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The Bering Target Tracking Instrumentation.

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Abstract – The key science instrument on the Bering satellite mission is a relative small telescope with an entrance aperture of 300mm and a focal length between 500 and 1000mm.

The detection of potential targets is performed by one of the target scanning ASCs, as described in a separate paper [6]. This procedure results in a simple prioritized list of right ascension, declination, proper motion and intensity of each prospective target.

The telescope itself has a dedicated ASC Camera Head Unit (CHU) mounted on the secondary mirror, largely co-aligned with the telescope. This CHU accurately determines the telescopes pointing direction. To achieve fast tracking over a large solid angle, the telescope pointing is achieved by means of a folding mirror in the optical pathway.

When a prospective target approaches the telescope FOV, the ASC on the secondary will guide the folding mirror into position such that the target is inside the telescope FOV.

During the telescope observation time, the ASC will constantly control the folding mirror to correctly position the target at the center of the telescope, basically performing a standard telescope tracking service.

The telescope will after the initial target acquisition track and observe the object of interest. To achieve milli-arcsecond accuracy the telescope is equipped with a tip-tilt system on the secondary.

The performance of the acquisition and telescope guidance has been tested and excellent noise, acquisition and settling time performance has been achieved. The operations have been verified for telescope focal lengths of 250 and 8000mm.

INTRODUCTION

The use of telescopes on space borne platforms face a unique class of difficulties associated with operations involving acquisition of non-distinct or moving target and the subsequent high accuracy pointing for longer time span.

The basic problem acquiring a moving target is, that the relatively long focal length of the telescopes limits the field of view, which in turn has adverse impacts on search-time and -efficiency. For extended targets the limited field of view typically will translate into problems locating the desired spot to lock on to. For faint or secondary objects, the problem is aggravated further by the longer integration times required to achieve a sensible signal to noise ratio.

The basic problems arising from tracking a target comes from the accuracy demand to the telescope attitude control system. Disturbance torques and other onboard noise sources tend to put rather strict requirements to this controller not only in terms of accuracy, but also to the time resolution of the closed loop so as not to cause motion smear of the telescope images. The accuracy demand is generally the design driver for long focal lengths, with their associated higher mass and moments of inertia, whereas the controller loop time demands becomes dominant for fast tracking and lightweight systems.

Common to all the mentioned applications of space borne telescopes, are the need for a fast, automatic and accurate guidance system. For most applications the usability, time on target and accuracy of the telescope system may be further improved if the guidance system is based on an absolute attitude system rather than just providing time derivatives of the attitude.

At the Technical University of Denmark, the Measurement and Instrumentation Section has developed a suite of telescope guidance methods intended for ground based as well as space borne applications. These methods can be utilized to enable full autonomous, robust, fast and accurate pointing of a medium sized space borne telescope as foreseen for the Bering mission.

This paper describes the instrument setup in details, discuss how the milli-arcsecond accuracy is achieved and the realized lock-in times. Ground test results are given, and it is demonstrated how fully autonomous calibration and bias elimination is performed.

INSTRUMENTATION

The key attitude sensor baselined for the Bering mission is the Micro Advanced Stellar Compass (uASC), which is a fully autonomous star-tracker featuring 8 true independent solutions pr. second from up to 4 different Camera Head Units (CHUs) [1]. The uASC has the additional feature, that for all attitude solutions, at list of non-stellar objects present in the image can be extracted. This enables a rapid separation of objects of interest (i.e. NEOs for the Bering application). A uASC featuring 2 CHU is depicted in Fig. 1.

