# Exoplanet Characterisation Observatory (EChO)

# Assessment Phase Payload Study

# FGS Electronics

# ECHO-TN-0001-UVIE

## Issue 0.1

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# 1 PREAMBLE

## 1.1 SCOPE

This document covers operational and electrical aspects of the EChO Fine Guidance Sensor. Thus it contains design considerations and budgets of the electronics, including calculations and estimation of performance.

## 1.2 PURPOSE

The purpose of this document is to give a more detailed view on the FGS, in particular its electronics and software.

## 1.3 APPLICABLE DOCUMENTS

| AD # | APPLICABLE DOCUMENT TITLE | DOCUMENT ID | ISSUE / DATE |
|---|---|---|---|
| 1 | EChO EID-A | ECHO-SRE-F/2012.097 | V0.2 / 22-4-13 |
| 2 | EChO Environmental Specification | JS-1-12 | V1 / 12-1-12 |
| 3 | EChO Mission Requirements Document | SRE-PA/2011.038 | V3 / 12-9-12 |
| 4 | EChO Scientific Requirements Document | SRE-PA/2011.037 | V3 / 14-9-12 |

## 1.4 REFERENCE DOCUMENTS

| RD # | REFERENCE DOCUMENT TITLE | DOCUMENT ID | ISSUE / DATE |
|---|---|---|---|
| 1 | EChO EID-B | ECHO-RS-0002-RAL | V0.1 / 30-11-12 |
| 2 | EChO Electronics TN | ECHO-TN-0001-OAA | V0.1 / 10-09-13 |
| 3 | EChO Optical Analysis of the FGS | ECHO-TN-0001-CBK | V0.1 / 09-09-13 |

## 2 INTRODUCTION

EChO, the Exoplanet Characterisation Observatory, is an M3 candidate in the ESA Comic Vision programme. It will provide high resolution, multi-wavelength spectroscopic observations of exoplanets, measure their atmospheric composition, temperature and albedo. It will orbit the L2 Lagrange point of the Sun-Earth system. The spacecraft is composed of the payload module, which includes the telescope assembly, the EChO science instrument and the fine guidance sensor (FGS) along with some of the support equipment, and the service module, which provides the majority of the means and resources required to support the payload and to keep the spacecraft running during all mission phases. The Korsch telescope uses a 1-m class elliptical primary. The scientific payload is a spectrometer covering the 0.4 – 11 micron waveband as a baseline, with an option to reach 16 micron. The FGS will provide additional high-precision photometry.

The service module handles all functions needed to operate the payload, including the telemetry, power systems, thermal control and the attitude and orbit control systems (AOCS).

High photometric stability over a time scale of about 10 hours is one of the most stringent requirements of the EChO mission. As a result, fine pointing stability relative to the host star is mandatory. This will be achieved with a combination of a fine guidance sensor (FGS) that uses a fraction of the signal from the optical channel, and fine AOCS actuators.

# 3 FINE GUIDANCE SENSOR

The FGS is a spacecraft subsystem, but will be provided by the instrument consortium. Its main task is to ensure the centering and guiding of the satellite, but it will also provide high precision pointing and photometry of the target for complementary science. In particular, the data from the FGS will be used for de-trending and data analysis on ground. From the scientist's point of view, it can be seen as a second payload instrument.
The system is composed of an optics box at the instrument optical bench (see Figure 1) containing cryogenic optics and redundant detector modules at 45 K. At an intermediate temperature stage of 55 K the redundant cold front-end electronics (FEE) are located. In the service module the FGS control electronics (FCE) are accommodated. These are also redundant and they control and read the detectors and carry out the data processing. The FGS systems are independent from the spectrometer instrument, thus have their own power and data interfaces with the spacecraft.

## 3.1 FGS DESIGN

The data quality of the spectrometer channels heavily depends on the stability of the pointing and guiding of the spacecraft. Consequently, a dedicated sensor is placed in the EChO optical chain – the Fine Guidance Sensor. It uses a fraction of the science target's light coming through the optical path of the telescope to precisely determine the changes in the line of sight of the EChO instrument.

