TITLE : STATUS OF MEFIST STARTRACKER DEVELOPMENT

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1. Introduction

This document is prepared by

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as a general document to provide technical information about the status of the MEFIST startracker development at TNO-TPD in cooperation with its industrial partners.

TNO-TPD has a long and successful history in the development and production of optical sensors for attitude measurement in AOCS subsystems in a variety of space missions.
The product range covers analog sun sensors for coarse and fine solar aspect angle measurement, a starmapper for spinning spacecraft and a medium accuracy CCD-startracker for three-axis stabilised spacecraft applications.

Besides the products that have built-up a heritage of successful operation in space missions, TNO-TPD is active in the development of new concepts, capable to satisfy the demands of future missions.

This technical note concentrates on information about the CCD startracker MEFIST.
In chapter 2 the company background and relevant experience in the field of space instrumentation is addressed.
In chapter 3 technical information is provided on the Wide Field Star sensor head, from which a pre-qualification model has been developed and built by TNO-TPD.
In chapter 4 a description is given of the medium field of view star sensor MEFIST, under development in collaboration with the industrial partner Austrian Aerospace, that has built a pre-qualification model of a DSP-based electronics unit.

For more detailed information on startrackers or any additional topics regarding optical attitude sensors please address to:
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2. Company background and star sensor experience

2.1 Company background

The TNO Institute of Applied Physics (TNO Technisch Physische Dienst TU Delft or TNO-TPD for short) was founded in 1941.
Today TNO-TPD is one of the largest institutes of the Netherlands Organisation for Applied Research (TNO).

TNO-TPD has about 425 employees and its annual turnover is 50 M$ (1998).
Typical "products" are development, research, advice, consultancy, evaluation and examination. Technologies involved are physics, computer science, electronics, mechanics, materials and process-technology.

The lion's share of TNO-TPD revenues comes from contract research for Dutch and foreign industries, the Dutch government and European institutions such as the European Commission, the International Energy Agency and the European Space Agency.

The space activities within TNO-TPD are part of the total scope of space activities within the TNO Organization, that are represented by the Business Center TNO-Space at TNO Corporate level.

The TNO-TPD Space activities involve about 10% of the TPD staff, the annual turnover in space contracts amounts to 8 M$.

2.2 Experience in space programs

TNO-TPD began its research and development activities for space instrumentation in 1964 with a UV stellar spectrometer for Europe's TD-1A astronomy satellite (launched in 1972). Since then the Institute specialised in optical instrumentation for science missions, for earth observation, for attitude measurement and in space mechanisms.

TNO-TPD capabilities cover all phases of space projects, ranging from feasibility studies and detailed design studies and prototyping to development, production and test of flight hardware. For production of equipment in larger quantities, collaboration with industrial partners is sought.

Main specialisation's today are:

- Scientific Optical Instruments for Astronomy and Astrometry, such as
  - Spectrometers from UV to far Infrared, flown on TD-1A, ANS, IRAS, ISO
- Photometers, flown on IRAS
  - Focal plane assemblies, such as for HIPPARCOS and for the FOC in HST

- Optical Instruments for Earth Observation:
  - Atmospheric Science in Environmental missions (Ozone detection). Examples hereof are GOME (ERS-2, METOP), SCIAMACHY (for ENVISAT) and the Ozone Monitoring Imaging Spectrometer OMI (for the NASA mission EOS-CHEM).
  - Focal plane assemblies, such as for MIPAS (ENVISAT)

- Calibration of Earth-observation instruments, such as GOME, MERIS, SCIAMACHY

- Space Mechanisms, i.e.
  - Refocussing mechanisms, such as for HIPPARCOS and MSG-SEVIRI
  - Calibration devices in micro-gravity instrumentation
  - Robotics, End-effectors for applications in attached payload handling on ISS

- Optical Attitude Sensors , such as
  - Sun sensors, flown on various telecommunication, earth observation and scientific missions
  - Starsensor for spinning spacecraft
  - Startracker for 3-axis stabilised missions

2.3 Star sensor experience

- ***Starmapper for spinning spacecraft***
  TNO-TPD developed the ESA Starmapper, for the attitude measurement on spinning spacecraft (spinrates between 10 and 20 RPM).
  The sensor has successfully flown on the comet Halley fly-by mission GIOTTO.
  Units were also on-board the crashed fleet of CLUSTER-1 S/C. Presently the production of starmappers for the second fleet of CLUSTER ‘s is in progress.