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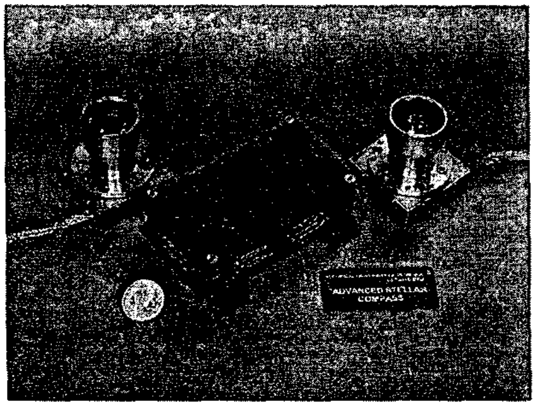

Fig. 1: A microASC is shown together with two CHUs. A 1 Euro coin gives the size. The 3W, 270g microASC effectively implements four separate fully autonomous star trackers.

The ASCFIT program is a publicly available software package developed at the Technical University of Denmark. It is used to compute the 3-axis attitude of a narrow field of view star image [2]. The ASCfit program is based on the same technology as the uASC, however it is optimized for smaller field of views and will need a seed, in order to compute the attitude, i.e. it does not implement the "lost in space" search algorithm. The obtained accuracy of the attitude output is field of view dependent, however images from the Bering telescope system will result in accuracies in the 10 milli-arcsecond ranges.

SYSTEM DESCRIPTION

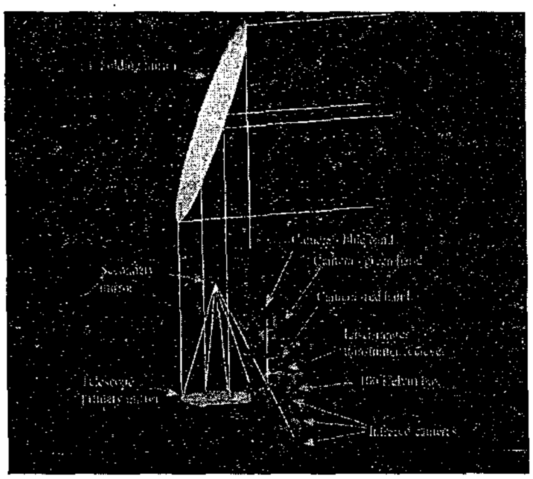

Fig. 2: Schematic view of the telescope and the imager baselined for the Bering mission. The CHU is mounted on the top of the secondary to minimize mechanical flexures.

The telescope system baselined for the Bering mission is designed around an ~0.3m entrance aperture, F ~1:4 refractor telescope. The full telescope system is depicted in Fig. 2

A schematic drawing of the high accuracy attitude determination system is shown in Fig. 3.

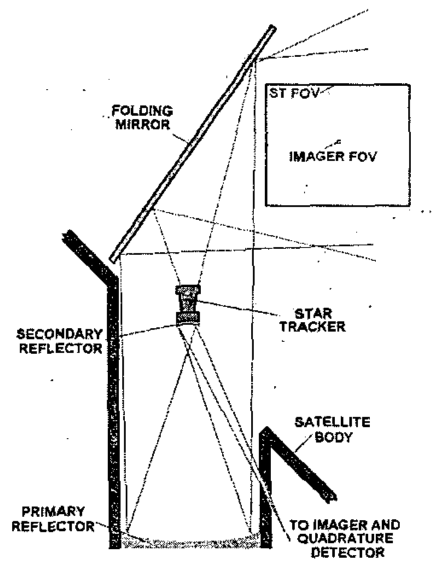

Fig. 3: The star-tracker/telescope components. The telescope FOV is showed with red lines, the star-tracker FOV is shown with green lines. Note that the actual position and orientation of the telescope FOV is inessential as long as it is relatively near the centre of the FOV of the star tracker.

The high telescope agility set forth by the mission requirements is insured by placing a lightweight folding mirror in front of the telescope. A large telescope view direction envelope can thus be achieved without severe impact on the spacecraft attitude control. A thermally clean and mechanically stress free interface between the spacecraft and the telescope (and imager) is at the same time easily achievable.

The folding mirror reflects the light onto the primary mirror, which in order to achieve a low mass, is planned to be based on a carbon-fiber structure. Because carbon fiber is sensitive to hygroscopic deformations, focus is insured by introducing a simple adaptive optics system (AO). Small relatively slow actuators mounted as an array between the carbon fiber and the telescope structure will be used to control the deformation and guarantee the telescopes optical quality.

