DEVELOPMENT AND COMMISSIONING RESULTS OF THE HYBRID SENSOR BUS ENGINEERING QUALIFICATION MODEL

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ABSTRACT

In order to reduce mass, AIT effort and overall costs of classical point-to-point wired temperature sensor harness on-board spacecraft OHB System AG has introduced the Hybrid Sensor Bus (HSB) system which interrogates sensors connected in a bus architecture. To use the advantages of electrical as well as of fiber-optical sensing technologies, HSB is designed as a modular measurement system interrogating digital sensors connected on electrical sensor buses based on I²C and fiber-optical sensor buses based on fiber Bragg grating (FBG) sensors inscribed in optical fibers. Fiber-optical sensor bus networks on-board satellites are well suited for temperature measurement due to low mass, electro-magnetic insensitivity and the capability to embed them inside structure parts. The lightweight FBG sensors inscribed in radiation tolerant fibers can reach every part of the satellite.

HSB has been developed in the frame of the ESA ARTES program with European and German co-funding and will be verified as flight demonstrator on-board the German Heinrich Hertz satellite (H2Sat).

In this paper the Engineering Qualification Model (EQM) development of HSB and first commissioning results are presented. For the HSB development requirements applicable for telecommunication satellite platforms have been considered. This includes an operation of at least 15 years in a geostationary orbit.

In Q3/2016 the qualification test campaign is planned to be carried out. The HSB EQM undergoes a full qualification according to ECSS. The paper concludes with an outlook regarding this HSB flight demonstrator development and its in-orbit verification (IOV) on board H2Sat.

1. INTRODUCTION

OHB System AG and its predecessor Kayser-Threde GmbH (KTH) established a good knowledge in fiber-optical sensing (FOS) applications for space. With SMAFO [1] and FOSAT [2] KTH demonstrated the applicability of FOS under qualification loads.

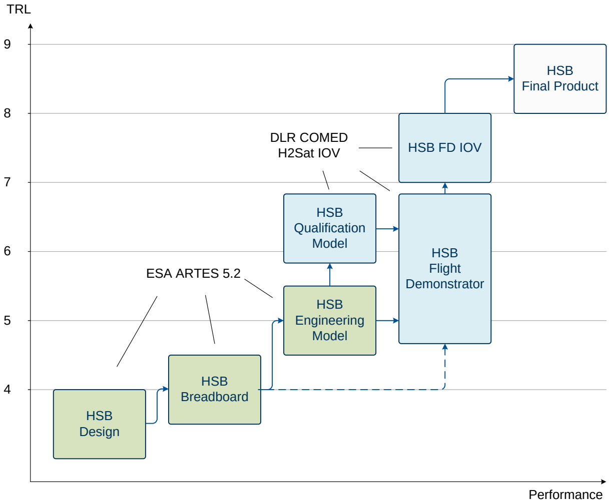

Figure 1. HSB development logic and model philosophy.

The heritage of KTH consists as well the development of the Sensor Bus System (SBS) which has been successfully flown on the TET-1 satellite [3]. SBS was designed to demonstrate the interrogation of digital temperature sensors in space [4]. Combining the gained knowledge of both bus network sensing techniques leaded to the development of HSB.

Fig. 1 shows the development logic and the model philosophy defined for the HSB project. This paper focuses on both the HSB Engineering Model and the HSB Qualification Model which has been combined to the EQM during the design phase. A Technology Readiness Level (TRL) 9 shall be achieved with the IOV of the flight demonstrator with the goal to bring HSB to the market for future spacecraft.

2. HYBRID SENSOR BUS

HSB is a modular sensor system which is able to read out electrical sensors over the I²C bus and fiber-optical sensors based on FBGs. These sensors are part of novel space applicable sensor bus networks which help saving costs in telecommunication satellites by replacing the complex point-to-point wiring of the several hundreds of sensors integrated mainly for housekeeping.