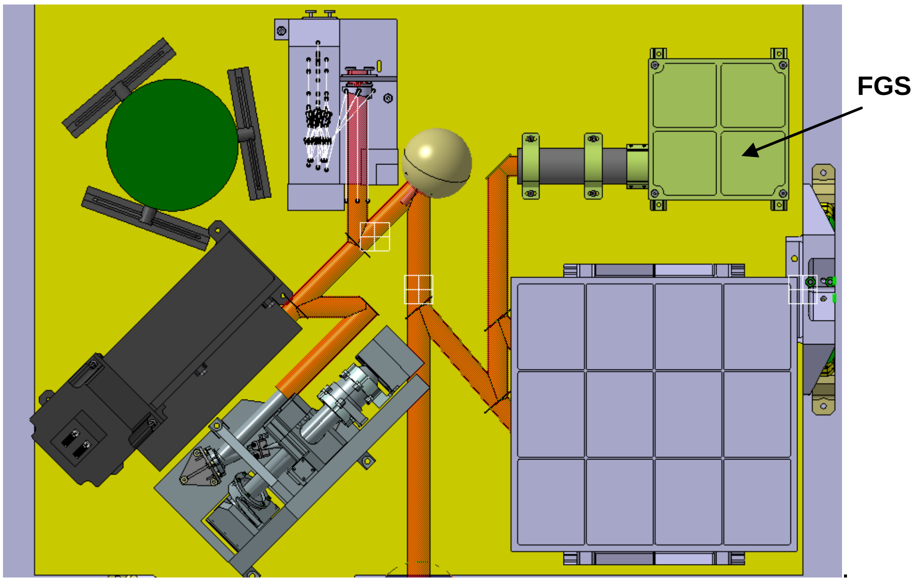


**Figure 1: The FGS beam is split off from the light going into the VNIR channel.**

The attitude measurement is then fused with the rate information from the Star Tracker, a high performance gyro and used as input for the control loop stabilizing the spacecraft.
The Fine Guidance Sensor is a critical equipment as it is an important contributor for the AOCS RPE performance in terms of the achievable single-star centroiding accuracy. It is a spacecraft subsystem, but will be provided by the instrument consortium. The FGS main tasks are centering, focusing of the telescope and guiding of the satellite, but it will also provide high precision astrometry and photometry of the target for complementary science. In particular, the data from the FGS will be used for de-trending and data analysis on ground. From the scientist's point of view, it can be seen as an independent instrument channel.
The system is composed of an optics box at the instrument optical bench (see **Error! Reference source not found.**) containing cryogenic optics and redundant detector modules at 45 K complete with cold front-end electronics (cFEE) at 55K. In the service module the FGS control electronics (FCE) are accommodated. These are also redundant and they control and read the detectors and carry out the data

processing. The FGS systems are independent from the spectrometer instrument, thus have their own power and data interfaces with the spacecraft. Figure 2 depicts the overall system layout.

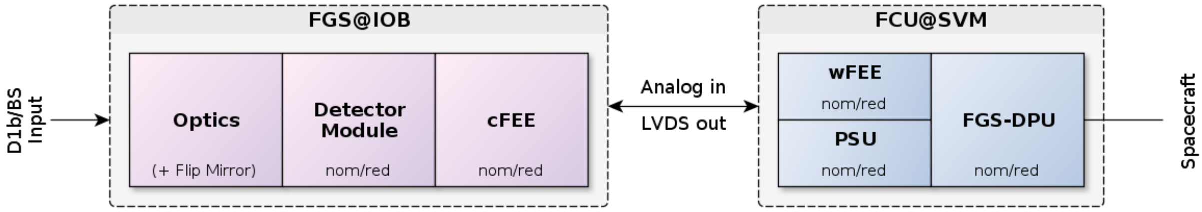


**Figure 2: FGS top-level architecture. The optical module in the cold and the warm electronics are connected via the cold front-end electronics.**

## 3.2 FGS Opto-Mechanical Module

The FGS Optical Module is the box at the instrument optical bench (see Figure 3), which contains the optical components and the detector modules (as separate work packages). The Optical Module will be provided by Poland.