- ***TPD Off-axis Star Tracker (TOAST)***
  On national funding TNO-TPD developed a breadboard model of a CCD-startracker system with arcsec accuracy capability (described in an article in the SPIE proceedings Acquisition, Tracking and Pointing III, 27-29 March 1989, Vol 1111 page 21).
  TOAST consisted of a sensorhead and a micro-processor based electronics unit.
  The sensorhead had a FOV of 5° x 8°, Petzval transmission optics and a focal plane with a Peltier cooled EEV CCD.
  The electronics unit had a micro-processor with software capable to operate the sensor head in a number of modes (acquisition, tracking, etc.)
  The TOAST breadboard output was star coordinates of multiple stars, with sub-pixel accuracy.

- ***Wide-and Medium field of view star trackers***
  The wide-field of view startraker WFS and the medium field of view startracker MEFIST are CCD-based sensors for application on three axes stabilised platforms.
  The product development of these startrackers is described in detail in the following chapters.

3. Star sensor for use on geo-stationary spacecraft

3.1 Initial Design of a Wide Field Star sensor

The design of the Wide Field Star sensor (WFS) aimed for a sensor suitable for operation on board a GEO telecommunication spacecraft, for continuous yaw measurement and fast recovery operation.
To fulfil these objectives, a FOV of 30° X 40° was selected and the pointing direction was analysed to be optimum for 60 degrees south of the equatorial plane. The number of stars needed in the FOV could remain very small. Bright star detection capability was sufficient for the task envisaged in the GEO telecom missions.
The required accuracy (better than 0.06 degrees of arc) allowed for an approach of bright pixel detection, that could be accomplished with fairly “simple” discrete electronics.
Stringent requirements were imposed on reliability aspects.
To make the star sensor system free of single point failures, even in case of sun blinding of a sensor head, a multiple head configuration combined with a self-redundant Electronics Unit (EU) was foreseen for the telecom application.

3.2 WFS Pre-Qualification

A contract was granted to TNO-TPD by ESA-ESTEC to pursue the upgrading of the initial design of the Camera Unit to the level of a pre-qualification model (ESTEC Contract No: 9973/92/NL/MXD). This pre-qualification model Camera Unit has been developed, built and successfully exposed to a pre- qualification test, using ARTEMIS environmental test requirements as "model mission" (Ariane 5 launch).

Its mechanical outline is shown in fig. 3.2/1. The hardware model is shown in the picture in fig. 4.2/3
The sensor head comprises an EEV MPP frame transfer CCD with 288 x 385 pixels in the image area, each with an angular dimension of about 0.11 degree^2 to span the FOV of 30° to 40°.
The optics is radiation hardened and the shielding of the CCD protects this device from radiation for long mission duration (design life 10 years)
The baffle provides straylight suppression with a sun rejection angle of 55^{o} and by design it facilitates passive cooling for the CCD so that no active Peltier cooling device) is needed.

To support the simple bright-pixel detection electronics, the video-amplifier in the sensor head clamps the video output to a dynamically determined (dark signal) background in the scene.
The electrical interface between a remote electronics unit and the sensorhead is minimised for wiring, and consists of the analog video line, two clock lines and one 10V power line.
The update rate of the video is 10 Hz maximum.

