Space Technologies Studies 2010: Results

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Presentation of the nine projects and the pilot study funded under the call for proposals issued in 2010 by the Swiss Space Office of the State Secretariat for Education and Research of the Swiss Confederation (SER/SSO) to “Foster and promote Swiss scientific and technological competences related to space activities”.

List of the projects:

- **Space Qualified Assembly Technique for Optical Systems**
  (CSEM, UniNE, HEXAGON, MICOS)

- **Compact and stabilized laser head for innovative Rubidium atomic clock**
  (UniNE, Spectratime)

- **Advanced High Precision Position Encoder**
  (MICOS, CSEM)

- **Reaction Sphere for Attitude Control Rotor Optimization**
  (Maxon Motor, CSEM)

- **Generation of DEMs based on the Fusion of Optical Stereo and SAR Interferometry Techniques**
  (SARMAP, ETHZ)

- **Gamma Portable Radar Interferometer**
  (GAMMA Remote Sensing, ETHZ)

- **TENCIA-1 RF Module for Space borne GNSS receivers**
  (Saphyrion, ALaRI)

- **Contactless Power and Data transmission**
  (RUAG, HEIG-VD)

- **Floating Point Operation Controller IP Core for Space Applications**
  (Syderal, EPFL)

- **Gravity Gradient Earth Sensor**
  (RUAG, EPFL)
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SQUATOS (Space Qualified Assembly Technique for Optical Systems) is a project funded by the Swiss Space Office in the frame of the positioning measures initiated in 2011.

**Project objectives**

- Increase the Technology Readiness Level (TRL) of the three dimensional miniaturized optical surface mounted device (TRIMO-SMD) technology
- Show the potential of TRIMO-SMD for space applications

**State-of-the-art**

- TRIMO-SMD: a technology allowing the miniaturization and precise alignment of optical parts
- Used in various ground commercial products
- Technological Readiness Level (TRL) at 3

**Project results**

- 12 endurance demonstrators (ED) and 4 functional demonstrators (FD) built
- TRL4 demonstrated with tests executed on FD
- Partial TRL5 demonstrated with tests executed on ED
- TRIMO-SMD qualified according to:
  - High vacuum constraint, large thermal changes and under micro-vibrations in operation
  - Launch vibrations and high thermal constraints survival
  - Resistance to peeling

**Outlook**

- TRIMO-SMD maturity and potential demonstrated for space
- Use TRIMO-SMD as assembly technology for future optical modules (e.g. optical part of laser pumped Rb or optically-pumped Cs clocks, miniaturization and ruggedization of the optics of interferometer, spectrometer, imaging LiDAR, etc.)

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Compact and stabilised laser head for innovative Rubidium clock

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Project motivation

This project concerns the development and realisation of compact and frequency-stabilized laser heads, for use in innovative Rubidium (Rb) atomic clocks. Rb clocks are used, among others, in all global satellite navigation systems, because they combine very low volume, mass, and power consumption with an excellent frequency stability from the $10^{-12}$ level at 1 second down to few $10^{-14}$ over one day (Allan deviation). While essentially all Rb clocks today rely on discharge lamps for atomic interrogation, it was demonstrated previously that the use of diode lasers can improve the stability of a Rb clock to the level of a passive hydrogen maser, but from a clock with much lower volume, mass, and power consumption.

Compact and frequency-stabilized laser heads for atomic clocks were previously developed by LTF, but required bulky external laboratory electronics. The goal of this project was to miniaturize the laser control electronics, and to fully integrate it into the new, redesigned laser heads. With the laser heads being fully temperature controlled, this integration strongly reduces the sensitivity of the electronics to external temperature variations and thus improves the long-term frequency stability of the laser, which is crucial for the Rb clock stability. The resulting laser heads are a valuable tool for the further development of novel laser-pumped Rb clocks towards a commercial product, and are an important step towards operating the full Rb clock under vacuum.
Project activities and main results

In this project, LTF was in charge of the optical and mechanical design, fabrication and tests of the laser heads, while Spectratime (SpT) was in charge of the electronics design and realisation.