In its basic configuration HSB consists of four modules which are the Power Supply Unit (PSU), the HSB Controller Module (HCM), the Interrogator Controller Module (ICM) and the Analog Front End (AFE) for the fiber-optical interrogation. The ICM handles both the electrical and fiber-optical sensor networks. For the latter it is to be completed by the AFE. On the AFE a tunable laser is implemented for the scanning of the FBG sensors. The reflected spectra are measured on multiple fiber channels and are then converted to temperatures by use of a peak find algorithm. To guarantee a stable operation over the full mission an in-orbit recalibration means is implemented on the AFE [5].

Fig. 2 shows the block diagram of the HSB system consisting of the HSB Unit for the interrogation and the connected sensor networks. The electrical sensor network is intended to consist of multiple digital temperature sensors connected in a bus topology. Several ESA contracted studies concluded the I²C bus as most suitable bus protocol for future digital sensor networks in spacecraft. Currently no qualified digital temperature sensors are available on the market. For the verification of the HSB Unit the I²C Sensor Multiplexer (ISM) was introduced by OHB. The ISM can read out up to 12 thermistors and provides the digitized temperature on the I²C bus. For a successful in-orbit demonstration of interrogating sensor bus networks a reliable remote terminal is more reasonably required than a network based on a non-qualified digital temperature sensors.

The HSB Unit is modularly designed which means that multiple ICMs can be accommodated to increase the number of sensors to interrogate. As well redundant PSUs and HCMs can be added to increase the system's reliability.

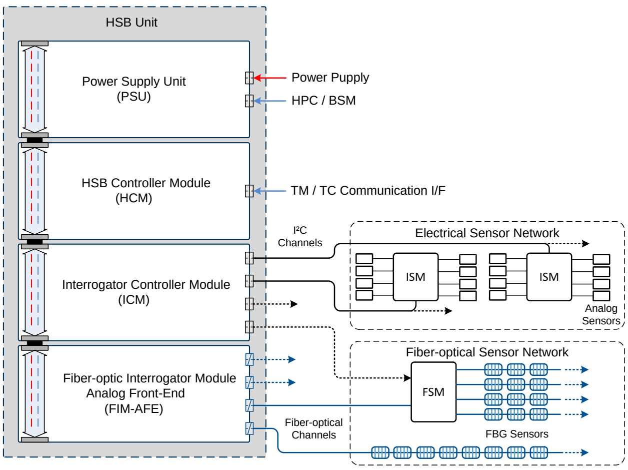

Figure. 2. HSB system overview with the four different modules and connected sensor bus networks.

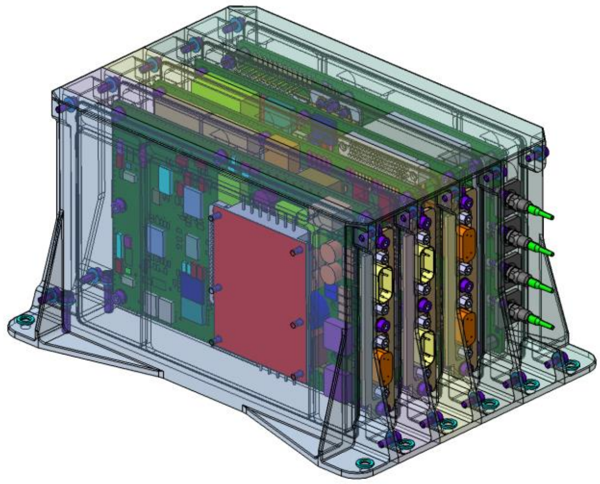

Figure 3. 3D model of the HSB Unit with PSU, HCM, ICM and AFE from the left to the right.

Fig. 3 shows a 3D model view of the HSB system in its basic configuration. The module accommodation order is PSU, HCM, ICM and AFE from the left to the right.