The physical characteristics of this sensor head are very attractive, i.e. its mass is 1.0 kg, its power dissipation is 1.0 Watt. The development work was presented in the second ESA conference on Guidance and Navigation Control in Noordwijk (ref.: Proceedings ESA WPP-071, page 217).

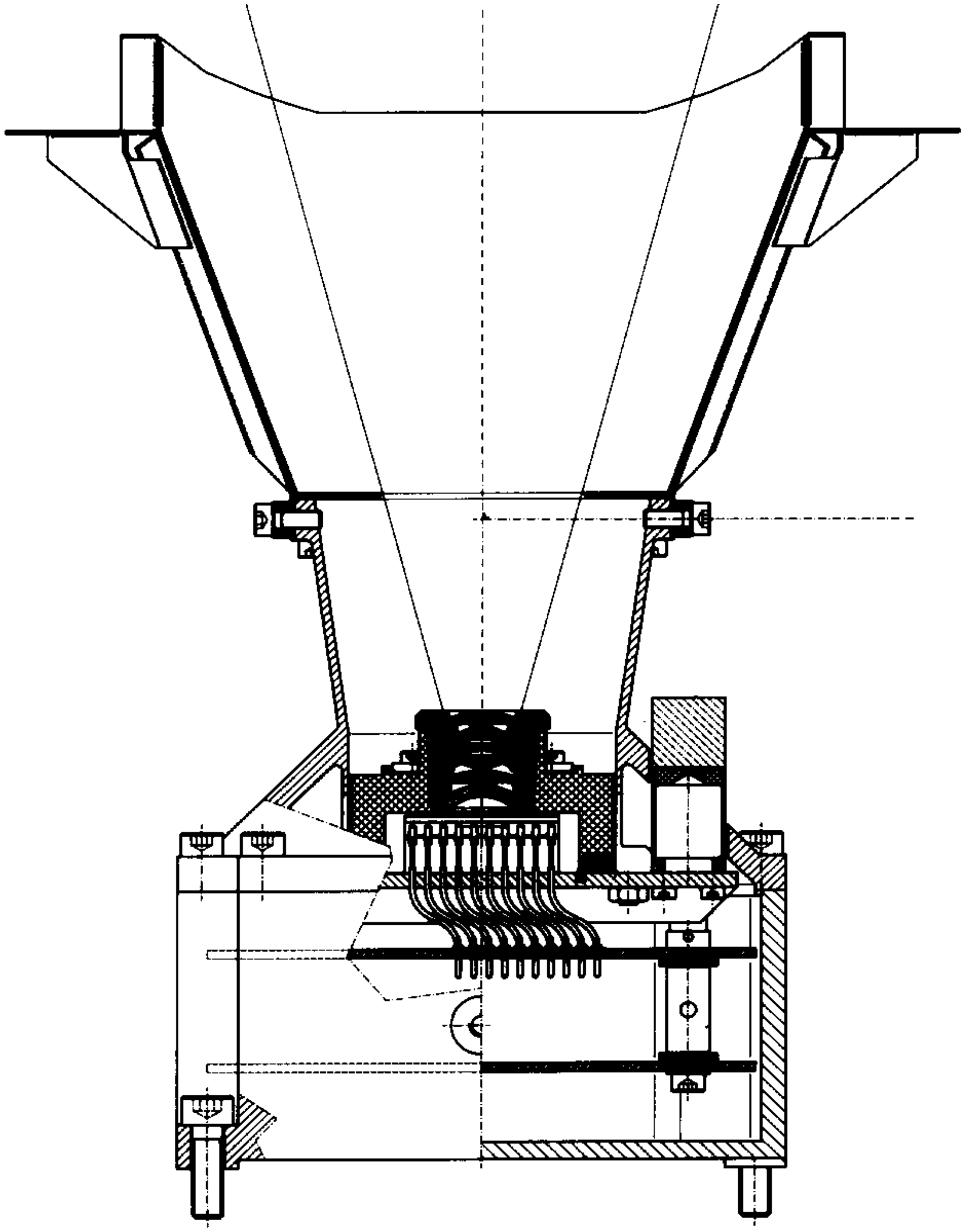

Fig 3.2/1: Mechanical outline of pre-qualification model sensor head of wide field star sensor for application in geostationary missions