As laser source we use a temperature-stabilised Distributed Feed-Back laser diode (DFB), integrated with a collimator and miniature optical isolator to avoid optical feedback into the diode. Passing the laser beam through a Rb reference cell setup provides saturated-absorption signals as references for frequency stabilization (Figure 1a). All mechanical parts and the Rb reference cells were designed and manufactured in LTF. Two photo-detectors are implemented: one is used for light intensity monitoring, the other one is used to monitor the saturated-absorption signal, for frequency locking.

The miniaturized electronics was designed and manufactured by SpT. This work included miniaturizing the laboratory electronics used up to now, and integrating it into the laser head. This electronic includes all required functions such as temperature regulation of the laser and cell, laser current driver, light amplification, full lock-in demodulation and the laser frequency servo loop in a volume of about 0.15 liters. These functions are spread on two double-sided PCBs that fit in the free space under the laser head PP (Figure 2a). A view of this electronic is given in Figure 1c.

The miniaturized electronics was integrated into two laser heads (Figure 2a and front page) that have an overall volume of 1 liter each. Functional test results reproduce the results obtained with laboratory electronics, with a good saturated-absorption signal (Figure 2b). The laser frequency stabilization works, and a short-term frequency stability of $5 \times 10^{-11}$ at 1 s was measured. This stability can be further improved by one order of magnitude by optimizing the stabilization loop. Tests of two Rubidium atomic clocks using these laser heads showed encouraging clock stabilities of $<5 \times 10^{-12}$ at 1 second, which proves the suitability of the laser heads for Rb atomic clocks. Issues of medium-term clock stability remain to be addressed, but are not due to the laser head performance.

Conclusions

Two compact laser heads with integrated miniature electronics were realized. Saturated-absorption signals have good quality, and the laser frequency can be stabilized to this references. The resulting laser stability is sufficient for clock operation, but can still be improved. Two Rb clock demonstrators using these laser heads were operated successfully and showed an encouraging frequency stability of $<5 \times 10^{-12}$ at 1 second. These laser heads are an excellent and innovative tool for the development of next-generation laser-pumped atomic clocks, including for space applications. They may also find their applications as stand-alone stabilized laser sources in metrology, earth observation, etc.
AHPPE (Advanced High Precision Position Encoder) aimed at initiating the development of a new generation of position encoder for spaceborne applications based on CSEM technology and to transfer the technology to the industrial partner Micos. The encoder technology allows absolute position determination along multiple axes for either translation or rotation sensing with high resolution (10 nm and 1 urad or better, respectively) and wide dynamic ranges. The sensing technology allows for compact encoders and the capability to separate between measured object and measuring sensor (target deporting).

The space market segment targeted is that of space applications dealing with high accuracy angular positioning or tilt adjustment systems. Scientific and operational space missions targeting high quality products are constantly pushing for performance improvement. Nowadays, high accuracy encoders available on European space market mainly deliver information along a single Degree of Freedom (DOF); multiple DOF detection is achieved by combination of multiple encoder units. Other manufacturers realize measuring systems sensing up to 6 DOF for rigid body tracking, but with limited accuracy. The main space applications targeted for the new generation encoders are high accuracy position sensors for scientific experiments, robotics (all movements and tactility sensing), ground support equipment, micro-acceleration sensor for satellite static acceleration, ionic propulsion, control loop, solar array drive mechanism and antenna positioning. The identified space related applications and requirements have been flown down to the project scope defining a target mission scenario and application.