The ICM represents the core module of the HSB Unit. It is responsible for the interrogation of up to four I²C buses as well as for conditioning the gathered sensor data. Furthermore, it interfaces with the AFE for the interrogation of the fiber-optical sensors. Table 1 summarizes the main properties of the HSB Unit.

Parameter	Value
Mass	3.0 kg
Dimension	159 x 115 x 218 mm³
No. of electrical sensors	4 buses x up to 25 sensors
No. of fiber-optical sensors	2 fibers x up to 12 FBGs
Measurement rate	1 Hz nominal, 100 Hz fast mode
Accuracy	±0.5 °C
Operational temperatures	HSB Unit: -20 °C to +65 °C FBGs: ±100 °C
Radiation load	< 100 krad inside Unit for 15 yr in GEO orbit
Power	16.7 W avg, 27 W max
Supply voltage	42 V to 52 V
Communication	MIL-Bus at 1 Mbit/s
Data Storage	5 MiB RAM (2 h sampling)

Table 1. HSB Unit properties in basic configuration.

All modules are interconnected by an inter-module interface leading the redundant power path, the redundant communication lines, module power switching lines and internal synchronization signals. The functionalities of all HSB modules are introduces in the following subsections.

2.1. Power Supply Unit

The Power Supply Unit is responsible for the generation of the intermediate module power of 12 V. The controller and interrogator modules then generate required low voltage power rails locally on the module. The PSU’s main DCDC converter operates at up to 52 V inputs voltage providing maximum 50 W at its output.

The PSU incorporates input and output filters to cope with platform requirements as wells as an internal housekeeping unit for monitoring the 12 V power rail and the converter’s temperature. The PSU is controlled by the platform via high power commands to switch on the HSB system. For status feedback redundant bi-level switch monitoring signals are implemented.

2.2. HSB Controller Module

The HSB Controller Module incorporates all functional blocks to control the entire HSB system in terms of operational states and data transfer. For the communication with the platform a redundant MIL-Bus interface is implemented. The HCM controller is the powerful GR712RC Dual-Core LEON3FT SPARC V8 processor running the HSB application software on the real time operation system RTEMS. The module generates all locally required power rails on-board from the intermediate 12 V rail.

Fig. 4 shows the functional block diagram of the HCM. EDAC protected SRAM and MRAM are implemented for the execution of the application software and its storage respectively. HCM furthermore offers the possibility to upload the software from the ground station.

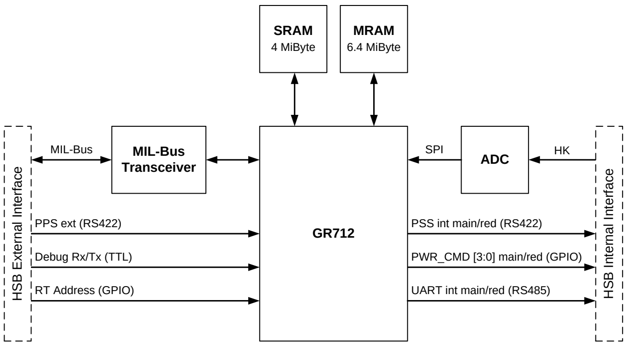

Figure 4. HCM functional block diagram.

2.3. Interrogator Controller Module

The Interrogator Controller Module is responsible to read out the sensors connected to the I²C sensor buses and to control the ADCs and DACs on the AFE in order to perform fiber-optical measurements. On the ICM as well all required power rails are generated on-board form the intermediate 12 V rail. The core of the ICM is the radiation tolerant and single event upset immune RTAX2000S FPGA. On this FPGA a state machine controls both the interrogation of the electrical and the fiber-optical sensors networks.

