THE TPD OFF-AXIS STARTRACKER (TOAST)

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ABSTRACT

The TOAST is based on a P8600 CCD detector with microprocessor control and starimage processing. The detector is operated at a temperature less than -15°C using thermoelectric cooling. The accuracy goal is 1.5" (1-σ) for a field of view of 5.4° x 8.1°. The guide-star magnitude limit is m_{si} = 6.5, which gives a 99% probability to find at least two guide-stars on the detector, permitting 3-axes attitude reconstruction.
Three modes of operation are provided. The camera mode permits visual interpretation of the starfield. In acquisition mode stars are searched for in regions specified by the on-board computer. In tracking mode the ultimate accuracy is obtained for a maximum of three stars.
A functionally representative model was built, software implementation is in a final stage.

Keywords: Starsensor, Attitude control, Sensors, Angular measurement, CCD detector

1. INTRODUCTION

The TPD off-axis startracker is the result of a further development of the BUSSOR, a starsensor designed and manufactured for use on a balloon platform. This sensor already possessed a number of features that are also fundamental for the present TOAST. These features are a two-dimensional CCD detector with Peltier cooling, microprocessor for control and starimage processing, different modes of operation and a high sample rate. The BUSSOR was based on the MA328 detector with 120 x 75 elements and capable of tracking one star with magnitude $1 \leq m_V \leq 5$ in the centre of its 1.7° x 2.3° field of view. The accuracy, limited by the digitization of the position data, amounted to 0.5', corresponding to approximately one-third of the element size.

The advent of larger CCD arrays was found to open the possibility of designing a more versatile starsensor with random pointing capability, while allways retaining a large probability to have two suitable stars in the field of view permitting a complete 3-axes attitude determination. This capability was still compatible with arcseconds accuracy and high sample rates enabling direct inclusion in the attitude control loop, if desired. On this basis the definition and development of the TOAST was started, with the first aim to produce a functionally representative model, to be used to verify the feasibility of the established design goals. To this purpose the sensor electronics was designed and built together with a partial sensorhead, representative only in so far as it contains the CCD detector and a Peltier cooler. Also the necessary software was developed and is now being implemented. To support tests on the sensor also a microprocessor based electronic testequipment was built, simulating the role of the on-board computer in sending commands as well as receiving and displaying sensor outputs. An in-depth mechanical and thermal design of the sensorhead was carried out to complete the picture of the instrument.

2. DESIGN GOALS

The design goals as summarized in Table 1 are based on a Petzval objective, with a focal length of 91 mm and a focal ratio f/1.4. This objective was developed for the ESA starmapper and also employed for the BUSSOR. Together with the dimensions of the P8600 CCD detector this defines the field of view to 5.4° x 8.1° and the detector element angular size to 50".

The guide-star magnitude limit is based on the requirement to have a probability of 99% of finding at least two guide-stars in the field of view, even at the sparsely populated galactic poles. This requirement is found to correspond to a m_{si} = 6.5 magnitude limit, which is exclusively applicable as far as meeting the position measurement accuracy is concerned. The detection limit is about m_{si} = 8.5.

In order to keep open the possibility to use the sensor directly in an attitude control loop, the sampling interval is put at 0.1 s. Integration times being approximately equal to this 0.1 s, starsignal are obtained which at m_{si} = 6.5 still permit star position accuracies better than 0.03 of a detector element. Experiments performed with the BUSSOR sensorhead showed that this also from other points of view appears a suitable goal. In combination with the 50" element size thus an accuracy goal of 1.5" emerges. The 0.1 s integration time also implies that saturation is to be expected for stars between m_{si} = 0 and 0.5, accounting for a nominal,defocussed starimage diameter equal to 3 detectorelements.

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Field of view	5.4° x 8.1°
Detection limit	m_{si} = 8.5
Guide-star limit	m_{si} = 6.5
Saturation limit	m_{si} = 0.5
Probability of 2 guide-stars near galactic poles	99%
Max. number of guide-stars to be handled	3
Accuracy	1.5" (1-σ)
Sampling period	0.1 s
Detector	P8600 385 x 576 elements 22 x 22 μm^2 element-size
Detector operating temperature	-15° to -20°C (Peltier cooling)
Optics	Petzval transmission optics. Focal length 91 mm, F/1.4

Table 1. Design goals of the TOAST.