The core of the technology is based on the absolute position sensing technology, referred as “shadow imaging” and being already deployed in Earthly applications. It is based on the shadow projection of optical gratings equipped with dedicated patterns and illuminated by LEDs light (Figure 1 and 2) on image sensor arrays and algorithms that process the data collected to determine the absolute position information with instrumental resolutions down to 10 nm (1 urad respectively) or better. Shadow imaging is without front optic and permits compact design, system simplification and cost reduction. In addition, the processing deployed has a low susceptibility to possible grating manufacturing inaccuracies. Depending on the arrangement of core elements, position encoders sensitive along one or more DOF can be manufactured (e.g. Figure 2). Encoders customization serving different tailored purposes are within the potentials of this technology.
High integration density can be achieved using System on Chip (SoC), such as the CSEM “Iycam”, dedicated to image acquisition and processing. The Iycam is the platform destined to host the AHPPE products in the future, with sample output rates from 100 Hz for 6 DOF sensing up to 5 kHz for 1 DOF sensing. To achieve space product compatibility, the Iycam packaging concept has been completely reviewed during the activity. Space industrial design aspects accounted were the selection of space compatible materials and the numerous electronic components, manufacturing processes and quality (e.g. contamination aspects). System implementation with opto-ASIC (Application Specific Integrated Circuit) has proved that sampling frequency of such an encoder may reach 100 kHz.

A functional demonstrator has been designed and tested to verify the attainable metrological encoder performances and investigation of methods to improve them. The functional demonstrator (Figure 3) aimed at simulating a high accuracy angular positioning system while deploying two encoder concepts. The Space Encoder aimed at demonstrating deporting capabilities, with circa 15 cm between target and detection, while the second concept applied a more traditional (Rotary Encoder) approach. In particular, the Rotary Encoder accounts for 6.3 million increments, allowing a nominal resolution of 0.99 urad per increment. The encoder technology is valued to present metrological performances of excellence, with 0.36 urad (2σ) uncertainty for the Rotary Encoder and down to 2.4 urad (2σ) for the Space Encoder. The linearity – 0.2% (2σ) over a 20 mrad (1.1°) measuring range – can be improved with a revision of the calibration approach, whereas in absolute terms it is envisaged to stay constant even for extended measuring ranges. The Space Encoder can operate with less stringent light conditions, at the cost of coarser performances. An environmental demonstrator has been designed and tested to verify the stability of the performances with the reviewed Iycam design. The environmental demonstrator has been successfully exposed to a selected set of environmental tests based on the envisaged mission scenario, providing accurate improvement specifications for the next development steps on the Iycam design.

Based on the actual development stage, it is valued that the AHPPE encoder technology for space application has fully reached TRL 4. Our new encoder technology is looking forward to jump into space!
Reaction Sphere

Several years ago, the European Space Agency (ESA) commissioned CSEM to design, build and prove the feasibility of a new momentum exchange device for satellite Attitude and Orbit Control Systems (AOCSs). The proposed approach is to use a single Reaction Sphere held in position by magnetic levitation as an alternative to traditional reaction wheels or control moment gyro approaches. The sphere can be accelerated in any direction by a three dimensional synchronous motor based on a magnetic bearing that makes all the three orthogonal axes of the spacecraft controllable by just a single device.

CSEM’s first laboratory prototype of a Reaction Sphere was based on a configuration of twenty stator poles (coreless coils), corresponding to the vertices of a regular dodecahedron. The associated rotor comprises eight poles, created using a mosaic of 728 cylindrical magnets so as to obtain a smooth flux distribution. This prototype was manufactured to validate force and torque analytical models and an open-loop control strategy.

Reaction Sphere rotor optimization

In the frame of the Swiss Space Office (SSO) initiative to foster and promote Swiss scientific and technological competencies related to space activities, call 2010, CSEM teamed with maxon motor to develop an optimized rotor for the reaction sphere actuator. The aim was to increase its robustness with regard to both magnetic and mechanical aspects. The new rotor design consists of eight solid permanent magnet poles shaped as a cut section of a sphere. They are parallel magnetized and adjusted on the back-iron structure, which is shaped as an octahedron. Several design architectures were investigated to maximize the strength of the rotor magnetic flux density while minimizing its distortion and the rotor mass. The design optimization relied on extensive finite element 3D simulations performed using COMSOL Multiphysics.