Four I²C channels are implemented on-board the ICM to interface the electrical sensor bus networks. Each channel offers a 5 V latch-up protected supply voltage rail for powering the connected digital sensing devices with up to 400 mA. All connected devices can be accessed by a dedicated I²C address stored in lists which can be reconfigured from ground if required. The measured temperatures are conditioned and packed by the FPGA to be queried by the HCM to provide them as telemetry to ground. The same applies for the temperatures measured by means of the fiber-optical sensors. For whose interrogation complex algorithms are implemented in the FPGA to control the laser diode on the AFE as well as to interpret the reflected spectra to defined the Bragg wavelengths.

2.4. Analog Front End

The Analog Front End incorporates all fiber-optical components and their required control electronics for the interrogation of the fiber-optical sensor networks. The AFE is based on a modulated grating Y-branch (MGY) tunable laser. This type of laser diode can be tuned in a wavelength range of 1528 nm to 1568 nm. Three currents are required to sweep the laser light over this spectrum in order to sequentially illuminate the all connected FBG sensors. The laser’s wavelength is set by dedicated triplets of the control currents which are stored in a look-up table (LUT) in the ICM’s memory.

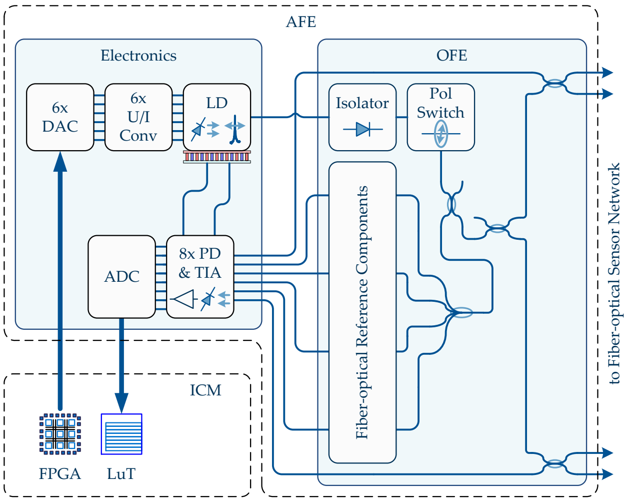

Figure 5. AFE functional block diagram.

For a measurement cycle the MGY laser scans stepwise through the full spectrum and the reflected light from the FBGs on each fiber-optical channel is measured by its photodiode. The reflected intensity signal is then assigned to the laser's wavelength again by use of the LUT. In the ICM's FPGA the reflected signals are evaluated in the FPGA by use of a peak find algorithm. From the detected peaks the Bragg wavelengths of every FBG sensor is then identified and assigned to a temperature value considering its sensitivity curve.

2.5. Analog Front End Electronics

The AFE can be subdivided in the Electronics part and in the Optical Front End (OFE) as shown in the block diagram in Fig. 5. The AFE Electronics consists of six DACs with subsequent voltage-to-current converter circuits control of the MGY laser. Three currents set the wavelength and other three currents are required of the laser operation and its temperature control by an internal Peltier element. The Electronics part furthermore includes a multiplexing ADC for the digitizing of the spectra measured by use of photodiode's (PD) signals converted by individual transimpedance amplifiers (TIA). For stable operation of the MGY laser their reference signals are fed to the FPGA on-board the ICM in terms of a closed loop control.

2.6. Optical Front End

The Optical Front End consist of the fiber-optical components required for the light guidance to the fiber-optical sensor buses by use of passive fiber couplers as well as required for the in-orbit recalibration.

An isolator protects the MGY laser from back-reflections caused by the FBGs. In order to handle occurring polarization effects in the fibers a polarization switch is implemented in the OFE. For every wavelength set by the MGY laser two measurings are performed, each in a polarization state differing by 90° realized by switching the polarization switch. With this a mean value can be calculated afterwards to even out birefringence effects caused by the fiber twists and bends.

The light leaving the polarization switch is then split up into the four fiber-optical channels. On two of these channels FBG arrays can be connected. The other two channels can be used to connect to sensor extension devices in order to increase the number of fiber-optical sensors interrogated by HSB. The tunable laser concept allows to distribute the light to multiple FBG channels for interrogation. Each channel needs then an individual PD with TIA and ADC for the signal evaluation.

