

## Digital electronics for electrostatic accelerometers interest for high resolution and in-orbit calibration

V. JOSSELIN, E. WILLEMENOT and P. TOUBOUL

*Office National d'Études et de Recherches Aérospatiales, Châtillon, France*

(Received October 4, 1998; accepted August 5, 1999)

**Abstract.** The new ultra-sensitive space accelerometers to come are designed to demonstrate a level of noise below  $10^{-12} \text{ m s}^{-2} / \sqrt{\text{Hz}}$ . This performance requires in-orbit calibration. For example, calibration consists in proof mass fine positioning and scale factor measurement. Working out these tasks of calibration is more relevant to digital electronics than to the present analog ones. The challenge for such a substitution is to preserve the wide dynamic of electrostatic accelerometers, and so maintain the performance calculated for the present, purely analog design. A prototype has been developed and tested at ONERA and the results are discussed here in terms of constraints upon calibration.

### 1. Introduction: limitations of the ground tests

The new generation of accelerometers is designed to achieve resolutions in the pico-g range. A dedicated pendulum bench has been developed at ONERA (Gay et al., 1992), to operate space accelerometers in the laboratory on ground "as if" they were in orbit. Those tests, coupled with the ones carried out at the ZARM free-fall tower in Bremen, have resulted in the qualification of two space accelerometers, ASTRE for the MSL mission flown in 1996-97 on board the space shuttle, and STAR devoted to the CHAMP mission, planned to be launched in October 1999 (Touboul and Foulon, 1996; Touboul et al., 1998a).

The pendulum bench exhibits a residual vibration noise of a few  $10^{-9} \text{ m s}^{-2} / \sqrt{\text{Hz}}$  along the horizontal axes, for frequencies lower than 1 Hz. The test limitations are caused by the residual seismic noise and the couplings between the 1 g vertical acceleration and the horizontal axes. The performance of the pendulum bench is compatible with the objectives of the ASTRE and STAR accelerometers, i.e., a working range extending from the milli-g to parts of nano-g.

The requirements of the space missions GOCE (GOCE Study Team, 1996), miniSTEP

---

Corresponding author: P. Touboul, Deputy Director of Physics, Instrumentation and Sensing Department; ONERA, BP 72, 92322 Châtillon Cedex, France; phone: +33-1-46-73 48 32; fax: +33-1-46-73 48 24; e-mail: touboul@onera.fr

(MinSTEP Study Team, 1997) and LISA (LISA Study Team, 1998), are, in terms of acceleration resolution, far below the nano-g range. The common specifications of these missions are a very high resolution from  $10^{-12} \text{ m s}^{-2} / \sqrt{\text{Hz}}$  to  $10^{-15} \text{ m s}^{-2} / \sqrt{\text{Hz}}$ , the requirement on the matching of the accelerometer characteristics and the feasibility of drag-free satellites. The ground tests are not able to ensure the full performance of this new generation of accelerometers. Tests and calibrations have thus to be refined in orbit. The tasks involved in calibration operations are, for instance, proof-mass centering, scale factor measurement, dynamic behavior measurement, parasitic stiffness measurement and damping measurement. These operations require calculation facilities in order to process calibration data and to feed the accelerometer control laws with these results. The accelerometer shall therefore get “smarter” to match these operational requirements. A digital control is more likely to perform such operations, rather than a purely analog correcting network.

A prototype of digital controller is currently under design at ONERA. The architecture is compatible with the interface requirements of the micro-satellite ODIE (Orbiting Drag-free International Explorer). This mission is devoted to the demonstration of the relevance of the technologies employed to realize a drag-compensated satellite for the observation of gravitational waves (ODIE web site, 1998). Obviously, the demonstration, in orbit, of such a drag-free spacecraft will be a major step for future gradiometry geodesy missions.

## 2. Controller architecture

The operation of electrostatic space accelerometers for which the digital electronics has been developed is presented in the proceedings of the IGC/IGeC conference (Touboul et al., 1998b). The sensor electrical configuration is, seen from the controller, a Multiple Input, Multiple Output (MIMO) system. The controller has to handle the 6 degrees of freedom of the mass through the capacitive sensors, has to control, by electrostatic actuators, these degrees according to the satellite operation, has to process the position and the acceleration available data, and has to communicate with the satellite computer for the TeleMetry/TeleComands (TM/TC). The sensor operation bandwidth is a few hertz.