Results

The optimized spherical rotor has been manufactured and experimental measurements have shown a strong correlation with specified magnetic flux density values. Full system tests with the new optimized rotor are in progress.

Market potential

European organizations working in the aeronautical and aerospace domains have confirmed their interest in CSEM’s Reaction Sphere for strategic applications in the telecommunications, earth observation and low-orbit metrology areas.

References


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Generation of Digital Elevation Models by Fusion of Optical Stereo and SAR Interferometry Techniques

DEMFuse

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The focus of this project has been the integration of Optical and SAR technologies based on spaceborne sensors, aiming at the generation of very accurate Digital Elevation Models and exploiting the advantages of both techniques. The proposed methods can be easily extended to airborne sensors, possibly including other DEM generation technologies like Airborne Laser Scanning and map contour digitization.

The study focused on two main topics to perform the mentioned integration:

- Fusion of DEMs obtained from stereo-optical and interferometric techniques. Both mentioned techniques, although established since several years for the generation of DEMs exploiting data obtained from spaceborne platforms, cannot be considered separately as solutions accurate enough for every type of topographic relief and land cover. Vice-versa, each of them suffers from limitations that in many cases do not allow to obtain accurate results without the integration of other information: nevertheless, many of the problematic areas for one of these technologies can be very often covered with the other one to a high level of success. Hence, the smart combination of DEMs obtained from the two technologies allows to obtain fused DEMs that may provide higher accuracy and less blunders in almost every land cover and topography conditions, exploiting complementarities of the technologies and not just considering them as mere alternatives.

- Automatic estimation of Ground Control Points (GCPs) through matching of optical imagery with already geocoded SAR images. Due to the precision of orbital information in currently available spaceborne SAR systems and to the peculiar characterization of the localization of such data through the corresponding Range and Doppler equations, their precise geolocation is possible without the need of manual measurement of GCPs. On the other hand, due to the higher sensitivity of optical imagery to the precision of orbit and especially attitude information, their precise geolocation is still not possible without GCPs. The fusion of the two technologies through optical-SAR image matching shall allow the automatic measurement of GCPs in optical images and their automatic geolocation, hence providing many advantages in the affordable generation of high accuracy DEMs. Furthermore, the optical-SAR matching can be used for other applications like automatic co-registration of optical and SAR images, e.g. for fast post-disaster mapping.

The developed fusion methodology has been implemented within an operational COTS satellite imagery processing chain, SARscape®, that already includes two dedicated modules for the generation of Digital Elevation Models based on SAR Interferometry and on Optical Stereo matching, resulting in a commercial software product that can fuse the best of the two technologies.
Left column: PALSAR DEM, a-priori quality map, difference with reference DEM
Middle column: SPOT DEM, a-priori quality map, difference with reference DEM
Right column: Fused SAR+Optical DEM, reference DEM, difference of fused with reference DEM

From left to right: Radarsat-1 image, Landsat-7 image, Radarsat-1 and Landsat-7 edges (used in matching) with the 100 best match points (red) and the best match points in tiles that were empty (green). Here, 3 x 3 image tiles were used.

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Terrestrial Ku-band measurements for space applications

Satellite SAR (Synthetic Aperture Radar) has been extensively used for land use mapping and ground-motion monitoring with good success. While traditional SAR sensors operate at L- and C-band, recent sensors operate in X-band and the mission candidate CoReH20 is designed to operate at X- and Ku-band. As a consequence, there is an identified need for Ku-band terrestrial target measurements to better understand wave-target interaction.