Figure 6. AFE Electronics board with first version of the OFE design integrated in the mechanical AFE frame.

As sensor extension device the Fiber-optical Sensor Multiplexer (FSM) was introduced by OHB which incorporates the functionality for leading the laser light to up to four additional channels and digitizing the reflected spectra by means of a an ASIC. The spectral data then can be read out be the ICM via the I²C interface. With the use of an FSM the number of FBG sensors to be interrogated by one AFE can be increased by a factor of three. For the IOV on H2Sat the FSM however is not part and no EQM is currently developed to undergo qualification together with the HSB Unit and the ISM.

The other part of the light which leaves the polarization switch is split up to four fiber-optical reference channels. The reference signals are used to recalibrate the AFE in-orbit since the fiber-optical components for the interrogation are affected by radiation causing wavelength shifts which negatively influence the measurement accuracy.

In Fig. 6 the first AFE module (refer to section 5) with the mounted fiber-optical components is shown. With this AFE module the fiber routing has been set up to gain handling experience and to parallelize the commissioning and test possibilities of the complex fiber-optical interrogation. The lessons learnt form the OFE manufacturing especially led to an optimized mechanical structure for the fiber guidance in the AFE EQM.

Since the implemented fiber-optical components are not available as space qualified parts irradiation tests has been carried out with identical parts. For all parts an adequate performance after radiation could be demonstrated. Occurring wavelength shifts can be recalibrated by means of the reference components which does not show radiation induced wavelength drifts.

3. IN-ORBIT RECALIBRATION

Long term drifts of the MGY laser's wavelength mainly caused by radiation are to be compensated for stable an accurate operation of the HSB system. For this an in-orbit recalibration algorithm has been developed by the company FAZ Technology who contributes to the HSB project. The spectra of the fiber-optical reference components are used for the recalibration since they are not affected by long term wavelength drifts. Radiation tests with this components showed that they are not severely affected up to a total ionizing dose of 100 krad, what is calculated to be the highest load inside the HSB Unit for 15 years in a geostationary orbit. With the information of the reference components the in-orbit recalibration shall be performed on a weekly basis during operation in space.

With the HSB system's upload capabilities it is also possible to perform a recalibration on ground resulting in a completely new LUT for the MGY laser sweeping. This option is intended to be tested during the in-orbit verification of HSB.

4. SENSOR BUS NETWORKS

In this section the development of the sensor bus networks interrogated by the HSB system is introduced. For the implementation of HSB in future spacecraft the sensor bus networks shall consist of several hundreds of digital and fiber-optical sensors. The qualification campaign will be carried out using a reduced network with only a handful of sensors. With this the sensor technique will be qualified. Full performance of the HSB EQM will be verified during the qualification testing using the bus emulators introduced in section 5. The EQM sensor bus network consist of two flight representative fiber-optical sensors and one I²C Sensor Multiplexer (ISM).

4.1 Fiber-Optical Sensor

An accurate and robust sensor is mandatory for fiber-optical temperature measuring. For this a radiation hard fiber and FBG configuration has to be selected as well as a suitable mechanical transducer solution which is capable to totally decouple strain and temperature shifts in the reflected peak.

In cooperation with the Fraunhofer institutes INT and IOF a suitable combination of a radiation hard fiber and FBG writing technology has been found and successfully demonstrated [6]. A representative reflection spectra of the measured FBG is depicted in Fig. 7. The FBG sensor written in the optical fiber is very small and lightweight but also very sensitive to mechanical forces like twist, stress and shear strains.