The number of stars of which the positions can be simultaneously determined is selectable from 1 up to 3. One star provides only partial attitude information, whereas two stars permit a full 3-axes attitude determination. The actual reconstitution accuracy depends except on the position measurement errors also on the positions of the stars with respect to each other and the sensors optical axis. As error contributions from the optics tend to be especially pronounced along the field radius, an interesting improvement is possible by using three stars. In disregarding their distances to the optical axis, by basing attitude reconstitution solely on their azimuth angles, effects of optical aberrations are largely eliminated.

It should be noted that different sets of performance figures can be obtained by appropriate scaling of the optics or changes in the electronic cycle times.

3. MODES OF OPERATION

The flexibility of the sensor manifests itself most clearly in the different modes of operation that are available. The essence of each mode is now briefly explained.

3.1 Camera mode

This mode enables a complete survey of the field of view for stars above a selectable brightness level. Only a coarse position of the detected stars is obtained as detectorelements are joined together in blocks of 3 x 3 up to 6 x 6 at choice. As per readout the nominal integration time of 0.1 s is maintained, which is insufficient to process the total field, the picture is split up into slices, as illustrated in Fig. 1. This results in repetition frequencies between 0.8 and 1.7 Hz. The collected information can be used to create a map of the starfield which is suitable for visual interpretation on ground.

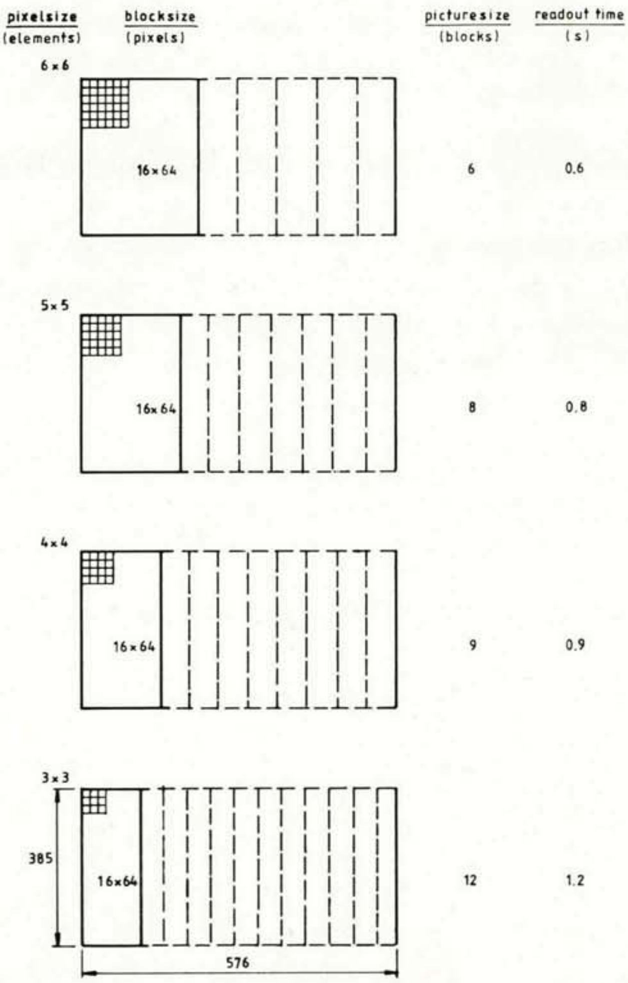

Fig. 1 Implementation of camera mode

The camera mode is believed to be very useful in emergency situations where attitude is lost completely or where predicted guide-stars can not be found.

3.2 Acquisition mode

In this mode the on-board computer may specify a maximum number of three areas where guide-stars are expected. The shape of these areas is rectangular with a maximum size of 31 x 31 detectorelements. Again starbrightness thresholds can be selected. The sensor signals the presence of stars in the acquisition areas and also issues the starpositions with an accuracy already at the sub-element level. As soon as the predicted stars are found, if desired after further confirmation by the on-board computer on the basis of the provided position data, the sensor is ready to switch over to the tracking mode.