The GPRI project

The aim of the Swiss Space GPRI project led by GAMMA Remote Sensing in collaboration with ETHZ and associate partner Terrarsense Switzerland AG, was to address these needs by developing and testing dedicated hard- and software. Four tasks were identified:

1) development of a terrestrial radar interferometer based on the GAMMA GPRI prototype,
2) development of instrument software
3) development of post-processing software
4) implementation of dedicated field campaigns (validation and proof of concept).

Instrument development

The GPRI (see figure beside) is a portable multi-mode real aperture FM-CW radar operating at 17.1-17.3 GHz (Ku-band) using one transmit and two receiving antennas. The instrument is fully coherent and suitable for backscatter observations and interferometric measurements to determine target motion. In addition, the dual antenna configuration allows measurement of a terrain surface hull (i.e. DTM). The instrument has an operational range from 20 meters to 10 km, and can operate autonomously in the field. The design allows for quick setup and conducts a 360 degree scan in 30 seconds. Post processing software was developed for radiometric data calibration, interferometric analysis, data visualization and exchange. Integration of the derived information layers into a terrain point cloud and terrestrial photos was crucial for client-acceptance of the product. The developed post processing procedures are generic and can also be used for satellite data.

Conducted campaigns

Several measurement campaigns were successfully conducted where different targets such as an ice glacier, rock glacier, unstable rock slopes, bridge vibrations, flowing river, and corner reflector displacements were investigated. For several targets joint satellite data (Cosmo, TerraSAR-X and Radarsat-2) were available through the FP7 project DORIS. The campaign results and processing techniques developed showed the potential of the GPRI instrument for measuring displacements ranging between meters/sec to millimeters/year.

Main Achievements

Development of a completely new portable radar interferometer was possible with the support of the Space Office project. The real aperture based technology competes well with existing terrestrial radars, which
either utilize synthetic aperture or point-wise scanning techniques. The GPRI is market competitive, and brings the potential for new applications. In comparison to existing instruments, the advantages of GPRI lay in its portability (setup at virtually any location), fast image acquisition (seconds rather than minutes), lack of defocussing when imaging moving targets, reduced setup/takedown time, and large operational range. Data visualization through the fusion of radar images (derived from terrestrial and space), photogrammetry and lidar is an additional achievement of the project (see Aletschwald figure on the right). Due to its ease-of-use in field campaigns, the overall service pricing is competitive. While the GPRI is presently more expensive than SAR-based radars, it is significantly more cost competitive than point-wise scanning radars on the market.

Success and Impact

The success of the project is reflected by the scientific and economic impact. In particular there is a strong relevance for space applications. The instrument has already been allocated to conduct measurements in the context of the upcoming ESA CoReH20 activities and EU FP7 DORIS (services based on satellite and terrestrial radar). Instruments have been ordered by universities and a commercial company is testing the equipment for mining applications.

The commercialization of services related to the GPRI is the key business of an ETH spin-off company, Terrarsense Switzerland AG. The spin-off uniquely focuses on developing service products that combine spatial displacement monitoring, with expert geological/geotechnical know-how, particularly in the natural hazards domain. Between Gamma RS and Terrarsense commercial services have been conducted for communities, Cantons, SBB, ASTRA, TransitGas and BAFU.

Within the FP7 GIONET project a PhD student located at GAMMA is investigating the joint use of very high resolution satellite SAR and the GPRI.

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TENCIA-1
RF MODULE FOR SPACE-BORNE
GNSS RECEIVERS

The TENCIA-1 Project
The objective of the project was the development of a prototype of a future space qualified multichannel RF module for an on-board GNSS receiver, with its validation environment (digital subsystem, related software procedures, analysis and validation methods):

- manufacturing and testing of several test boards as well as the design and layout of an elegant breadboard for the RF subsystem;
- realization of a digital subsystem integrating signal filtering and conditioning functional blocks for pre-processing of the signals prior to sending it to a host computer for analysis;
- computer application for initializing the RF module, monitor data transfer, log and process data in real time or after their storage.

Required signal processing functionalities:

- programmable fractional sample rate conversion;
- data-path gain and DC-offset control;
- programmable stream resolution control.