### 3.2.1 FGS Optical Design

The FGS optics and associated information is provided in detail in RD003.

### 3.2.2 FGS Detectors

There are two detector modules (nominal and redundant) inside the optical module. Each module assembly consists of: Detector Chip and ROIC, Housing, Supports and Internal Harnessing. The detector Chip and ROIC will be the same type as for the VNIR spectroscopic channel. The baseline is a European MCT operating in the 0.55-1 micron range with 256x256 (512x512) pixels of 15 micron pitch.

### 3.2.3 Cold Front-End Electronics

In order to guarantee the high signal stability that EChO needs, the A/D conversion will be done close to the detector. To minimize heat dissipation by the digitizing circuits, the cFEE will be located at an intermediate temperature stage at 55 K. We will use the FAIR ASIC, which is an ongoing development from SRON. Figure 3 shows which functions will be implemented in the cFEE and which ones remain to be carried out by the wFEE.

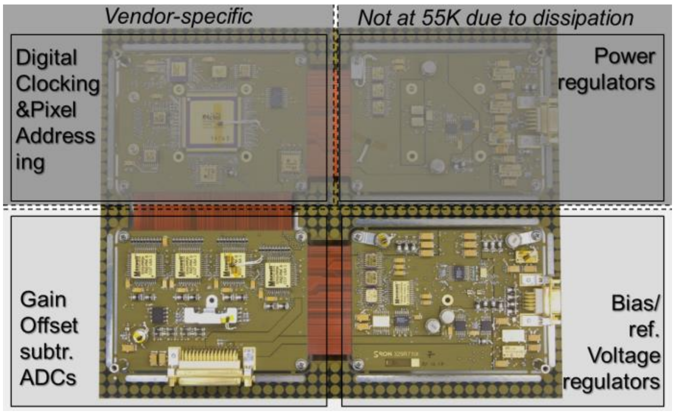


**Figure 3: Functions implemented in the cFEE are Gain offset subtraction and A/D conversion as well as bias and voltage regulation. Clocking, addressing and power regulation will not be done by this unit. (Image provided by SRON)**

### 3.2.4 Warm Front-End Electronics

The FGS control electronics (described in the next subsection) are located in the SVM, and they will contain cold redundant interface boards which are connected with the FGS internal subunits. While the ADC and bias regulation are carried out by the cFEE, digital clocking and pixel addressing are not included in the cFEE ASIC, because they are specific to the detector chip vendor. Also, the detector power regulators are in the FCE, because power dissipation in the cold has to be kept low. So these functions must be provided by the FCE.
Additionally, there will be a flip-mirror in the optics of the FGS, which needs to be controlled, as well as a number of HK sensors, which will report FGS@IOB temperatures, status of flip-mirror, cFEE status.

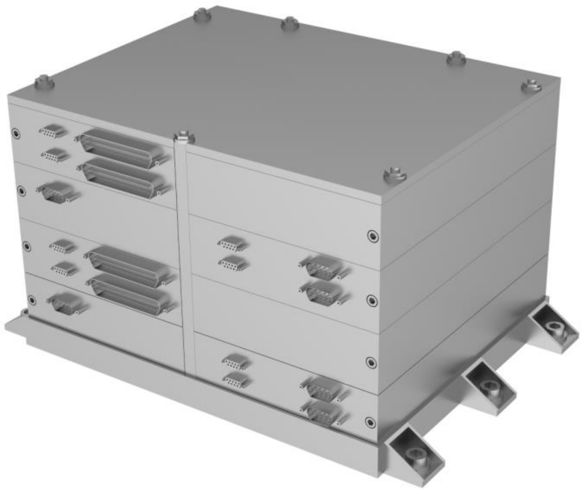

**Figure 4: Initial design of FGS Control Electronics box consisting of 2 processing board units and 2 interface/PSU elements.**