3.3 Tracking mode

The principle by which the ultimate accuracy obtained in tracking mode is achieved, is illustrated by Fig. 2. The starimage is defocussed over a diameter equal to 3 detectorelements. The contents of the elements in an area of 5 x 5 covering the starimage is measured. A "centre of gravity" algorithm is then

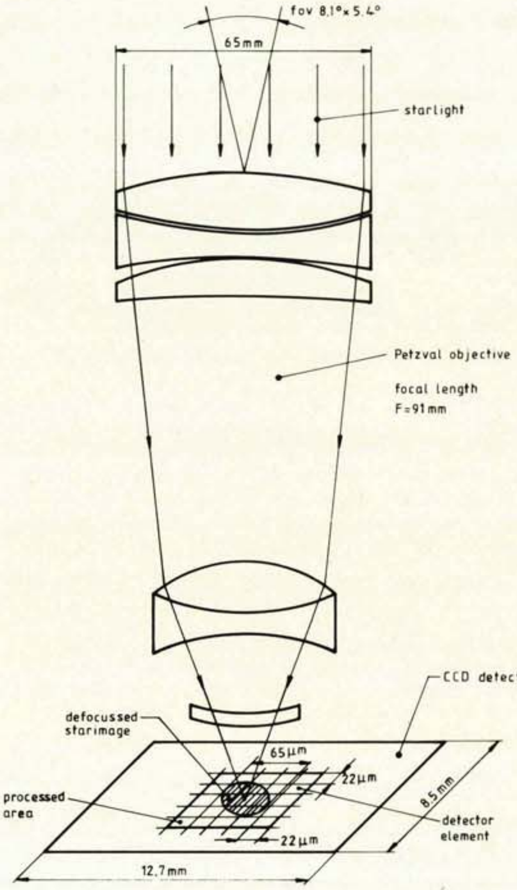

Fig. 2 Measurement principle

applied rendering the centroid coordinates of the image. Actually the algorithm is used twice per coordinate axis on areas which are shifted over one element. Taking the weighted average of both results the ultimate, enhanced accuracy is reached. The procedure is shown in Fig. 3 for the nominal 5 x 5 processed area size. Other area sizes up to 13 x 13 however may be selected by the on-board computer.

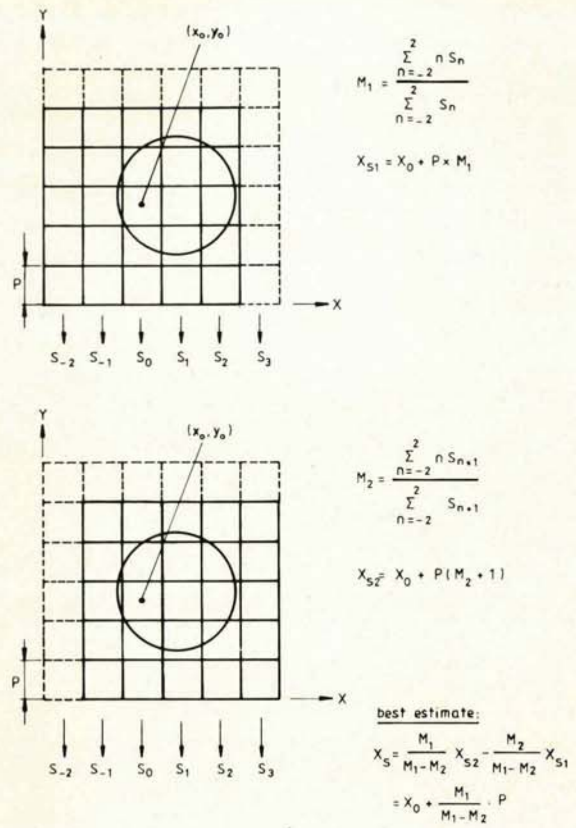

Fig. 3 Illustration of the "centre of gravity" algorithm

4. SENSOR LAYOUT

A schematic presentation of the starsensor configuration is given in Fig. 4. The sensorhead consists of an optical system, adaptation of which can provide a variety of performances, the cooled detector housing and some electronics operating the CCD detector and processing the video signal, including the analogue to digital conversion. The sensor electronics box accomodates the microprocessor system which on one hand provides the setpoints for the CCD control electronics and on the other controls the acquisition of the videodata. Processing of the data and organizing the communication with the ACS are other tasks it performs. The video channel electronics controls the path between detector and microprocessor system. The CCD control electronics generates the CCD drive signals depending on mode of operation and selected parameters. Both video channel electronics and control electronics make use of programmable array logic. The ACS interface electronics constitutes the link to the on-board computer.