In order to better monitor and optimize the operation of both the RF subsystem and digital data-path, some signal distribution measurement blocks have been added to the digital subsystem. Monitoring of the signal distribution at the different stages of the processing pipeline is required in order to optimally control the different data-path gains and the other conditioning parameters (RF AGC, digital data-path gains and the DC-offset cancellation parameters).

The RF Subsystem
RF down-converter section main characteristics:

- up to 4 channel RF front-end for the GNSS L1/E1, L2, L5/E5a and E5b bands;
- each channel implemented using the Saphyrion’s space qualified chipset consisting of SY1007R (RF down-converter ASIC) and SY1017C (AD/DA and interface ASIC);
- RF channels input: 50Ω SMA connectors;
- near base-band quadrature outputs: converted to digital (3-bit resolution) and delivered to the digital signal processing subsystem;
- target of the study: whole RF down-converter section designed on a single PCB.

Digital Subsystem
It consists of equipment able to capture up to 4 digitized GNSS streams (3 bit I/Q) from the RF board and store them on a computer hard disk.

The developed solution provides support for:

- simultaneous 4 channel “raw” or “preprocessed” stream capture and transfer (including a significant stream buffering capability to overcome the various system access latencies and delays);
- signal conditioning functionality such as DC cancellation, data path gain control, stream re-quantization, programmable fractional N sample rate conversion;
- RF board configuration and control by means of an SPI like interface.
The digital subsystem has been implemented on an XpressV6-550 development board from PLDA with Virtex-6 XC6VLX550T FPGA and a PCIe 2.0 compliant endpoint interface.

Measured data throughput: above 215MB/s (measured from the V6-550 board to a 7200 RPM RAID 0 storage).

**The TENCIA-1 Application Software**

Starting from a prior existing development framework, a specific software application was developed with the following functionalities:

- **Hardware configuration:** allow initializing all hardware components, prior and during the stream capturing session.
- **Testing:** real time signal histograms and spectrum charts allow direct verification of the quality of the down-converted GNSS signals. It also allows fine tuning the system (e.g. adjusting all signal gains).

- **Data logging:** the captured data are saved in a file (for multi-channel operation, RAID-0 storage is recommended for performance reasons).
- **Data splitting:** data in the logged file can then be split to obtain one file for each captured signal for post-processing and analysis purposes (e.g. using MATLAB or GNSS software receiver environments).

**Conclusions**

The project resulted in an elegant RF front-end breadboard and digital subsystem with the controlling software application. To date, intense testing sessions allowed refining the digital system to a valid prototyping and signal study platform. Deep characterization and fine tuning of the RF system is ongoing with the objective to achieve an optimized design, ready to be validated for a final flight model. The realized system represents an important development environment for the future GNSS RF boards Saphyrion intends to develop. The TENCIA-1 activity gave Saphyrion the opportunity to win expertise for the design of space-borne RF and analogue systems. Saphyrion had the chance to reinforce cooperation and synergies with an academic partner. ALaRI acquired expertise in the design of signal processing solutions for the GNSS domain.

**Reference Documents**

SY1007 GNSS RF Front End, Preliminary information, Literature Number DS-SY1007, Rev. 1.1, Saphyrion Sagl, 25 November 2009.

SY1017 AD/DA Converter, PLL, Preliminary information, Literature number: DS-SY1017, Rev. 1.1, Saphyrion Sagl, 20 November 2009.

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Contactless Power and Data Transfer

Introduction:

The Contactless Power and Data Transfer is composed of two single channels, one for up to 200 W power transfer and one for up to 1 Mbit/s data transfer between two mechanical rotating parts of a mechanism.

Technical overview:
Both channels are based on magnetic technology. The block diagrams are represented hereunder:

The power transfer uses a magnetic core transformer and two DC/DC switching converters.