The primary mirror reflects the light onto a secondary mirror, which structure is mounted in the telescope opening. The secondary mirror is mounted on the structure via small relatively fast actuators (e.g. piezo crystals) in order to take out secondary motion components.

The secondary mirror reflects the light through a ~5% mirror, reflecting a small portion of the light onto a quadrature detector, controlling the position of the secondary mirror actuators at a frequency of ~500Hz, whereby a simple relatively slow tip-tilt system is realized. The remaining ~95% light is focused onto a multi-spectral imager, baselined to 6 spectral bands [5].

On the backside of the secondary mirror structure, one of a uASC star-tracker CHU is mounted. The mount is made, such that the star-tracker line of sight is co-aligned with the telescope line of sight. This setup gives the obvious advantage, that the absolute telescope attitude is determined autonomously independently on the folding mirror position. The co-alignment used in one of the test setup, is sketched in Fig. 4.

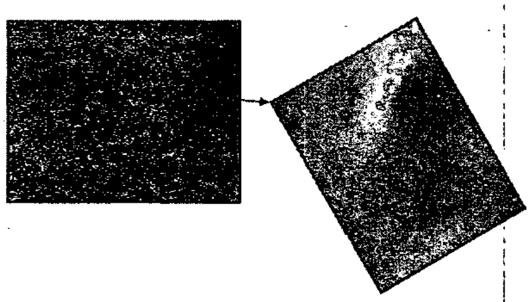

Fig. 4: A small FOV telescope image (right) is recognized in a large FOV star-tracker image (left). The images shown is from a real sky verification of the principle of operation using a 250mm telescope and a 20mm CHU.

The co-alignment between the star-tracker and the telescope will drift during the mission, influenced as it is by thermal changes, launch load impacts, focus changes imposed by the primary mirror AO, etc. An autonomous tool to perform this alignment frequently must therefore be foreseen. The ASCFIT software tool that determines the attitude based on a telescope image and an attitude seed accomplishes this. Tests show, that this procedure can be performed in 2 seconds for a 250mm system, but it may take up to 10 seconds for very long focal lengths.

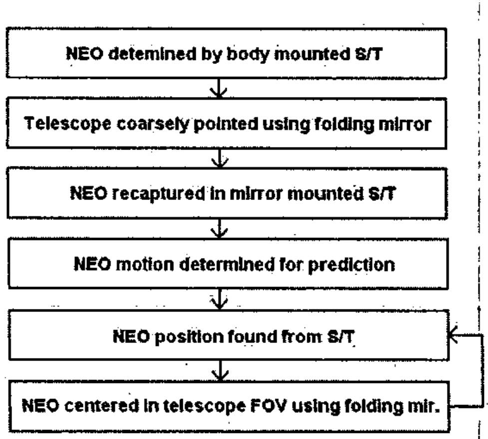

Fig. 5: Flow diagram showing the operational flow from the detection of the NEO to the acquisition of the telescope

The operation sequence starts as shown in Fig. 5, by the detection and selection of a NEO by one of the spacecraft body mounted star-trackers. The selection criteria include a considerable motion, visual magnitude, a sufficient residence time inside the telescope viewing envelope, etc. Secondly, the telescope is coarsely pointed at the NEO using the folding mirror. Thirdly, the NEO is recognized on the secondary star-tracker taking any folding mirror biases into account. Since the 3-axis alignment between the star-tracker and the telescope is known, the target attitude is commanded for the telescope, by fine-tuning the folding mirror position. The motion of the NEO is determined by a sequence of measurements, and is finally compensated for by moving the folding mirror in a closed loop, using the star-tracker as detector.

The object will now be approximately centered in the telescope with arcsecond accuracy for the duration of the observation. The residual position error is determined by the quadrature detector, that based on the offset measurement controls the secondary mirror piezos in a closed loop during image integration, in order to obtain the required ~10 milli-arcsecond pointing accuracy during image integration.

