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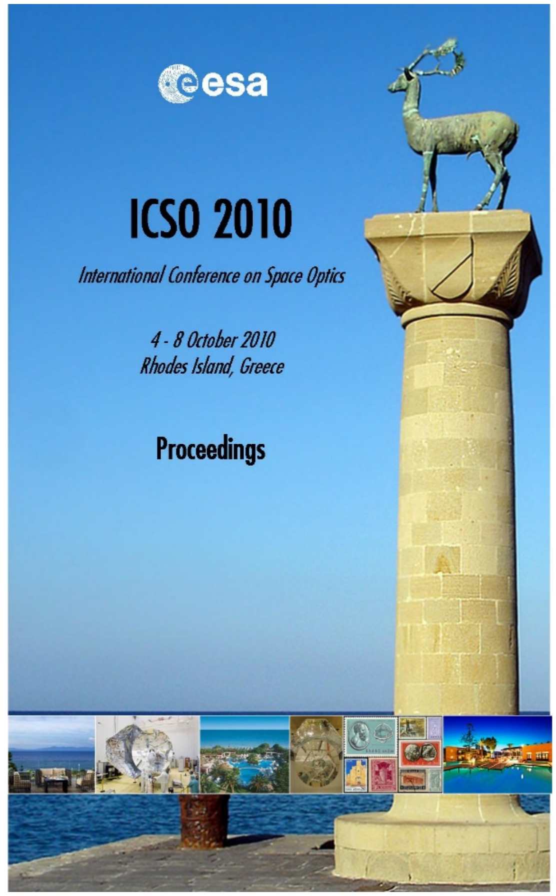

A new star (sensor) is born

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A NEW STAR (SENSOR) IS BORN

Johan Leijtens[1], Willem Vliegenthart[1], Dimitris Lampridis[2], Guiseppe Vacanti[2], Bert Monna[3], Elbert Bechthum[3], Koen Hagenaars[4], Erik van der Heide[4], Michiel Kruijff[5] , Eddie van Breukelen[6], Anita LeMair [6]
[1]TNO, [2] cosine Research, [3] Systematic Design, [4] Bradford Engineering, [5] Delta Utec, [6] ISIS, The Netherlands

INTRODUCTION

In the frame of the Dutch Prequalification for ESA Programs(PEP), as part of the efforts to design an integrated optical attitude control subsytem (IOPACS), a consortium of TNO and several SME's in the Netherlands have been working on a novel type of startracker called MABS (Multiple Aperture Baffled Startracker). The system comprises a single cast metal housing with four reflective optical telescopes which use only structural internal baffling. Inherent to the design are a very high stability and excellent co-alignment between the apertures, a significant decrease in system size and low recurring production cost. The concept is a radical change from more common multiple startracker setups. The presentation will concentrate on the validity of the concept, the predicted performance and benefits for space applications, the produced breadboard and measured performances as well as the costing aspects.

I. BACKGROUND

TNO has been involved in the design, manufacturing and qualification of sunsensors for more then 30 years but never got actively involved in the startracker market (although some attempts where made with a medium field of view startracker MEFIST in the nineties). Therefore a very legitimate question would be: “why would TNO like to get involved now in startracker developments”. The answer to this question is found in the increasing attention (worldwide) for small satellites. TNO is active in miniaturizing space components and systems. Its mini digital sunsensor is an example of this, but also micro propulsion, RF MMIC’s and small instruments are part of this activity. The start for the development of a small startracker is related to an ESA tender for an integrated attitude and orbit control subsystem. TNO replied to the tender with the system given in fig 1.

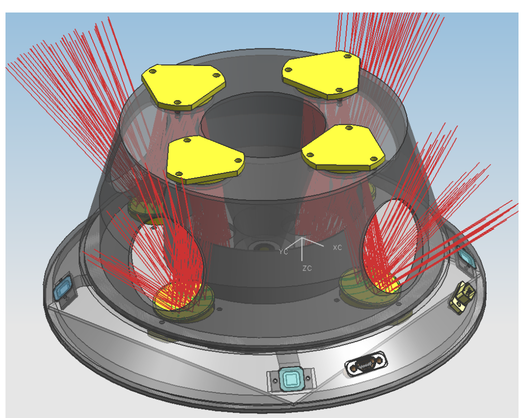


Fig 1 Attitude and orbit control subsystem AOCS

The AOCS system consisted of an earth sensor, four startrackers and four sunsensors integrated in a single mechanical housing. The core performance of the system was related to the very high mechanical rigidity of the concept and the exceptional co-registration in combination with the compactness of the solution. TNO was under the impression that it proposed a potential solution to a specific problem (the core of this solution being the integration of the startrackers in a single housing). Although the proposal was rejected by ESA, the solution in itself was seen as unique and the idea of co-registering several apertures in a single housing was patented by TNO. The potential of the concept was thought to be more then just a solution for geostationary spacecraft and the concept of IOPACS (short for Integrated Optical Attitude Control Subsystem) was born (see fig 2).