The data transfer uses a coreless transformer and two line drivers. A communication protocol permits the half-duplex transfer. Without protocol the present hardware can be used as a rotating single galvanic insulated link.

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<td>Max. Power</td>
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<td>Input voltage</td>
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<tr>
<td>Output voltage</td>
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<tr>
<td>Efficiency</td>
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<td>Duty-cycle</td>
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<tr>
<td>BER</td>
<td>&lt; 10^-9</td>
<td>-</td>
<td>@ 1 Mbit/s</td>
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<td>Interfaces</td>
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<td>Half-Duplex</td>
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<td>Including electronics</td>
</tr>
<tr>
<td>Data transfer weight</td>
<td>&lt; 0.1</td>
<td>kg</td>
<td>Including electronics</td>
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<tr>
<td>External diameter</td>
<td>&lt; 85</td>
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**Design presentation:**
The power transfer is composed of a power transformer, a primary side electronic PCB and a secondary side electronic PCB.

The data transfer is composed of two PCBs including the electronic components.

**Complete prototype demonstrator:**
A demonstrator has been developed and manufactured. It includes both power and data transfers, an additional slipring and a motor. The additional slipring brings back the rotor side signals to the stator side permitting by the way easy tests measurements.
Floating point Operation Controller IP core for Space application (FOCS)

Project Description
FOCS Project is a partnership between SYDERAL, EPFL-IMT institute and EPFL-LSM Laboratory.
Partners responsibilities were shared as follow :

SYDERAL :
- Project Office
- FOCS requirements specification
- FOCS Design final test on HW target

EPFL-IMT :
- FOCS Feasibility Study and Trade-Off
- FOCS Design Implementation

EPFL-LSM :
- FOCS IP verification using Verilog and OVM.

Development plan was planned as follow :

Reviews definition:
- RR : Requirement Review
- ADR : Architectural Design Review
- CR : Coding Review
- DDR. Detailed Design Review
- FR: Final Review
- MTR. Mid Term Review

FOCS Applications
- High accuracy / complex mechanism control
- High accuracy thermal control
- Mathematical co-processor (For LEON or ERC32 processors)

FOCS Overall Description
The MBFOCS is a 32-bit general-purpose processor, compatible in a large extend with the Microblaze instruction set, and equipped with a hardware execution unit implementing hardware multiplications (32 x 32 bit), hardware barrel shifts (on 32 bit) and hardware floating-point operations on 32-bit numbers following the IEEE754 standard. The supported FPU instructions are addition, subtraction, multiplication, division, square root, comparison (7 types), float to integer and integer to float conversions.

Main Characteristics
- IEEE 754 Standard Compliant
- Supported operations are addition, subtraction, multiplication, division, square root, comparison (7 types), float to integer and integer to float conversions.
- FPGA technology independent
- Verified at 50MHz on a Spartan 3E FPGA

Main Advantages
- Basic Debugging Capabilities
- Provide the Final User with simulation capabilities within the early development phase
Floating point Operation Controller IP core for Space application (FOCS)

**FOCS Design**

**FPU Architecture:**

- Based on FPU100 which is an IEEE754 compatible, open-source FP unit available on www.opencores.org
- Completely re-engineered to fit the needs of the FOCS project, because it is much too big to fit into the desired hardware target (40% ACTEL RTAX-1000).

**MB-Lite Architecture:**

- The MB-lite, is a clone of the Microblaze processor, which needed modification to receive the execfocs new execution unit.
- 5-stage pipeline, with fetch, decode, execute, memory write

**FOCS Verification**

- Simulation-based
- Modern verification technology and tools
  - SystemVerilog hardware modeling and verification language (IEEE 1800-2009)
  - Open Verification Methodology (OVM)
  - SystemVerilog class library 2.1.1
  - Mentor Graphics Questa simulator version 10.0a
- Modern verification strategy
  - Constrained-random stimulus
  - Functional coverage
  - Layered virtual testbench

**FOCS Test on HW**

- IIR Filter implemented:
Gravity Gradient Earth Sensor

Earth Sensors have been traditionally used as main attitude sensor for Earth pointing missions. Currently, they are typically of relatively high accuracy and expensive. The development of a low cost coarse Earth sensor is therefore of interest for the prime satellite manufacturers. It will allow them to decrease the recurrent cost of the AOCS or to offer, at low cost, a backup for the increasingly used and more accurate star trackers.