4. Medium Field of View Star Tracker MEFIST

4.1 MEFIST Sensor head

To extend the use of the WFS to beyond the scope of station-keeping in GEO telecom missions, more demanding requirements must be imposed on it:

- FOV should be smaller for higher accuracy and more easy accommodation in S/C
- Sensitivity should be larger to enable the detection of weaker (thus more) stars
- Accuracy should be improved to sub-pixel level
- Autonomous operation for attitude measurement without a-priory knowledge about the pointing direction

To be responsive to these demands, TNO-TPD has started a design upgrade of the WFS, with the aim to maintain the focal plane assembly, the front-end electronics, the passive cooling approach via the straylight baffle, the low power consumption and the mechanical shielding against particle radiation.

The modifications involved concentrate on the optics, for which a new rad-hard more powerful F/0.9 is designed, with uniform performance characteristics in the whole FOV.
In stead of being optimised for bright pixel detection, MEFIST optics will be slightly de-focused to allow for the application of centroïding algorithms in the data processing.
With the modifications in optics (FOV and size of front-lens component) also the baffle will modify to dimensions of the kind depicted in fig. 4.1/1.

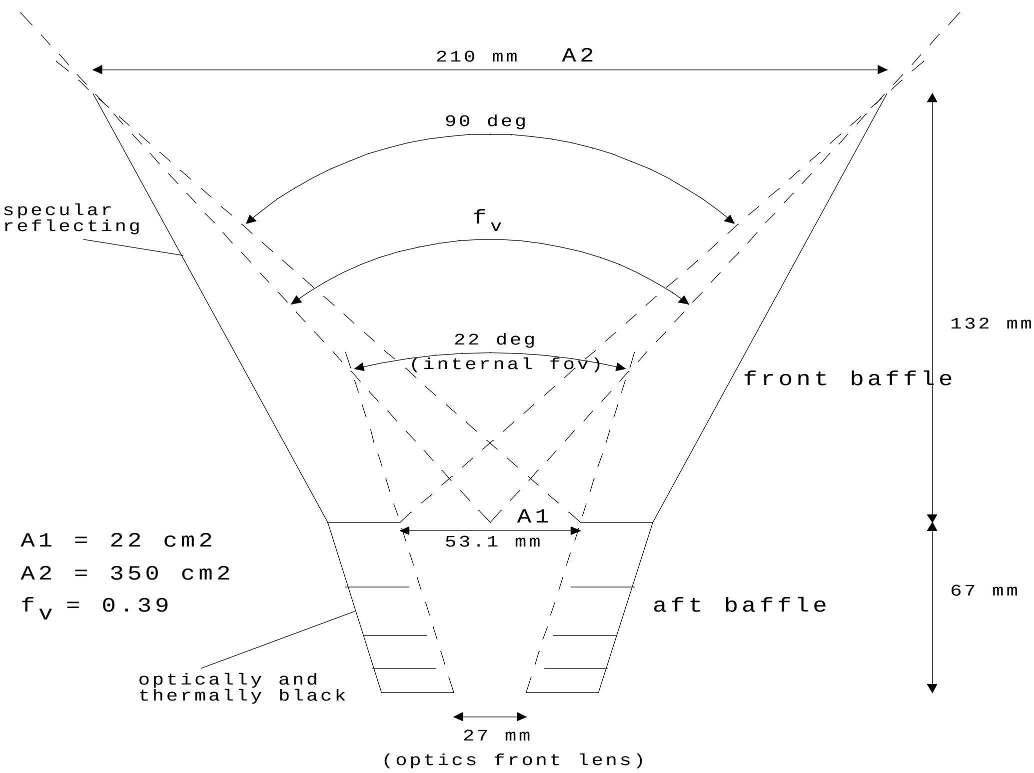

Fig. 4.1/1: Conceptual outline of straylight baffle for a passively cooled startracker: minimum sun angle: 45 degrees of arc

These modifications lead to a Star Tracker Camera Unit referred to as MEFIST (Medium Field Star Tracker) , which has a FOV of 15° x 20°, a star sensitivity Mv=+6 and an accuracy potential of better than 0.03° in all three axes directions (for details see paragraph 4.4).