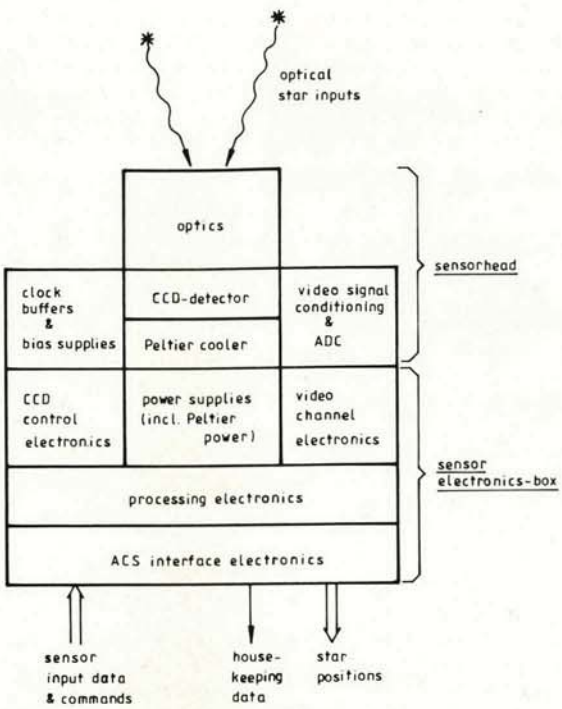

Fig. 4 Schematic organization of the starsensor

5. COOLED DETECTOR MODULE

It was decided to base the design of the cooled detector module directly on a CCD chip, rather than on a packaged device. Existing experience at our Institute in handling and mounting linear CCD chips facilitated such a decision, offering several advantages in the module design. Also the mechanical positioning of the detector and the cooling function are completely decoupled. This permits a good mechanical stability over a large temperature range as well as giving considerable freedom in adapting the cooling to specific mission requirements.

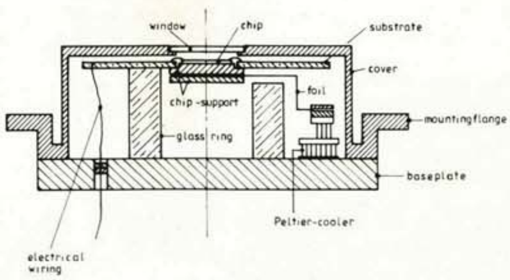

Fig. 5 Sketch of cooled detector module

These starting points resulted in the principal design as shown in Fig. 5. The CCD chip is mounted on a thermal mass, coupled to 4 dual stage Peltier coolers via highly thermally conductive silver foils. The chip support is bonded to a substrate which carries a printed conductor pattern providing the electrical connections to the detector. This substrate is fitted to a ring of thermally insulating material which in turn is bonded to the supporting structure of the module. With an appropriate selection of materials the position with respect to focus can be maintained even in the event of large temperature fluctuations. A suitable material selection is an invar chip support, a quartz substrate and ring and again an invar baseplate. With these materials also a high thermal resistance between the CCD chip and the module baseplate is achieved. In addition the electrical connections to the substrate must be made of a material with rather high thermal resistivity, inevitably compromising on electrical conductance.

Although the module is designed for use with Peltier coolers, they can be deleted in the extreme case if performance requirements permit so. The detector is then directly coupled to the baseplate via the silver foils. Anyway other types of coolers can be implemented without major design changes. To improve the cooling efficiency the module is evacuated, avoiding heat leakage by conduction and convection.

The current design enables the module window to be placed at only a small distance from the detector surface. This is important when using objectives with a short back focal length, wich is not unusual. The dimensions of the module are an 8 cm diameter and 2.5 cm thickness.

6. SENSOR ELECTRONICS

Following the schematical presentation of Fig. 4 the different electronical functions are now explained in more detail, in particular with the aim to provide some insight in the sensor operation.