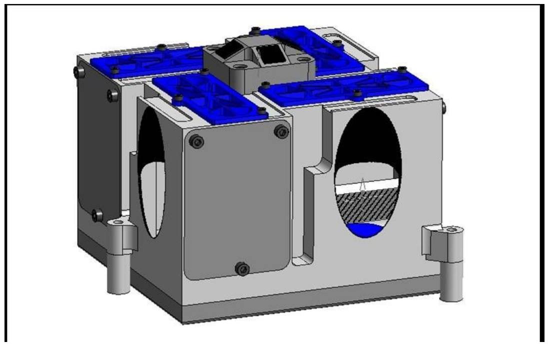


Fig 2 IOPACS basic setup

The basic setup of IOPACS consists of several optical sensors mounted in a single housing in order to reach very compact, highly stable solutions for attitude sensing of spacecraft. Such a setup can be used for very diverse purposes. By adding an Earth sensor a geostationary attitude and orbit sensor can be made. By adding GPS receivers the same for low earth orbiting spacecraft can be made (although not fully optical). By adding a laser range finder a rendezvous and docking sensor system can be made etc, etc. Core of the system for most of the solutions we could come up with, is a compact multiple head startracker.

The ideas for the startracker where there, but some vital knowledge was lacking due to the fact that TNO didn't work on startrackers for the last 15 years or so. Compliant with the task of TNO to assist Dutch small and medium enterprises in obtaining a technological edge with respect to the international competition and while some of the lacking knowledge was available in other Dutch companies it was decided to team up for looking into mainly the multiple startracker in IOPACS. The program is co-funded by the Netherlands Space Office NSO

II. THE TEAM and WORKLOAD SPREADING

The final team became quite large but based on good grounds.

Bradford Engineering was drafted in because from the onset the intention to make a cost effective sensor system was driving for a lot of design decisions and they are also producing the TNO sunsensors in larger quantities and are therefore very well suited to look at production aspects and potential cost savings. For the project they did the procurement and manufacturing of the opto mechanical components as well as the mechanical assembly.

cosine Research was drafted in because they have experience in noise modeling and designing embedded software for (for instance) LEON processors but also knowledge about stars detection and star catalogues. Apart from this they have their own labs where they can do verification tests like the point spread function test necessary to measure the performance of the optical system.

Delta Utec was drafted in because they provided the star recognition algorithms to TNO years ago when TNO was still working on startrackers. The main task of Delta Utec was to simulate the images that would be seen by the different apertures and based on the noisy images simulated calculate the accuracy that is expected for the startracker.

ISIS was drafted in because the intention of the project is to make a startracker which is enabling for small sensor systems that can be used on small satellites. Apart from the fact that they have system testing facilities, ISIS is also reseller for a number of smallsat components and therefore well connected to the potential market.

Systematic Design was drafted in because they have experience in designing compact and low power electronics and FPGA programming which was needed to produce the cameras (apart from this their knowledge about micro electronics packaging came in very handy).

TNO last but not least did the opto mechanical design (which was later on transferred to Bradford Engineering) optics and electronics integration, systems engineering and project management.

III. THE BASIC DESIGN

The basic design of MABS (at least the current version) consists of a single housing containing four independent camera's, each having a reflective imaging system made with two mirrors one of which is aspheric.

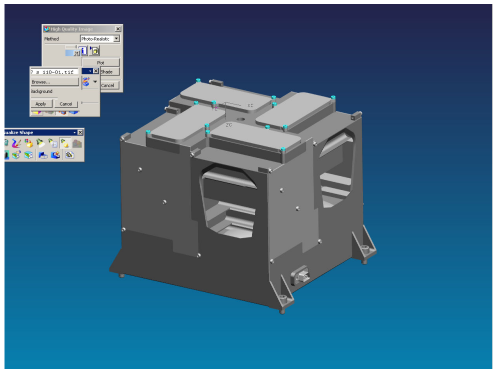
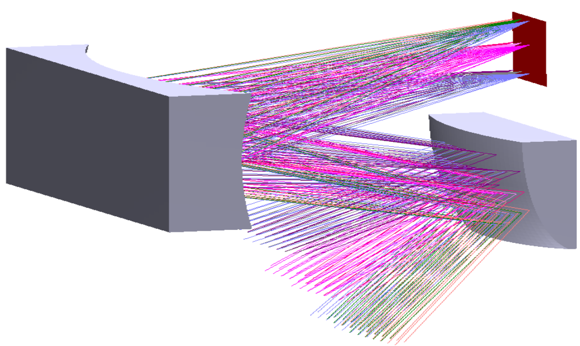