4.2 MEFIST Electronics

The front-end electronics in the pre-qualification model Camera Head provides the controls to the CCD and outputs the analog video signal of all pixels in the CCD, amplified for safe transport across interface cabling. The gain can be controlled in steps (1,2,4,8) by the EU, as well as the integration time (in steps of 100 ms, with 100 ms as minimum). So the maximum update rate is 10 Hz. The video-output is automatically clamped to a dynamic average of the darkcurrent.

Austrian Aerospace (owned by SAAB-ERICSSON Space of Sweden) and TNO-TPD have developed an intelligent electronics unit (EU), designed to interface with the MEFIST camera. This activity is carried out under ESA contract 11858/96/NL/DS and has resulted in a prototype unit, exposed to a pre-qualification testprogram with testlevels derived from the ARTEMIS mission (ARIANE-5 launch).

Important features of this MEFIST system are:

- Up to 3 sensor heads can be connected to the EU.
- Few interface lines between sensor head and EU.
- Possibility to implement a wide range of star detection/attitude determination algorithms.
- Possibility to trade power consumption for processing performance.
- Possibility to load S/W into the Electronics Unit (EU) via the command interface.
- Possibility to adapt to different S/C command interfaces.
- Possibility to implement Camera failure detection and recovery procedures.

The functions included in the EU are:

- DC-DC power conversion that interfaces with the spacecraft power subsystem and provides the power for the EU internally and for the sensor head in operation.
- Clock generation for submission of the required master and control clocks to the sensor head in operation
- Clock logic for the control internally in the EU of the video signal input from the sensor head
- DSP based processing of the video signal to derive the desired functionality of the star sensor system
- Telecommand and telemetry interface with the spacecraft datahandling subsystem

The EU is powered by the S/C primary power bus. The command and control interface with the spacecraft can be made mission-specific; the prototype includes the RS-422 serial interface. The EU includes a Digital Signal Processor core (rad-hard type TEMIC TSC21020E), which handles most of the tasks. This provides a very flexible concept which allows mission-specific requirements to be introduced in the S/W.

The EU provides ample processing power and memory space to allow for complex autonomous attitude determination algorithms and on-board star catalogues to be implemented.
Due to the flexibility of the design, the amount of memory can be adapted to the specific needs.
A block diagram illustrating the EU architecture is shown in Figure 4.2/1.

