig. 6. PSF for the field center and the marginal field points.

B. Straylight Analysis

A field stop at the position of the intermediate image and a Lyot stop at the exit pupil provide an effective means to mitigate stray light induced by in-field as well as out-of-field light sources. To show the potential of stray light mitigation of the Cook TMA system a simplified baffling has been implemented in ZEMAX®. The baffle geometry is shown in Fig. 5. The amount of stray light impinging onto the FPA has been evaluated using the ZEMAX® non-sequential straylight simulation feature. In addition to the field- and Lyot stop several surfaces have been placed to effectively block straylight paths. All non-mirror surfaces are assumed to be Lambertian reflectors with a reflectivity of 5%. There hasn't been made use of additional vanes to block stray light paths in the proximity of a surface.

Aside from light directly reflected at the detector surface, there is no 1st order stray light getting through. (The order of stray light refers to the number of non-specular reflections from stray light entering the entrance pupil to hitting the detector surface.) Within a FOV of ~4° light is scattered in the proximity of the FPA which induces 2nd order stray light. As there are no bright objects (sun, earth, moon, illuminated baffles) to be expected in this region, this near in-field stray light isn't considered to be critical. The internal baffling scheme mitigates stray light by factor of $\sim 1 \cdot 10^{-4}$ overall. Irrespective the in-field stray light the mitigation ratio is $\sim 3 \cdot 10^{-8}$. Most part of the out-of-field stray light is induced by 3rd order scattering. The reference for the stray light levels is the amount of light that is reflected specularly at the mirrors without scattering at any other surface.

Depending on season and observation angle light originating from the earth scatters at the external sun/earth shield and enters the entrance aperture of the telescope. While the fraction of light scattered at the internal baffling of the telescope may be neglected, light scattering caused by mirror contamination – esp. the primary mirror – can reach significant values. Fig. 5 shows the path of rays scattered at the external baffle and at the contaminations of the primary mirror. The scattering at the external baffle is assumed to be Lambertian with a reflection coefficient of 5% and the primary mirror contamination corresponds to cleanliness level L300. The light originating from earth hits the external baffle under an angle of ~15° and for simplicity is assumed to be parallel. For a power of 3W of light from earth ~5mW of scattered light from the sun/earth shielding external baffle enter the telescope's entrance aperture. A fraction of $2 \cdot 10^{-10}$ of light entering the entrance aperture reaches the FPA. This leads to a background of $2 \cdot 10^{-19}$W/pixel total or $3 \cdot 10^{-20}$W/pixel in the V band which is well below the limiting sensitivity of $1 \cdot 10^{-18}$W/pixel defined by the Zodiacal light background.

V. MIRROR AND STRUCTURE MATERIAL TRADE OFF

A. Thermal Design and Analysis

For a purely passive thermal design as is the case for the AsteroidFinder telescope, the main objectives for the thermal design are a minimum temperature gradient within the telescope housing and a temperature level below -30°C. To achieve these requirements the thermal design exhibits following key features: Insulation of the telescope from external environment by multi-layer insulation (MLI), minimization of the radiative heat exchange between the telescope and the MLI by providing low emittance surfaces on the external sides of the telescope housing and entrance baffle as well as on the internal MLI layer and minimization of heat leaks by thermal decoupling over the following interfaces: telescope housing – S/C bus, telescope housing – entrance baffle and telescope housing – detector.

Analogous to the orbital stray light analysis a preliminary ESARAD®/ESATAN® radiative-thermal analysis has been implemented for an all-aluminum and an all-HB-Cesic® telescope. The analysis for the two configurations led to the conclusion, that the temperature level of the telescope housing is in the target range of -30°C for any orbital/seasonal configuration and that the temperature gradient within the telescope housing is about 2.5K. With a safety margin factor of 2 a temperature gradient of 5K might be assumed. It is ~20% lower in case of HB-Cesic® due to the increased wall thickness, which needs to be larger than for aluminum, since the allowable stress level for HB-Cesic® is lower. The temperature gradient is smaller than the given tolerance range for the telescope of 15°C. The gradient however is still in a range, where it will have an impact to the optical performance and consequently will drive the selection of mirror bulk and structural material as discussed below.