Fig 3 Basic MABS design

The straylight baffling is solely performed within the envelope of the housing, no external baffles are foreseen. The baffling structure is designed in such a way that at least three reflections are needed to reach the detector for light coming from parts that are not in the optical path. This includes the exterior of the spacecraft. In order to reach a very compact design with good straylight properties, it has been decided to use an elliptical aperture and only two optical elements. (see fig 4)



Focal length	44mm
Entrance pupil diameter	10mm*30mm eliptical
F#	4,5 *1.5 (2,6 eff)
FOV	16˚horizontal, 20˚ vertical
Detector LCMS	12.8 * 12.8mm^2 with 25 µ pixel size

Fig 4 Optical system with key data

During the production optimization it was decided to go for an aluminium housing made by means of investment casting in stead of a housing which is machined from solid (see fig 5).

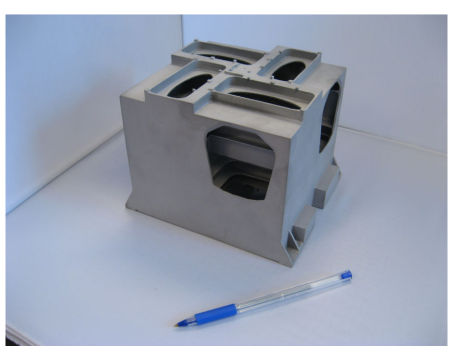


Fig 5 Cast aluminium housing

One of the main advantages of using a housing made out of a single piece is the fact that the relevant tolerances (for mounting the optical components) can be milled in a single go. This way the maximum accuracy is obtained, and by using the appropriate references, a system can be build where you just mount the optical parts and have a fully functional system without further alignments. This leads to a drastic cost reduction during the manufacturing of the startracker. The thermal resistances in between the four startracker sections are minimized by the chosen approach. And if we take into account that the mirrors are also made of aluminium, it is quite obvious that the thermal stability of the system is excellent.

FEM analysis performed on the breadboard show a very high eigen-frequency in the order of 800Hz for the bottom plate and 1350Hz for the actual housing (fig 6).

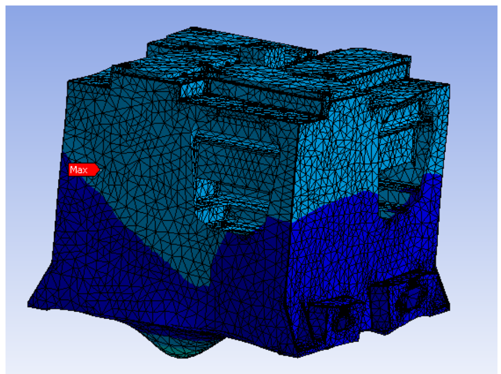


Fig 6 Fundamental eigen-frequency of housing at 1350 Hz

IV. PERFORMANCE ANALYSIS

The system design needed a number of design iterations. A major problem to tackle was caused by the penetration of straylight in association with sunlight reflected from the spacecraft. Solving this problem required a significant increase in size of the system. Fortunately this size increase was found to come together with better attitude measurement performance.

Based on a market survey that was performed as part of the development work, it was concluded that an accuracy of 5 arcseconds would be sufficient to cover the needs of 90 to 95 % of all missions. Therefore the target accuracy for the system under design was set to this level.

The performance analysis basically took place in an iterative way as the field of view of the optical system is largely determining the radiometric performance of the system. The general approach was to take the initial optical design (TNO), to analyse how many stars for given brightness would be within the field of view (Delta Utec), to compute the signal level from these stars (raw data) and to include the detector noise to the raw data (cosine Research), to analyse the expected accuracy on the basis of several thousands of simulated noisy synthetic images and of the saturation properties of the camera's used (Delta Utec) and if considered necessary to adjust the field of view in the analyses (leading to adaptation of the initial optical design).