## 3.3 FGS CONTROL ELECTRONICS

The FGS has its own electronics box in the service module, the FCE (FGS Control Electronics). All communication, control and data processing tasks will be carried out by this unit. As a spacecraft subsystem, it has to be fully ECSS compliant. It will drive and read the FGS detector electronics, establish a control loop with the spacecraft and deliver scientific data products. The FCE box in the service module will have its own power supply and be independent from the spectrometer channels and the spectrometer ICU. It will consist of the following sub-units:

- Mechanical Chassis: Typical Warm Electronics box, its envelope is 281(323 with mounts)x230x156 mm, and its mass estimation is 6.5 kg incl. electronics.

- Processing and control boards: Two processor boards (cold redundant) will be available for data processing and control. Most data processing operations will be in floating point arithmetic.

- Interface boards (cold redundant): Interfaces to spacecraft: power, data, commanding. SpaceWire 1355 / 1553 where applicable. Interfaces to cFEE: Digital (LVDS), power and HK lines.

- FGS power supply unit (cold redundant): S/C 28V input, secondary voltages to FCE, cFEE, FGS detector, FGS Flip Mirror and HK sensors.

### 3.3.1 Data Processing Boards

For the data processing boards the use of the Panther Processor Board of RUAG Space AB (RSE) is proposed (see Figure 5). The processor boards will have to carry out the centroiding in real-time. For this task, the data frames need to be calibrated first. The most demanding operation is the flatfield correction of the full frame, which requires 655360 floating-point multiplications per second. Once the ROI has been set to a smaller window, the number of pixels and thus the number of operations is greatly reduced. But also the centroiding takes great advantage of available floating-point arithmetic.

All these criteria are met by the “Panther” board, which comes with a rad-hardened LEON2 ASIC at 64-80 MHz, FPU, MMU, 8 MB EDAC-protected RAM, numerous interfaces and EEPROM. With 22 MFLOPS and 54 MIPS, all calibration, centroiding and compression tasks can be carried out.

The power budget of one board is 6W.

**Figure 5: RUAG processing board unit. The “Panther” board provides a LEON core with FPU, cache and additional amenities.**

### 3.3.2 PSU and wFEE

In Figure 6, a rough block diagram of the Power Supply Unit (PSU) & warm Front End Electronics (wFEE) is shown.

The internal power converter supplies the DPU and wFEE electronics. The FGS, cFEE converter supplies FGS, cFEE with individual galvanically isolated supply voltages. This allows to shift the ground star point to the cFEE or FGS. The main converter is controlled by the Spacecraft Management Unit via High Power Commands according to ECSS-E-ST-50-14C. Two inputs, one to the nominal side and one to the redundant side, are provided together with on ON/OFF status for monitoring (TBC). The FGS, cFEE converter is switched on by a command from the FGS-DPU tbc. Both converters are synchronised to the Master Clock delivered by the FGS-DPU.

The control and protection circuitry of the FGS, cFEE converter is related to the local secondary ground (FCE ground) of the main converter. The outputs of the FGS, cFEE converter are galvanically isolated from the FCE ground and to each other. In order to get stable output voltages, a separate sense winding is provided, which is used for the output voltage control loop. A coupled inductor is foreseen for all secondary voltages including the sense voltage (Vsense) to achieve a good cross regulation.

All converters are protected against output overvoltage, overcurrent and input undervoltage. In case of failure, the affected converter is switched off in a latching way. It can be restarted by deactivating the corresponding On/Off signal and activating it again after a short delay (typically a few 100ms).
The main converter provides a power good signal which can be used to reset digital circuit. It is low until the supply voltages are within their limits with some delay added. This signal is generated by the converter control and forced to low before the supply voltages start to raise.

The wFEE contains an ACTEL RT54SX72 Field Programmable Gate Array (FPGA) together with LVDS drivers/receivers to generate clocks for the cFEE and to receive digital data back for transmission to the FGS-DPU. Alternatively the ACTEL AX2000 FPGA which can be mounted optional on the FGS-DPU can be used for this function. It has to be checked during future proposal work if this could be a reasonable alternative.