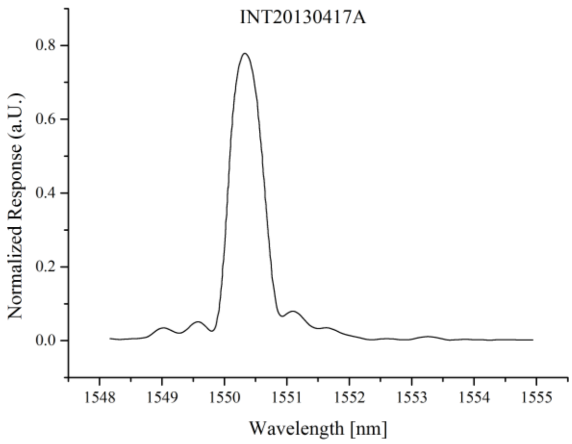

Fig. 7: Reflection spectra of FBGs written by fs-IR technique into the selected radiation hard fiber.

For a proper decoupling of these mechanical forces from the temperature the FBG needs to be mounted on a transducer. OHB analyzed existing transducer solutions and proposed new designs as shown in Fig. 8. The transducer designs base on a middle paddle where the FBG is mounted. With bending tests the mechanical decoupling has been successfully demonstrated.

A delicate issue is the selection of an adequate material for the mounting of the FBG and the transducer itself. For this a set of configurations has been assembled and thermal-vacuum cycled. With this the accuracy can be determined to conclude which configuration is best suited for the fiber-optical sensor. A further parameter is the sensitivity which has to be considered for the selection. The higher the sensitivity the better the accuracy which can be achieved with the fiber-optical sensors. This however reduces the number of sensors in one string of fiber-optical sensor bus network since a higher wavelength range is required for an adequate temperature range. Thus, this needs to be balanced for the dedicated application.

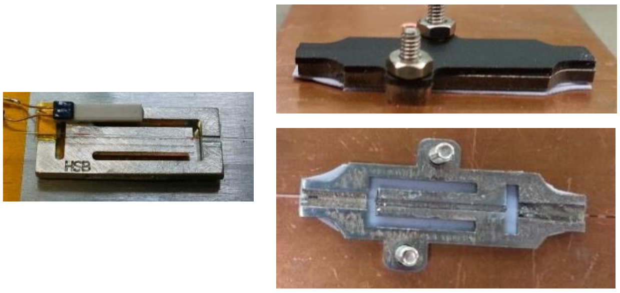

Fig. 8: Aluminum transducer with fiber mounted in silicone (left) and steel transducer mounted in silicone (right bottom) and with protection cover for characterization measurements (right top).

4.2. I²C Sensor Multiplexer

The I²C Sensor Multiplexer (ISM) is an intelligent interface between analog electrical temperature sensors and the I²C bus handled by the ICM. Since no qualified digital temperature transducers are available yet, the ISM has been introduced in the HSB development for the in-orbit verification of the electric sensor bus based on the I²C protocol [7]. Eight connected analog temperature sensors (thermistors) are read out and digitized by the ISM EQM as shown in Fig. 2. The digitized temperature values are then provided to the central HSB system via the I²C bus. With this the ISM acts as a sensor concentrator. On one I²C bus up to 10 ISM can be connected. This number is driven by the power provided by the ICM for every of the four I²C buses. A bus network combining ISMs and future space qualified digital temperature sensor on the same bus is applicable if required by the platform.

5. COMMISSIONING AND TESTING

For the HSB EQM a complete set of data packages for every module has been prepared and approved for manufacturing containing all necessary design documents and analyses required according to ECSS. The EQM modules are currently under manufacturing at OHB’s electronic manufacturing department. For FAZ Technology an AFE module including the OFE has been manufactured and delivered in January 2016. With this FAZ Technology started to test and commission the HDL code for the fiber-optical sensor bus interrogation and the in-orbit calibration. The HDL code for the electrical sensor bus interrogation has been developed by OHB and will be synthetized with the code for the AFE control on the ICM’s FPGA during the module commissioning.