As this was a fairly intensive process which caused the generation and analysis of tens of thousands of frames of data, the number of iterations has been kept to a minimum. In order to ensure that the system will meet the 5 arcsec goal requirement, we have settled for a system which is slightly oversized, and consequently is calculated to have a significantly better performance than targetted.

In addition to this, it should be noted that the stated accuracies are all referring to the condition of lost in space and accuracy can therefore be increased beyond what is currently projected by using for instance Kalman filtering (which is common in most startrackers).

Apart from the general radiometric calculations a number of additional analyses were performed like searching for the optimum PSF (point spread function) size and estimating the sub pixel interpolation factor that can be reached.

In order to ease the analysis, a dedicated star simulation program was developed that calculates and displays all four apertures at the same time (see fig 7). The program not only calculates the raw star data, but can also be fed with the simulated system data (including detector noise and/or saturation) and was used to determine the main performance predictions.

As can be seen in fig 7, the accuracy calculated for most of the images is well below the 5 arcsecond target.

During the simulations it was found that the expected limiting magnitude is in the order of M6.25 (see fig 8), which on average gives about 200 stars in the total field of view of the four camera's. These stars are determined with a probability of 99.95 %, leading to a predicted accuracy of 3.4 arcseconds.

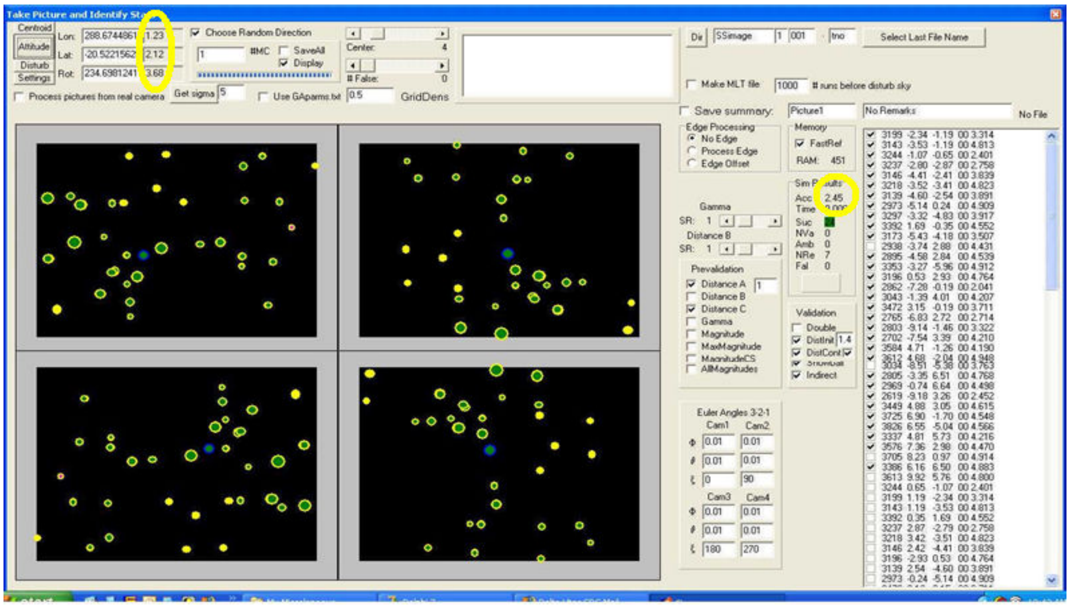


Fig 7 Star simulations and accuracy estimation

The detection probability and star recognition is poorer for weaker stars, as the centroïding accuracy decreases due to the influence of the detector noise (see fig 9). Analyses rendered that for bright stars (M<4.2) the sensor can start to saturate (fig 8) which has also a negative effect on the centroïding accuracy (fig 9). From fig 8 it can be seen that the best stars for an optimum centroïding process have a brightness between M4.2 and M5.4. If the brightness threshold for star detection would be set to M5.4, then detection probability increases to > 99.99%. The added advantage of this would be that fewer stars need to be processed and consequently a smaller processor can be applied. The predicted accuracy in that case is with 4 arcsec still significantly less then the target of 5 arcsec. For all of these calculations it is presumed that the fixed pattern noise is not removed.