Further a M2 ASIC is provided which is controlled via OBDH bus from the FGS-DPU and is able to acquire up to 64 channels of type Temperature Acquisition, Analog Voltage, Digital status.
The M2 includes a 12bit ADC with 64 input analog multiplexer, DACs and digital IOs according to ECSS-E-ST-50-14C.

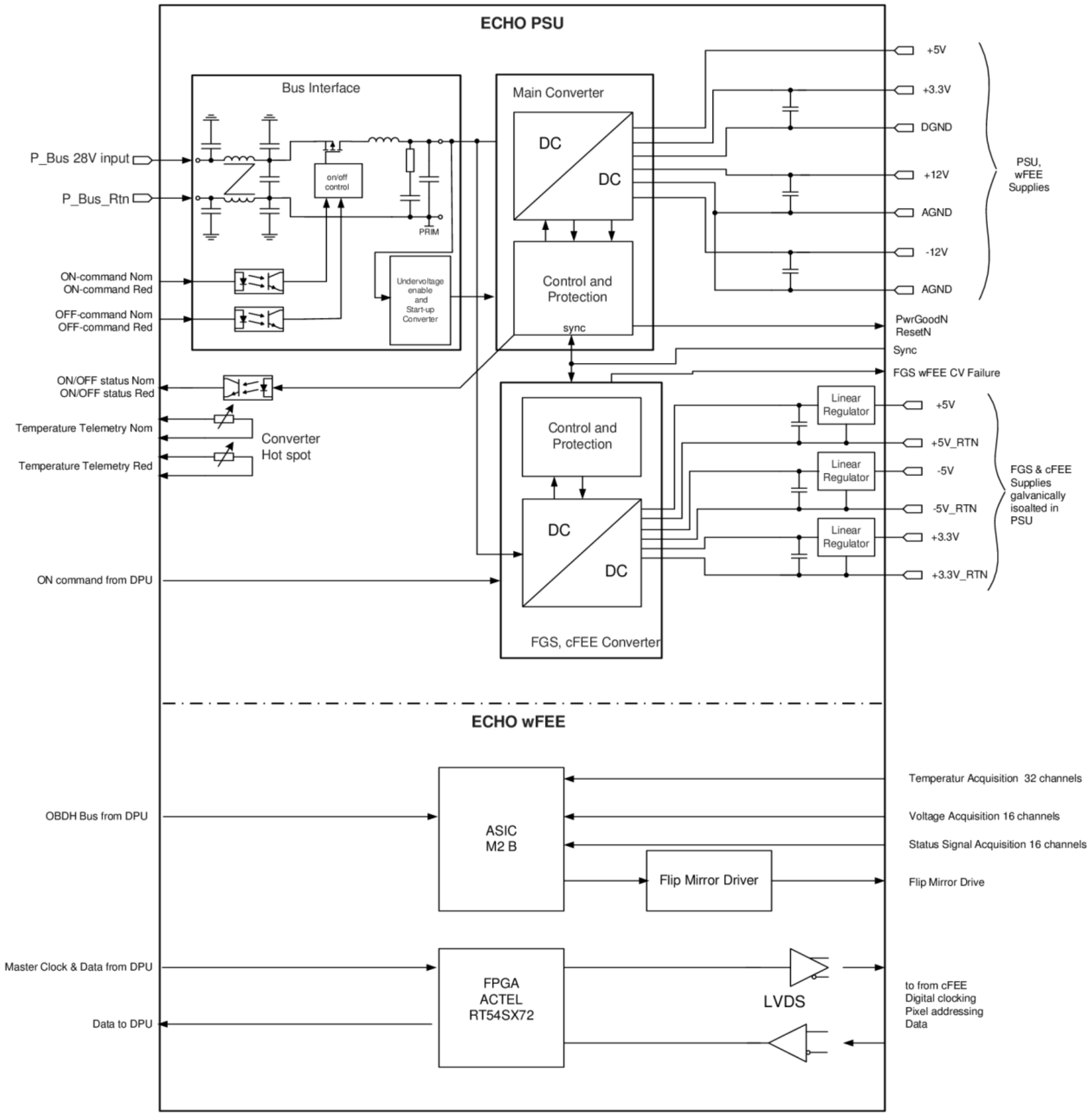


**Figure 6: PSU and wFEE electronics board. "DPU" designates the FGS-DPU.**

## 3.4 FCE INTERFACES AND BUDGETS

### 3.4.1 FCE electrical I/F

Nominal and Redundant Power Supply and control:

- Power line: 28V + RTN (From S/C PCDU to ICU)
- HPC (Signal + RTN) (From S/C DMS to ICU)

### 3.4.2 TM/TC IFs

Nominal and redundant I/O digital data interface:

- MIL-STD-1553 bus between S/C and FGS (TBC), otherwise
- Standard Spacewire link (configured @ 10 Mbit/s)

## 3.5 MECHANICS

The mechanical design of the FCE is driven by the existing FCE-DPU board. The PSU & wFEE function will be located on a PCB with the same size as the FCE-DPU, connected via integrated flex PCB to the FCE-DPU connectors. External connectors are located on the front side. The box is composed of frames that are stacked over each other. The nominal and redundant halves are separated by a sandwich plate. Overall dimensions are W323mm x H156mm x L230mm. The mass estimate excluding contingency is approximately 6.5kg.