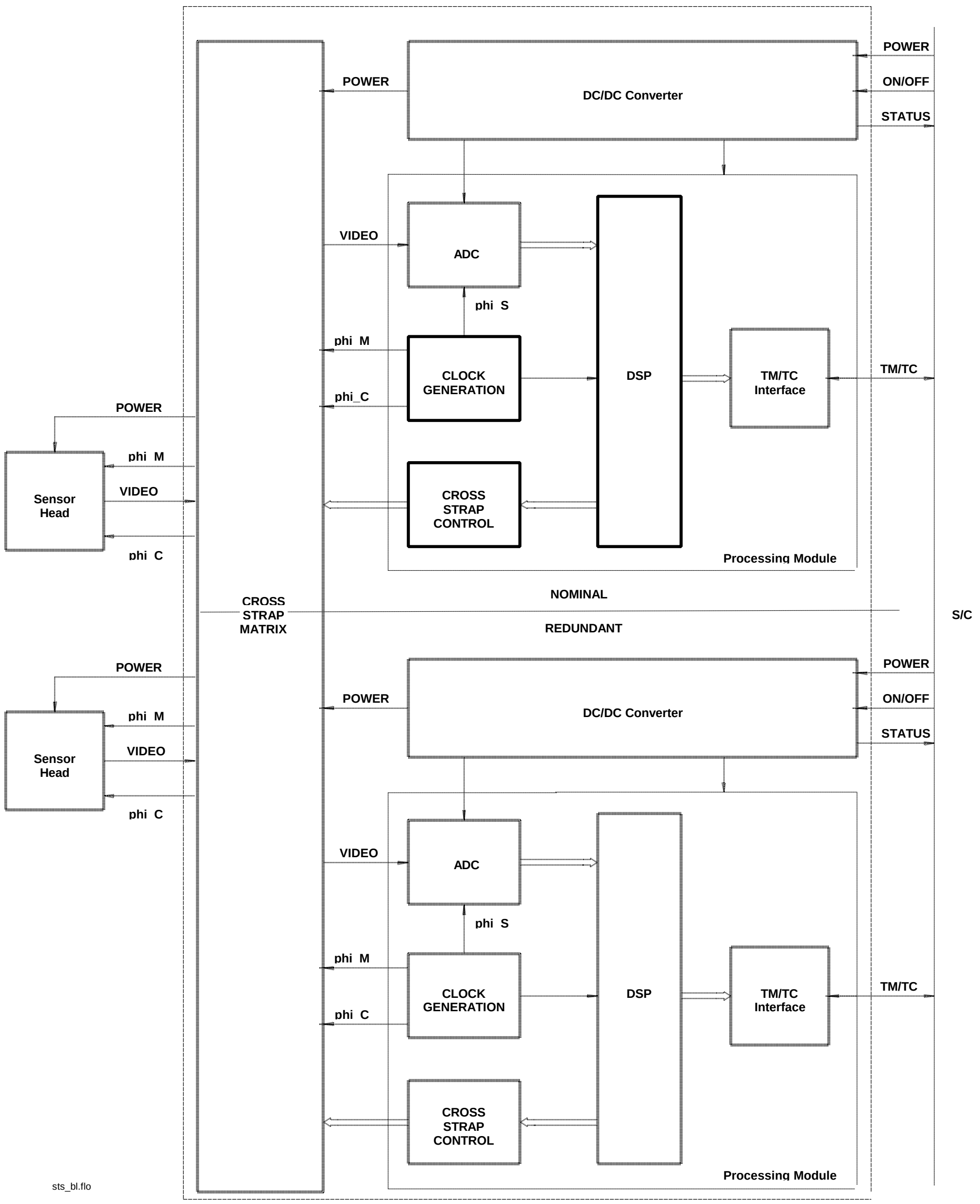

Fig 4.2/1: Architecture of internally redundant electronics unit for MEFIST, based on DSP

The EU incorporates a cross-strap module for interfacing each of the two EU sections to up to three Cameras. The cross-strap module switches power and clock signal lines from the active functional chain of the EU to the Camera to be used and routes the video signal from this Camera to the powered ADC module. Which Camera is active is typically defined by means of a telecommand. However, considering autonomy requirements it would be possible to implement control S/W to automatically perform switching of the Camera in case of an anomaly.

The EU is powered by a 28V DC primary power bus. The internally needed voltages are converted from this primary bus by means of the DC/DC converter. The modular design approach can accommodate different telecommand/telemetry interfaces, such as MACS, Mil-Std 1553, etc. The prototype includes the hardware for a bi-directional command and data bus type RS-422.
The EU also provides features such as a Watch Dog and a Direct Memory Access (DMA).

The mechanical configuration of the EU is shown in Figure 4.2/2. The real prototype hardware is depicted in fig.4.2/3

The structure is built up with three layers:
- The lower frame contains the nominal and redundant DC-DC converters, with circuitry completely electrically separated and with a heatsink in between.
- The middle frame comprises an single board with the video-processing (ADC and DSP), TM/TC interface and cross-strap electronics
- The upper frame comprises the redundant video processing board.