GROUND TESTS

In order to verify the system performance, a number of ground simulations have been carried out. The closed loop control of the folding mirror using the secondary mirror mounted star-tracker data as input, has been simulated by mounting a star-tracker on the secondary mirror structure of a medium size mobile outreach telescope. The star-tracker mounted on the equatorial mounted 0.5m, F1:8 telescope is shown in Fig. 6.

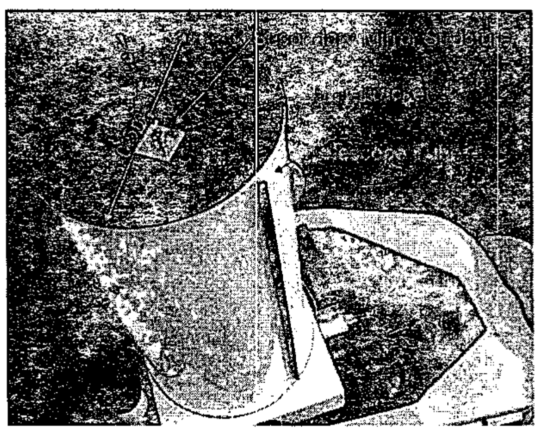

Fig. 6: The ASC star-tracker mounted on the secondary mirror structure of the 0.5m telescope. The telescope is capable of slewing at 4°/s and has a pointing resolution in the milli-arcsecond range

For the simulation, a software console was implemented that generated the telescope control signals based on the star-tracker input. The telescope was deliberately misaligned more than 90 deg. A short preprogrammed initialization sequence moved the telescope a few degrees in the RA drive, whereby a full determination of the telescope drive orientation based on the star-tracker data was achieved.

A successful test of open loop sidereal tracking (on the un-aligned telescope) verified, that using a priori knowledge of the target motion relative to the spacecraft, a tracking of the object can be carried out without the star-tracker being able constantly to detect the target. Fig. 7 shows the star-tracker output for a period of 120s. A residual drift of ~0.30mas/s is observed. Fig. 8 shows the control signals to the telescope RA-drive, the telescope Dec-drive and the residual field rotation that the 2-axis drive cannot compensate for.

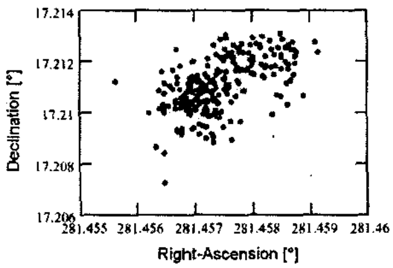

Fig. 7: A worldplot showing the star-tracker output during 120s of open loop sidereal tracking on a misaligned telescope. The star-tracker output is converted into the telescope drive frame. The attitude one second later is predicted from the sidereal motion of the earth. The difference in the RA and Dec drive is calculated and commanded. The plot shows a fairly accurate tracking containing a residual drift of ~30milli-arcseconds/s.

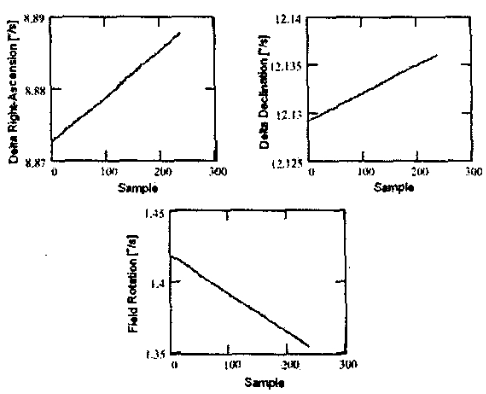

Fig. 8: The control signals to the telescope RA-drive (upper left), the Dec-drive (upper right) used to perform the tracking on a misaligned telescope. The residual field rotation (bottom) cannot be corrected for using the 2-axis drive. All signals are given in arc-seconds/s

A successful test of closed loop guiding (on the un-aligned telescope) verified, that using the star-tracker output of the target position, the folding mirror can be controlled to acquire the object for a prolonged period of time. Fig. 9 (upper left) shows the star-tracker output during the guiding of three selected targets. Fig. 9 (upper right) shows a zoom of one of the targets, showing no drift.