The box is a stack of four segments: 2 processor boards and 2 power supply / interface boards. Their mechanical structure (and weight) is more or less the same, initial mass estimates are given in Table 1:

| Component | Basic Mass Estimate [kg] |
|---|---|
| FGS-DPU box segment (nominal) | 0.3 |
| FGS-DPU processing board (nom.) | 1.15 |
| FGS-DPU box segment (redundant) | 0.3 |
| FGS-DPU processing board (red.) | 1.15 |
| | |
| PSU/IF box segment (nom.) | 0.3 |
| PSU/IF board (nom.) | 1.15 |
| PSU/IF box segment (red.) | 0.3 |
| PSU/IF board (red.) | 1.15 |
| | |
| Top/bottom plate, screws, mounts | 0.7 |
| **Total** | 6.5 |

**Table 1: FCE mass breakdown.**

## 3.6 BUDGETS

| Description | Basic (EID-A R-1880) | Nominal (with 20% contingency) (EID-A R-1890) | Margin (EID-A R-1910) (EID-A R-0570) |
|---|---|---|---|
| **Power** | 6 W | 7.2 W | 20% |
| **Mass** | 6.5 kg | 7.8 kg | 20% |
| **Volume** | 281(323)x230x156 $mm^3$ | | - |
| **Telemetry** | 5 kbit/s (TBC) | 6 kbit/s (TBC) | 20% |

**Table 2: FCE budgets**

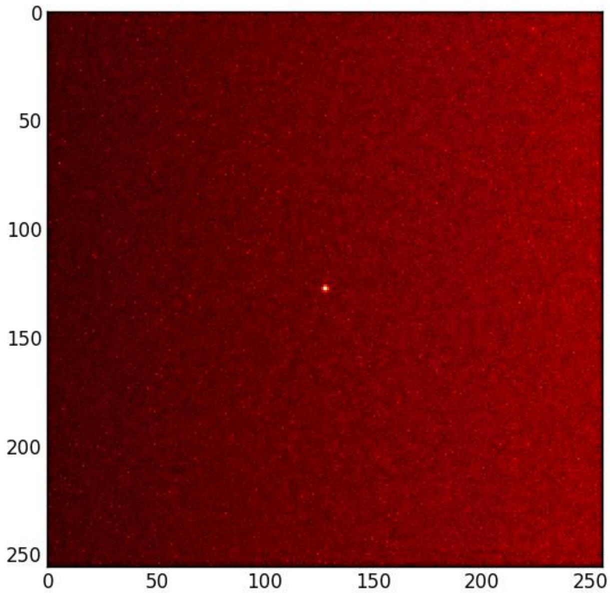


**Figure 7: Data frame from first version FGS simulator.**

## 3.7 SOFTWARE

The FCE unit will have to carry out and support a number of different tasks. There will be functions to control the FGS subsystems, process the detector data, communicate with the spacecraft, all according to the current mode of operation.