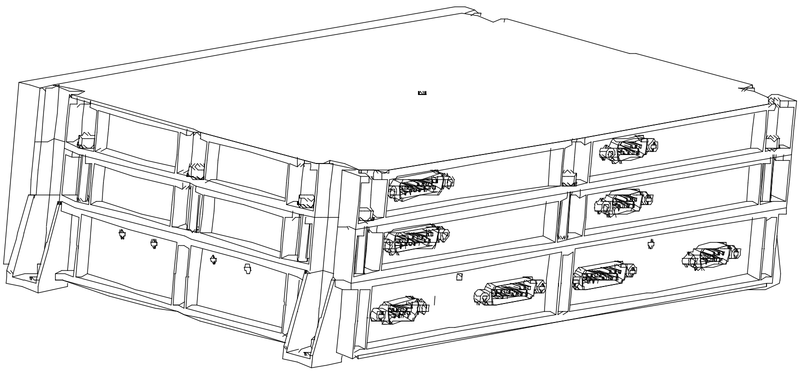

Fig. 4.2/2: Mechanical outline of the MEFIST redundant Electronics Unit.

4.3 Software for autonomous operation

The development of software for autonomous starsensor operation is a specialist task, which is in Europe in progress at a few companies, under contract to ESA or with company or national funding.

Some of these activities have been specific for a given application (OERSTED Startracker), other teams work on software development with a more general purpose character. Examples of the latter are developments at MMS and at ALENIA.
These teams have successfully performed simulations and/or performance tests of their software on a DSP platform of the kind incorporated in the MEFIST Electronics Unit.
MMS has carried out a simulation using the performance characteristics of MEFIST as a model. This has led to the prediction of performance reported in the next paragraph (4.4).

Recently, another development for further improvement of software for autonomous operation of star sensors is started, in which the performance characteristics of the MEFIST have been used as model inputs.
This work is under performance by Delta Utec Space Research and Consultancy in the Netherlands with support from TNO-TPD and the Dutch Space Agency NIVR.

An outline of the method was presented during the IAF conference held in September/October 1998 in Melbourne and is described in the paper IAF-98-A.6.05.
The software modelling forecasts, like the analysis made by MMS, that the accuracy potential of the MEFIST system is in the range of some tens of arcsec for all three axis directions.