B. Choice of Materials for Mirror Segments and Structure

For different material combinations the telescope temperature and the maximum temperature gradients have been analyzed. The impact of the thermal effects on the optical performance has been analyzed with a ZEMAX® optical model, which included a simplified thermal model as outlined in Fig. 7. Three material configurations have been considered:

- CFRP tube design of the main support structure and Zerodur® mirrors
- All-aluminum design
- All-HB-Cesic® design

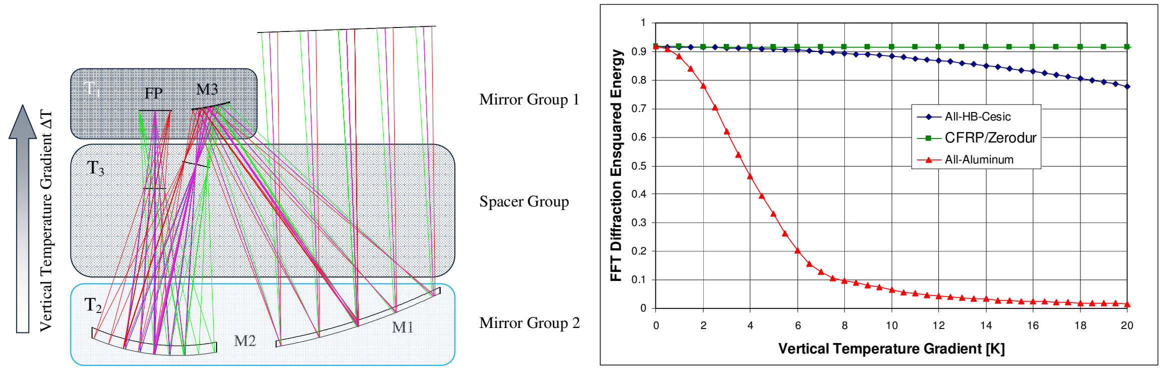


Fig. 6. ZEMAX® model comprising a simplified thermal model; optical performance analysis.

The encircled energy (EE) at the field center is shown in Fig. 6 for the three material configurations as a function of the temperature gradient. With an EE criterion of 80% the maximum tolerable temperature gradients are found to be:

- 2K for an all-aluminum telescope design.
- >30K for Zerodur® Mirrors supported by a CFRP structure.
- >15K for an all HB-Cesic® telescope.

An all aluminum design without active temperature control is not able to fulfill the optical requirement for a temperature variation of 15K. While on first sight the material combination CFRP/Zerodur® seems to be favourable moisture absorption of CFRP during fabrication and storage leads to a not well controllable dimensional change on the order of the thermal effects of the all-aluminum design. As there shall be no focusing mechanism, only the HB-Cesic® design is compliant with the mission and optical payload requirements.

VI. CONCLUSION

The optical and radiative-thermal analyses show the feasibility of the space-borne AsteroidFinder telescope in compliance with the mission and optical payload requirements utilizing an all-HB-Cesic® design approach. The non-obscurated off-axis TMA telescope optical design is able to cope with the challenging straylight environment of in a LEO and to achieve the critical requirement of a limiting magnitude of 18.5mag for asteroid detection and orbital parameter determination.

ACKNOWLEDGEMENT

Funding for the development of the AsteroidFinder telescope is provided by German Aerospace Center DLR.

REFERENCES

[1] D. C. Harrison and J. C. Chow, “The Space-Based Visible Sensor”, John Hopkins APL Technical Digest, vol. 17, pp. 226-236, 1996.

[2] Lloyd Jones, “Reflective and Catadioptric Objectives”, Handbook of Optics, 2nd ed., M. Bass, ed., Vol. 2 (McGraw-Hill, 1995).