Indeed, even where star trackers are the main attitude sensor on-board, there are still many conditions in which a direct measurement of the Earth vector would greatly ease the AOCS design. These needs demand only low accuracy and, due to their transitory nature of use, it would also require the sensor to be of low cost.

ESA has already started activities to promote the development of such devices and feasibility studies have been conducted under TRP and ARTES programs. One of these studies has been carried out by EPFL Lausanne (under ESA contract #20267) with the support of RUAG Space.

This study concentrates on a novel micro-machined Earth sensor based on the detection of the gravity gradient. As this concept does not require optical access it is considered very promising in view of meeting mass, power consumption, ease of accommodation size and cost requirements.

The activities herein presented have been carried out by EPFL-LMTS and RUAG Space, Zürich with support from Astrium, Friedrichshafen.

Part 1 reviews various Earth Sensor technologies and concludes that Gravity Gradient Earth Sensors using this technology are not currently available, but that they would be an attractive solution to satellite providers who need to provide coarse resolution pointing information for the satellite's attitude control system. It also summarizes the the main/key requirements for such a device, taking already known boundary conditions into account.

Part 2 provides the Design, Micro-fabrication and Testing Reports for a MEMS sensor that is sensitive to the Earth’s Gravity Gradient effect.

MEMS structures are in regular use in commercial applications that require small and robust sensors such as accelerometers and pressure sensors. However the typical accelerometer design used in these applications are not sensitive enough to be used directly as an Earth Sensor.

Normal MEMS structures are designed to be as small as possible, but because of the very small gravity gradient at typical satellite low Earth orbits, the forces on the pendulum sensor are also very small. In order to amplify this effect the length of the pendulum needs to be as long as possible. This leads to a design that is unusual for a MEMS structure in that the substrate is measured in centimetres (~5cmx1cm) while the pendulum movement is still measured in microns.

To avoid manufacturing problems associated with the unusual structure, the design has been optimised to reduce the effects of manufacturing tolerances on the sensor performance and to make the sensor robust enough to survive the loads experienced during launch.

Testing of such a sensitive structure in a 1G environment, when it is designed to operate in microgravity, is also a challenge and has required the design of special test equipment that will have to be further developed to provide final product GSE.

Part 4 provides a baseline design for a GGES instrument using the pendulum MEMS sensors. The inherent 180° periodicity of the pendulum sensor further increases complexity, with multiple sensors required in specific orientations to each other in order to unambiguously determine the Earth Nadir vector. This also increases the amount of front end electronics required to convert the sensor’s capacitive outputs into digital values.

Electronic processing of the signals from the GGES sensors requires high resolution front end electronics (24 bit Δ-Σ capacitance to digital converters). These parts are not available as radiation hardened components and therefore the use of COTS parts has been adopted for the characterisation of the MEMS sensors and for the proof of concept phase of the project.
Constructional analysis and radiation testing of these parts will be required in future phases of the instrument development.

If the COTS parts prove to be unsuitable, a dedicated mixed signal ASIC development will be required to achieve the performance, mass and power requirements.

The conceptual design of the digital controller is based on an Actel FPGA. The FPGA provides the data processing of the sensor signals, the Earth vector calculation, the external communications to the satellite and also provides feedback controllers for the pendulum sensors in order to damp their response and increase readout rate.

Preliminary Error, Mass & Power budgets are provided, based on the proposed design.

PART 4 also provides a Further Development Plan for design activities involved with developing a GGES instrument.
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