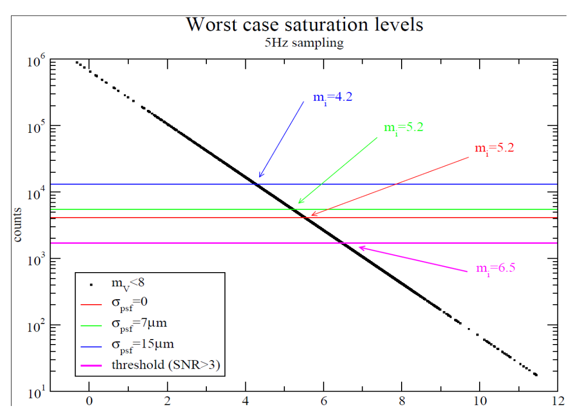


Fig 8 Dynamic range calculations for LCMS based camera in MABS

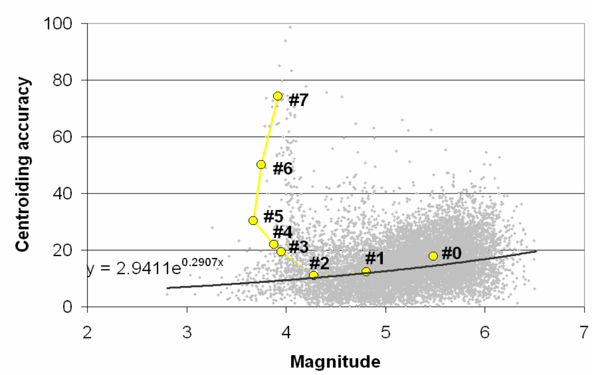


Fig 9 Centroïding as a function of magnitude (for LCMS based camera in MABS)
(#n indicates the number of detector pixels which are saturated in a 4 x 4 interpolation frame)

The centroïding and quality indication (number of saturated pixels) is done autonomously in the camera electronics. The camera electronics are build on a small flex rigid PCB (fig 10), four of which are mounted in the MABS breadboard. The electronics consist of the Cypress LCMS detector, an Actel FPGA and some power supply and USB communication circuits. The LCMS detectors cannot be purchased anymore as they are obsolete, but the team managed to get hold of the last wafer (with some help from ESA), cut it up and packaged the devices our self (Systematic).

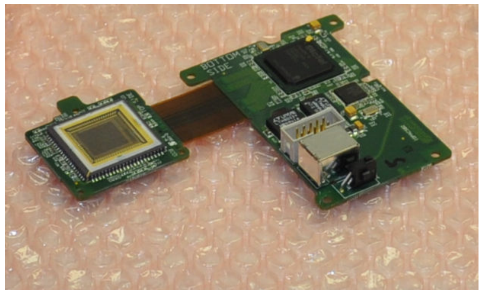


Fig 10 LCMS camera and processor

Through this board, the LCMS detector is readout at a maximum rate of 8Hz per sensor (design limit of the LCMS) and at the same speed the centroïds are calculated, the quality indicator added and the results communicated to the main processor. For the purpose of the breadboarding program, the latter is a standard laptop computer, which uses USB2 interfaces. Therefore the camera board is made USB2 compatible.

V. MAIT

At Bradford Engineering the housing was produced and the mirrors were mounted (fig 11), after which the unit was shipped to TNO for electronics integration (fig 12). Optical check-out and detector alignment took place at cosine Research, which was relatively simple because the system is defocused for stars in order to allow for sub pixel interpolation, but focused for 10m distance. This allows for a straightforward optical system check by putting some crosses on the wall in a 10m long corridor (fig 13).

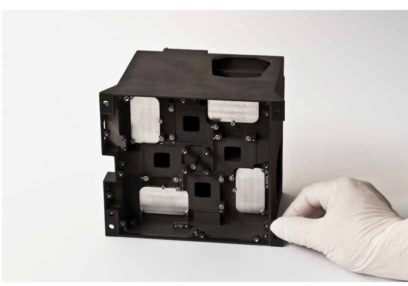


Fig 11 mirrors mounted

Fig 12 electronics mounted

Fig 13 alignment

At the time of writing this paper the system was at cosine Research for PSF measurements. So full MAIT results were not yet available, but the following conclusions could be drawn already.

- MABS was manufactured and assembled on manufacturing tolerances only and consequently didn't need any further alignment after manufacturing.
- The electronics fit nicely into the housing but there is not much room for further miniaturization without incurring significant costs for hybrid manufacturing or 3D packaging

The manufacturing is finished and the testing will continue with PSF measurements. For the moment the demonstrator is ready and nicely living up to its expectations, but the final prove of the concept we hope to give with a real sky test. To this extent the startracker will be coupled to a high accuracy telescope available at cosine Research and the images taken and attitudes calculated will be compared with the attitude of the telescope.

VI. CONCLUSIONS

A new star(sensor) is born

which holds many nice promises for the future.