The absolute pointing error of the star trackers is 10" RMS, pointing is then handed over to the FGS. The FGS will find and measure precisely any point sources in its 20” field of view. During peak-up a frame rate of 2 Hz (TBC) is required, during guiding 10 Hz of a 7x7" region of interest, corresponding to a 70x70 window.

The FGS will also be used for focusing the main telescope. This is limiting the amount of intentional defocus or diffusion. The PSF will be spread over 50-60 pixels, with a FWHM of 3x3 pixel. The main requirement is a 10 milliarcsecond centroiding performance at 10 Hz for the faint targets. The operating wavelength range is 550-1000 nm.

In the warm FGS control electronics the data will be processed in real-time. Output data products are calibrated, cropped and reformatted images, centroid coordinates, dimensions and errors in both axes, photometry, glitch count and housekeeping. On-board compression will be used to reduce the telemetry. Additional data processing capabilities include frame stacking for PSF measurements. Figure 7 shows the output from a first simulator software used to assess the required processing capabilities of the FCE.

### 3.7.1 Centroiding

For the best support of the operating modes, several centroiding and data extraction algorithms will be implemented, fully configurable by parameter and command.

A number of calibration steps need to be carried out before the centroiding can be applied, most importantly bias and flatfield correction. The detector is foreseen to be operated in read-reset mode, so no ramp fitting will be required. For the purpose of glitch detection and correction, several frames will be buffered.

Configurable windowing methods to extract the region of interest (ROI) will be available.

Center of Gravity (CoG) based algorithms with different weighting and thresholding strategies will be used to extract the astrometric and photometric parameters. Alternatively, correlation methods will be implemented, as well as general fitting strategies.

### 3.7.2 Data Products and Telemetry

The FGS will deliver centroid data products and images to the spacecraft. In addition, these data products will be sent as science data products to ground. On top of that, HK are generated and sent. All rates and window sizes are configurable.

A typical centroid dataset will consist of astrometric and photometric measures, plus several bits of status information. Table 3 gives a list of the centroid fields.

| | CONTENTS | SIZE (BYTES) |
| --- | --- | --- |
| Astrometry | X/Y position, X/Y FWHM (if applicable), variances | 24 |
| Photometry | Integrated flux, FWHM flux, background flux, variances | 24 |
| Status | Operating mode, time tag, glitch count, star count, validity flags | 6 |

**Table 3: Centroid data product. Floats are used where applicable.**

During guiding, a 70x70 pixel window will be analyzed at 10 Hz. Assuming 16 bit words, the raw ROI data rate will be 784 kbit/s. In case 256x256 pixels should be transmitted at 10 Hz, a data rate of 1 Mibit would be achieved. Thus, a SpaceWire link would be preferred over MIL-STD-1553. The centroid data will be 54 bytes per frame, or 4.32 kbit/s at 10 Hz.

Science data products that will be downlinked will be compressed in a lossless manner. Images will be compressed using an integer wavelet transform with an arithmetic compression backend. This will yield a factor 3, depending on the noise. For the centroids, compression will be much less efficient, as most parameters will be floats. Given the estimated numbers from above, a downlink rate of ~300 kbit/s would be needed for a 10 Hz resolution.

A typical scenario could be lossless compressed images of 30x30 pixel at 1 Hz (4.8 kbit/s) plus centroids also at 1 Hz (0.432 kbit/s). All of these rates are configurable to the needs on ground.

The FGS has few sensors and HK values, yielding a data rate in the order of 1 kbit/s. The precise overall telemetry contribution of the FGS depends on the parameter configuration, which is at this point TBD, but our current estimation is 5-10 kbit/s.