First commissioning results with the connected FBG sensors discussed in section 4.1 are shown in Fig. 9. Two FBG sensors were connected to both AFE FBG channels. The interrogation has been controlled by a LabVIEW software which communicates with the FPGA. The two reflection peaks on the bottom of Fig. 9 are measured by the ADC on the AFE. The peak find algorithm and the temperature conversion has been implemented in LabVIEW for testing purposes. This resulted in the temperature curves shown at the top of Fig. 9.

Dedicated Ground Support Equipment (GSE) has been designed for the commissioning and testing of the HSB EQM and the flight demonstrator later on. Since the qualification campaign is planned to be carried with a reduced sensor bus network the full interrogation operability shall be tested and verified by means of emulators. For this an I²C Emulator and an FBG Emulator has been manufactured to emulate the sensor bus networks to be interrogated by HSB. The I²C Emulator is capable to emulate up to 25 digital temperature sensors on four I²C buses. A full set of individually configurable temperatures for every sensor can be generated by the I²C Emulator with an update rate of 1 Hz. HSB then interrogates the emulated data under different environmental conditions. The GSE software then compares the emulated and measured data for the HSB system verification. The I²C Emulator furthermore allows to emulate shorts and breaks possibly occurring at the individual I²C buses during flight. This allows reliability simulations and the verification of the failure detection, isolation and recovery (FDIR) means of the HSB application software. Single event latch-ups (SEL) in the I²C sensors caused radiation can be emulated as well as occurring capacitive load changes which could violate the I²C communication.

For the fiber-optical sensor network an FBG Emulator has been introduced [8]. In contrast to I²C Emulator the FBG Emulator simulates the temperatures of the sensors by means of generated reflection spectra as shown in Fig. 7, which are interrogated by the AFE and converted to temperatures by the ICM. For each step during the FBG sensor scanning by the AFE the FBG Emulator synchronously emulates a programmed reflection intensity. This allows as well to simulate corrupted reflection peaks in order to test the peak find algorithm’s performance and with this the HSB system’s temperature measurement accuracy.

The HSB EQM system assembly and commissioning is planned to be completed by end of July to carry out the qualification in Q3/2016. As baseline for the qualification with the HSB EQM the General Equipment Requirements Document (GERD) for Equipment flying on the SGEO platform is applicable. The GERD is fully compatible with the ECSS standards and shall allow HSB to be operable on other platforms which apply ECSS.

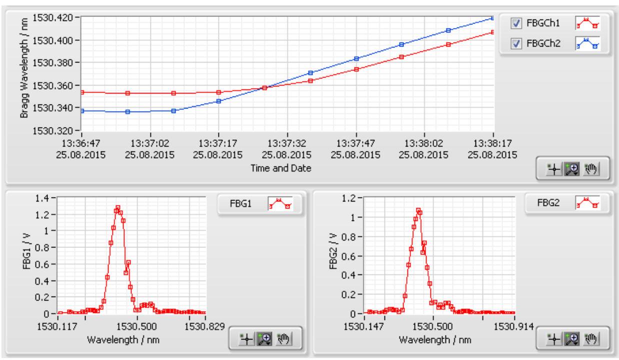

Fig. 9: Commissioning results of the AFE module interrogating two FBG sensors.

6. CONCLUSIONS AND OUTLOOK

In the frame of the HSB project a temperature measurement system for electrical and fiber-optical sensor bus network interrogation has been designed. The dedicated functional parts has been successfully demonstrated for operation in a geostationary orbit. Currently the EQM is manufactured and commissioned for the subsequent qualification testing campaign planned in Q3/2016, where the full performance under space conditions on system level shall be verified. After this the flight model shall be built and provided as technology demonstrator on board the German Heinrich Hertz satellite.

For the IOV the sensors interrogated by HSB shall be integrated close to selected platform sensors for on ground evaluation of the system's functionality and temperature measurement accuracy. With a successful IOV HSB is intended to become a future platform equipment to interrogate the housekeeping sensors by means of mass saving sensor bus networks.

7. ACKNOWLEDGEMENTS

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