The heavy computational load, the specific type of software (mostly filtering operations), and low-power, volume requirements make it worth the use of a Digital Signal Processor (DSP). Communications between the DSP and the converters are based on a serial bus. It is a Printed Circuit Board (PCB) area-cost effective solution for this multi-converter design. The sampling frequency of the converters, a few hundreds of hertz, does not require a parallel 8 or 16 bit bus. The serial bus is managed by a Field Programmable Gate Array (FPGA). The interface can either be a MIL1553 bus or an RS422. The bootstrap program (stored in non-volatile memory) determines whether the DSP loads the program stored in EEPROM in RAM and runs it or downloads to the EEPROM an updated (earth telecomands) program via either the MIL1553 bus or the RS422. Analog to Digital (ADC) and Digital to Analog (DAC) converters are serially linked to the DSP.

### 3. First results on the prototype

The digital controller has been designed to pass the performance specifications and not to alter the sensitivity of the instrument. The realization of the electronics does not require any breakthrough in the technology to be completed. The major elements of such a controller have been already tested in closed loop and a complete prototype is being designed and realized. A degree of freedom has been, successfully, digitally controlled on an accelerometer this year. Considering the accelerometer core geometry envisaged for the GOCE mission, the resolution of the capacitive sensor corresponds, in terms of proof-mass displacements, to  $5 \text{ pm} / \sqrt{\text{Hz}}$ . This resolution has been preserved in this new electronics configuration; the control law exploits it to maintain the mass motionless and to determine the acceleration of the sensor.

The control of the six degrees of freedom requires further developments that are in progress. The software development to handle the control of the six axes is also ongoing: it is basically made of two layers, one for the I/O operations and one for the control laws and the calibration operations. The possibility offered by this new electrical configuration to modify the frequency behavior of the control law has been tested. For instance, the damping factor of the corrector can be progressively reduced from the nominal value of  $\sqrt{2} / 2$ , to a very weak one of a few  $10^{-3}$ . Besides the interest of verifying the frequency response of the instrument, the “cold” damping obtained with this electrostatic loop can be established to the benefit of the resolution demonstration. Another interest is the capability to adjust a correct transfer function of the instrument in order to obtain the sensitivity needed for the accelerometers mounted on the gradiometer for the gravity missions. Gains can be adjusted at low frequencies, lower than 1 Hz, with a  $10^{-5}$  accuracy and a phase shift difference limited to  $10^{-5}$  rad in the same bandwidth.

### 4. Conclusion

The essential limitations of the ground testing in the nano-g range are not compatible with the objectives of the new missions involving accelerometers. In orbit calibrations must outperform these limited ground tests. To fulfill these operational requirements, a new family of digitally controlled accelerometers is planned to be substituted to the present, purely analog, accelerometers. A prototype has been defined and tested: it constitutes a baseline for the configurations of accelerometers and inertial sensors dedicated to geodesy missions like GOCE, and also to gravitational wave missions. It has been successfully tested on a model accelerometer, along one degree of freedom. In the near future, these electronics will be fully developed and optimised for the accelerometers which are being proposed to constitute the sensing elements of the gradiometer - the major scientific payload of the envisaged GOCE mission.

## References

- Gay M., Foulon B. and Canny J. P.; 1992: *Accéléromètre GRADIO : Amélioration des performances du banc d'essai pendule et développement des moyens de test des détecteurs capacitifs*. Technical Report ONERA RF44/6114PY.
- GOCE Study Team; 1996: *Assessment report of the Gravity field and Ocean Circulation Mission*. ESA SP-1196 (1).
- LISA Study Team; 1998: *Pre-Phase A report*. Edited by K. Danzmann.
- MiniSTEP Study Team; 1997: NASA research announcement NRA-96-HEDS-03 (Submittal).
- ODIE web site; 1998: for a more detailed description of the ODIE mission visit <http://ssdl-pegasus.stanford.edu/dragfree/intro.html> maintained by A. Floyd.
- Touboul P. and Foulon B.; 1996: *ASTRE Accelerometer: Verification tests in drop tower Bremen*. In: Proceedings of Drop Tower Days in Bremen.
- Touboul P., Foulon B. and Le Clerc G. M.; 1998a: *STAR, the accelerometer of the geodesic mission CHAMP*. IAF Symposium.
- Touboul P., Willemenot E., Foulon B. and Josselin V.; 1998b: *Accelerometers for CHAMP, GRACE and GOCE: synergy and evolutions*. IGC/IGeC Conference Proceedings (to be published).