6.1 Clock buffers and bias supplies

The clock buffers are performing buffering and shaping of the CCD clock signals. These clock signals bring about the transportation of the charge packets generated by the stars imaged on the detector. Two sets of transport clocks are needed, one set effecting the line by line vertical transport and a second set controlling the element by element horizontal transport and read out. Vertical frequencies range up to 400 kHz, horizontal frequencies up to 7 MHz. Apart from clock signals the detector is also provided with the required DC-biases.

6.2 Video signal conditioning

The detector output is amplified and processed to a shape and level suitable for conversion to a digital form. in fact conversions are performed in two parallel chains. On chain simply uses a comparator with adjustable threshold, providing a binary signal indicating the video signal level to be below or above this threshold. The readout frequency of this chain can be high. It is employed in camera and acquisition mode. The other chain contains a 12-bit ADC capable of a 40 kHz output rate.

6.3 Video channel electronics

The video channel electronics provides the analogue signal conditioning chain and the ADC with the correct control signals. It also performs the acquisition of ADC or binary data from the comparator in a buffer memory where it is accessible to the microprocessor. Another function of this electronics is the generation of the comparator threshold.

6.4 CCD control electronics

The CCD control electronics generates the clocks controling the charge transport in the detector. Using data tables available in random access memory and compiled by the microprocessor, detector areas of arbitrary position and size can be defined and read out selectively. Video information outside these areas is read out fast and further disregarded. Video signals of detectorelements inside the selected areas are read out at the appropriate rate, depending on whether the ADC or the comparator is used, and after conversion stored in memory. This readout principle is applicable to all three modes of operation.

6.5 Processing electronics

In order to give an impression of the functions performed by the microprocessor electronics and its complexity a brief description of the software architecture is presented. Fig. 6 gives the software architecture as an hierarchical scheme of software modules. Each software module is a cluster of procedures or macros of which a number serve as links with their surroundings.

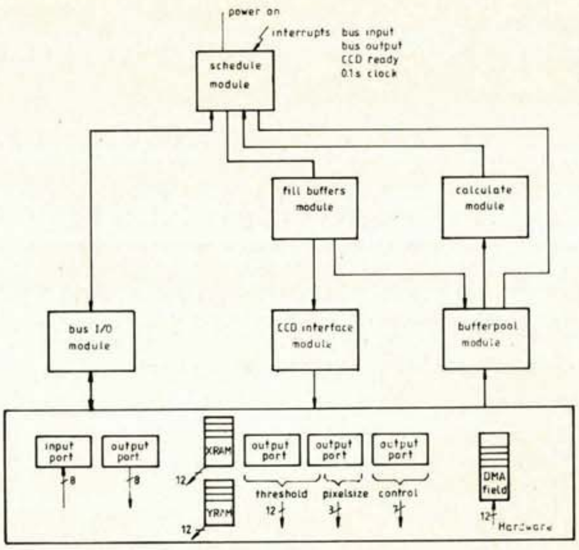

Fig. 6 software architecture

Following Fig. 6 top-down one first encounters the schedule module, which is the main module, performing both long term as well as short term scheduling. The long term scheduling consists of executing the commands assembled in the bus I/O module, as issued by the on-board computer.

The short term scheduling involves synchronization of the actions due to the board bus commands with the 0.1 s cycle time of the sensor decreasing the four tasks that are scheduled are, in order of priority, a bus output task, a command decode task, a task which cyclic processes the detector data and a bus input task.

The bus I/O module mainly contains an input buffer where bytes from the board bus are assembled to a command and a cyclic output buffer (spooler) where other modules can drop their outputs to the board bus. The input buffer is filled by the input task, the output buffer by the output task. The fillbuffer module fills the datalists in the memory with data that is used by the CCD control electronics to perform the selective read out. It deals with the problem of overlapping areas and it provides the bufferpool module with index tables in order to enable this module to search for items in the DMA field. The CCD interface module deals with the interfacing of the CCD hardware. It mainly hides hardware aspects to the other modules.
The calculate module asks data from the bufferpool module and calculates the centroid. Centroid data is returned to the scheduler which takes care of the output at the right time. The bufferpool module contains the DMA field that is filled under DMA control by the CCD control hardware. The module contains index tables which permits to look up data in the DMA field for both the calculate module as well as for the scheduler. The module mainly acts as a kind of librarian.