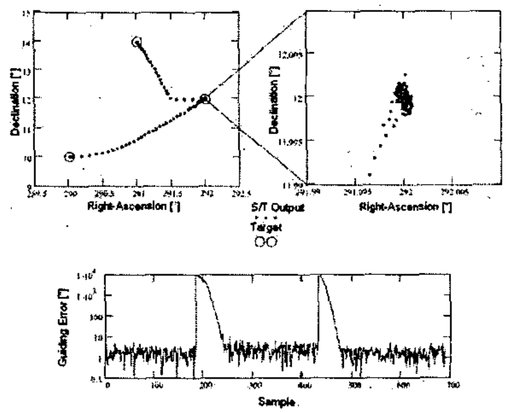

Fig. 9: The star-tracker output during closed loop guiding of three targets. Upper left is a worldplot of the entire test sequence, with the three targets marked with blue circles. Upper right is a zoom of the second target. The lower plot is a logarithmic plot of the error throughout the test sequence. The plots shows, that the pointing error of the telescope is around 1arc-second.

A more thorough description of the telescope track and guide tests and the test results can be found in [3].

The simulation of the attitude determination combining the wide FOV and the narrow FOV has been carried out by controlling two camera head units (CHUs) from one data processing unit (DPU); the one CHU being a standard FOV star-tracker (f=20mm), the second CHU having a reduced FOV (f=250mm). The advantage of having one DPU driving two CHUs is that they are fully synchronized in time. The calculated attitudes therefore refer to the same point in time, enabling the attitude from the wide FOV CHU to be used as seed for the narrow FOV CHU attitude computation. The test setup featuring the two CHUs mounted on an optical bench in front of the test mirror is shown in Fig. 10.

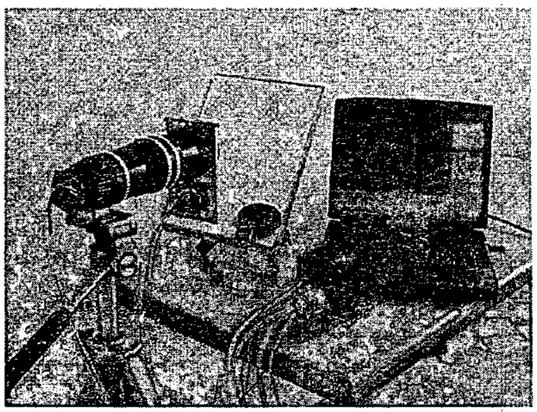

Fig. 10: A wide FOV (20mm) star-tracker and a narrow FOV (250mm) telescope is mounted on an optical bench in front of a front side mirror. The star-tracker DPU is located to the right

The simulation yielded a series of attitude determinations from the narrow FOV CHU. The relative accuracy of these measurements was in the range of 50mas. Taking the telescope scaling between the test system and the Bering telescope into account (0.25m: ~1.2m) relative attitude accuracies using the Bering telescope will be in the range of the required 10mas. Please refer to [4] for a more thorough description of the tests carried out.

CONCLUSION

The control of the telescope on the Bering spacecraft mission is based on the attitude determination from a star-tracker mounted on the secondary mirror structure. Instead of moving the entire telescope, a folding mirror has been located in front of the telescope (and the star-tracker), minimizing the movable mass.

Two ground tests have been carried out. The first test was designed to prove the concept of using a star-tracker to control the telescope. The test proved successfully that the telescope could be controlled in an open loop with a marginal drift. The first test also proved, that the telescope could be controlled in a closed loop without any drift.

The second ground test was designed to prove, that the required absolute attitude could be determined at an accuracy down to 10milli-arcseconds. The test proved successfully, that the required accuracy could be achieved by combining a standard-FOV star-tracker with a narrow-FOV tracker.

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