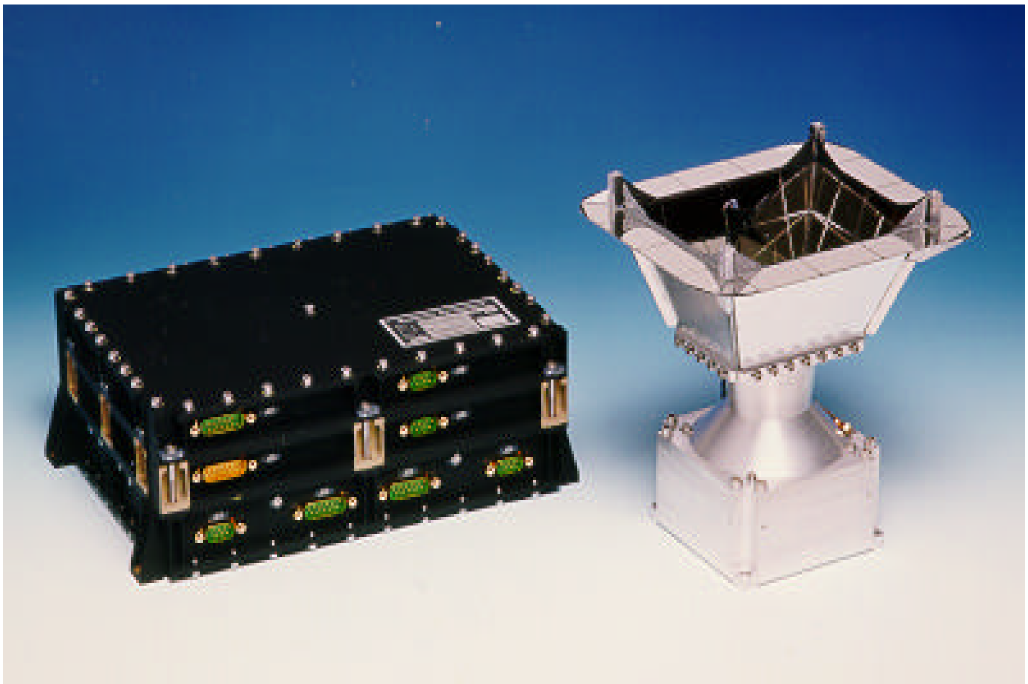

Fig.4.2/3: Photograph of qualification hardware with redundant electronics unit and one optical head of the WFS type.

4.4 Performance and Qualification status MEFIST Startracker

4.4.1 Performance prediction

The performance predictions in the table below are results of analyses in representative mathematical models of MEFIST.

Parameter / Characteristic	**Budget / Performance**
Total mass	1.3 kg (Sensor head) + 2.5 kg (non-redundant EU)
Power consumption	1 W (Camera) + 6 W (EU)
Envelope dimensions incl. baffle	100 x 102 x 115 mm^3 (Camera, no baffle) 225 x 200 x 75 mm^3 (non-redundant EU)
Full FOV	15° x 20°
Limiting starmagnitude	M_{Si}= + 6 @ 2 Hz (BOL)
Noise equivalent angle (NEA, 3σ) see note	< 15 arcsec @ pitch/yaw < 90 arcsec @ roll
Output frequency	Programmable from 1 Hz to 10 Hz. (CCD integration time range of 100 to 1000 ms)
Magnitude accuracy	0.2 M_{Si}
Operating temperature	-20°C to +40°C
Reliability (2 Cameras + 1 EU)	> 0.99 for a mission duration of 10 years
Data interface	RS422 (other bus I/F's optional)

Budgets and Performance characteristics for the MEFIST Star Sensor system

Note: The Noise Equivalent Angles (NEA) for pitch/yaw and roll were derived for a worst case analysis with only 4 stars detected in the FOV.
The roll accuracy is based on the assumption of an average star angular separation of half the FOV.

4.4.2 Qualification status

The prototype hardware is exposed to a functional and performance test program, including environmental testing for vibration and temperature cycling in vaccum. Test levels applied were for ARTEMIS as model mission, which correspond with ARIANE-5 launch environment.

The MEFIST camera will be subjected to a real sky test on the site of an astronomical observatory in February/March 2000.

5. Conclusion

TNO-TPD has a long and successful record for the production of optical attitude sensors, using the sun or stars as their reference(s), applied in many different space missions.

Startrackers for 3-axis stabilized platforms have been developed up to the stage of demonstrated space qualifiability. This activity is pursued with industrial partners to form a team with capabilities to produce hardware also for commercial programs.

TNO-TPD and its partners are interested in participation in programs at different levels:
- Through the supply of camera units, that can be interfaced to electronics produced by the customer
- Through the supply of dedicated camera units and remote electronics, running on software produced by the customer
- Through the supply of autonomous startracker systems

For an autonomous startracker, the MEFIST system, though not flight-proven yet, is an attractive solution. Major hardware elements of the system have been built as pre-qualification model prototypes by TNO-TPD and by Austrian Aerospace (a subsidiary of SAAB-ERICSSON Space), whereas software for autonomous operation is under development.

Besides production of flight hardware,TNO-TPD carries out research programs for the development of new sensor concepts.
We are very much interested in discussion with potential users of optical attitude sensors, about accommodation of our products to specific mission needs and about future needs for new products.