### 3.7.3 FDIR and SW Infrastructure

In order to guarantee the high reliability of the FGS, the software has built-in functionality for internal monitoring of hardware and software states, self-testing and error management. As a stand-alone unit, the FCE software also has to provide functionality for telecommand verification and execution, on-board time management, HK monitoring and provision, subsystems set-up, etc. Upon a defined set of anomalies the FCE puts its subsystems in a safe state and signals that state to the spacecraft.

The hardware specs are primarily defined by the amount of data to process, combined with the complexity of the centroiding and data compression tasks.

### 3.8 HARNESS

The respective interfaces, as listed in the FCE description, will be harnessed accordingly.
We assume that the instrument provides all internal harnesses of the subunits and ESA provides all harnesses linking boxes, in particular between the IOB and the SVM.

# 4 EGSE

A set of equipment will be needed to integrate, test and validate the FGS. Here is a preliminary list of components (TBC):

- **Spacecraft Simulator:** PC or µTCA unit with 1355/1553 interface for the development/testing of the S/C interface.

- **Front-End Simulator:** PC or µTCA unit simulating the interface between detector and FCE.

- **FGS Simulator:** PC or µTCA unit simulating the overall system. Essentially, this is a unit running a data generator and a representative version of the FCE software, including interfaces to the S/C.

- **TEM (Test Equipment Manager)** will control the test routines and thus be connected with the interface to test.

- **Power Supply Equipment** with multiple programmable outputs, controlled by the TEM.

# 5 FGS PERFORMANCE

## 5.1 OPTICAL PROPERTIES

The optical characteristics of the FGS are detailed in RD003. Only some basic considerations are made here, which are important for the operational scenario. As soon as the optical design is finalized, this subsection will be obsolete.

### 5.1.1 System Focal Length

The effective focal length of the telescope, given for a 300mm focal length focusing lens is 10568.3055 mm (from PDD).

Instead of that lens the FGS optics have a focal length of 667 mm. This means that the system telescope + FGS optics has a focal length of 10568.31/300*667 = **23496.88 mm**

### 5.1.2 Telescope PSF

The telescope is diffraction limited at 3 micron (Marc Ferlet at last CM). Our worst case assumption is that in our spectral band (0.55-1µm) the PSF is equally „bad“. Thus we calculate the resolution for 3µ.

The entrance pupil diameter is 1286.5 mm. (from PDD). At 3µm this gives a resolution of 1.22 * 3/1000 /1286.5 = 2.844928e-6 rad, that is 0.587“. With the system focal length we get the scale in focus: tan(2.844928e-6)*23496.8 = 0.066847 mm = **66.847 µm**. For now we will use the radius of the Airy disk as FWHM (they are not the same, but close enough). Depending on the shape of the PSF, we will need to look at windows of n-times this size to recover most of the PSF flux.

## 5.2 EFFICIENCY AND FLUX

The following considerations have been made using a 0.4-0.8 micron range. They need to be adapted to the 0.55-1 micron range, but the order of magnitude should be fine.

The beam splitter (FGS/VNIR) will only allow **50%** of the light into the FGS.

For the quantum efficiency of the detector we will simply assume **70%** over the entire wavelength range for now.

In any case, the faintest star input flux (goal) is 2.1e-14 Wm^-2 (SciRD, G-SCI-125). We need to multiply this with the effective area of the telescope (**1.131m^2** from MRD G-PERF-120) and all the efficiencies to get the flux at detector level. All the efficiencies we have so far are: 0.5 * 0.75 = **0.35**.

Hence we get a flux of 2.1e-14 * 1.131 * 0.3485 = **8.2772e-15 W** on the detector PSF. Within 1s we get an Energy of 8.2772e-15 Ws. In the worst case, these are all photons of short wavelength (0.4 µm). The energy of one such photon is **5e-19 J**, so we collect **16550** photons from the whole PSF in 1 s.