International Conference on Space Optics—ICSO 2014

La Caleta, Tenerife, Canary Islands

7–10 October 2014

Edited by Zoran Sodnik, Bruno Cugny, and Nikos Karafolas

Interferometer scanning mechanisms and metrology at ABB: recent developments and future perspectives

Frédéric Grandmont

Henry Buijs

Julie Mandar

esa icso proceedings cnes

International Conference on Space Optics — ICSO 2014, edited by Zoran Sodnik, Nikos Karafolas,
Bruno Cugny, Proc. of SPIE Vol. 10563, 105633X · © 2014 ESA and CNES
CCC code: 0277-786X/17/$18 · doi: 10.1117/12.2304165

INTERFEROMETER SCANNING MECHANISMS & METROLOGY AT ABB, RECENT DEVELOPMENTS AND FUTURE PERSPECTIVES

Frederic Grandmont[1], Henry Buijs[1], Julie Mandar[1]
[1]*ABB Canada, Canada.*

INTRODUCTION

Interferometers are devices meant to create an interference pattern between photons emitted from a given target of interest. In most cases, this interference pattern must be scanned over time or space to reveal useful information about the target (ex.: radiance spectra or a star diameter). This scanning is typically achieved by moving mirrors at a precision a few orders of magnitude smaller than the wavelength under study. This sometimes leads to mechanism requirements of especially high dynamic range equivalent to 30 bits or more (ex. Sub-nanometer precision over stoke of tens of cms for spectroscopy or tens of meters for astronomical spatial interferometry). On top of this mechanical challenge, the servo control of the mirror position involves obtaining relative distance measurement between distant optical elements with similar if not better dynamic range. The feedback information for such servo-control loop is usually the optical path difference (OPD) measured with a metrology laser beam injected in the interferometer. Over the years since the establishement of the Fourier Transform Spectrometers (FTS) in the 60's as a standard spectroscopic tools, many different approaches have been used to accomplish this task. When it comes to space however, not all approaches are successful. The design challenge can be viewed as analogous to that of scene scanning modules with the exception that the sensitivity and precision are much finer. These mechanisms must move freely to allow fine corrections while remaining stiff to reject external perturbations with frequencies outside of the servo control system reach. Space also brings the additional challenges of implementing as much redundancy as possible and offering protection during launch for these sub-systems viewed as critical single point failures of the payloads they serve.

I. The Early Days

Interferometer-based FTS technology quickly established itself as the ideal tool to reach very high spectral resolution. With meter-long longitudinal scanning mechanisms, commercial interferometers achieved spectra with richness in excess of 1 000 000 spectral elements in the early 80's. These instruments pioneered by ABB (formerly Bomem) opened up a new science field of experimental validation of knowledge and modeling of molecular properties in chemistry and physics laboratory around the world. These instruments used scanning mechanisms based on precision stainless steel rods and roller bearings as shown in Figure 1. One clever way of making these interferometers more robust to external environment perturbations was to scan relatively rapidly such that the observed temporal oscillations of the fringe pattern (visible or IR range) would move into the kHz range and could thus be easily distinguished and isolated from low frequency perturbation such as those caused by air turbulence or mechanical vibrations. These low frequency oscillations could be easily removed using high pass filters in detector amplification electronic such that they do not affect the measurement. Hence these interferometers were all scanned at constant speed with the science detector being sampled at tens of kHz. The challenge would then become that of stabilizing the speed in order to ensure the various delays in the detector electronic vs. that of the laser metrology channel triggering the sampling would not translate into position distortions between the two channel position scans. Such mechanisms were quite successful and some instruments are still in operation today some 30 years after installation without service on the mechanisms.

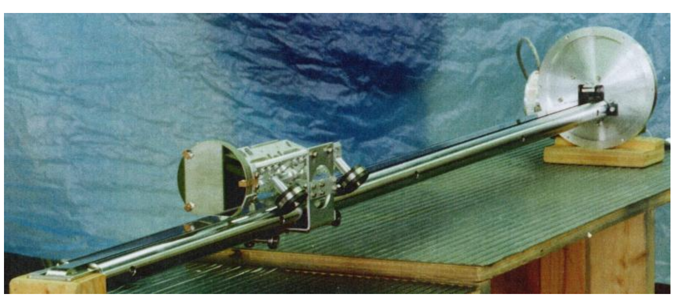

Fig. 1. Late 70's FTS 2 Meters Mirror Scan Mechanism

The constant and high speed scanning approach also greatly simplified the metrology electronics since the task of controlling the position is transferred into that of controlling the speed which is easily measured by monitoring the frequency of the interference pattern of the metrology signal (a sinus) or its reprocessed square wave signal sitting around the tens of kHz. A numerical fringe counter would be added to keep track of the absolute position and scan direction and thus great precision on optics position was achieved.

Smaller stroke derivative versions of these mechanisms have been used in space instruments (ex. AURA/TES, Envisat/MIPAS) but the lubricant of the bearing and the presence of friction always remains a concern in the absence of gravity and atmospheric pressure. Hence, the preference for friction-less scanning mechanism emerged naturally with systems dealing with lower spectral resolution. When the scan range gets in the cm regime, the use of flexure or flex bearings becomes possible with relatively compact assemblies without sacrificing the stiffness of the remaining 5 degrees of freedom. The next section discusses these mechanisms.

II. Past decade

Most interferometers operating today in space (Sisat/ACE-FTS, GOSAT/TANSO-FTS, Metop/IASI, NPP/CrIS) are based on frictionless flexure-based scanning mechanisms. Their optical stroke varies from 1 cm to 50 cm. Their architecture can be regrouped in two general categories:

1. Scan via angular rotation of a retro reflector located at the end of a lever arm (ACE, TANSO)
2. Parallelogram type translator (IASI, CrIS)

The first category is implemented with cube-corner type mirrors which reflection is insensitive to rotation of the cube in any orientation around its apex. The so-called double pendulum architecture used in ABB interferometers (ACE, TANSO) allows doubling the optical stroke by having two mirrors moving in opposite directions which creates a 4 to 1 optical vs. mechanical displacement ratio. The moving mass can also be balanced around a common centre of rotation by using the actuator as a counter weight. The ACE-FTS uses this interferometer configuration in double pass with the help of a mirror reflecting the exit beam back inside the interferometer. This brings the displacement ratio to 8:1 which maximises the scan range achievable with a flexure-based system such that the total optical displacement reaches up to half a meter in an interferometer footprint of about 30 cm square.

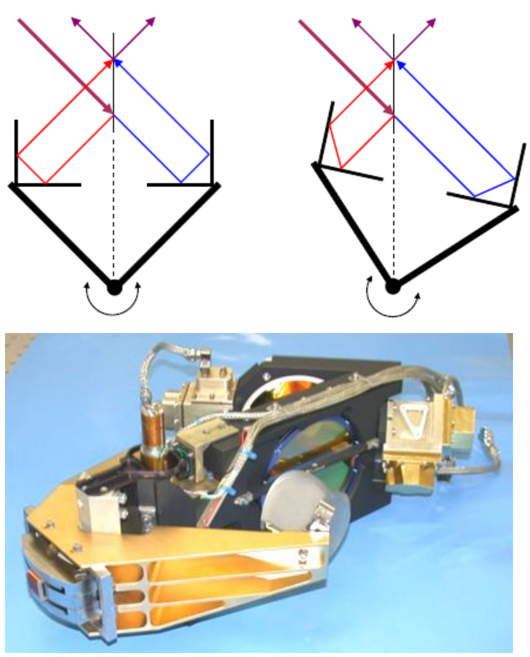

Fig. 2. Double Pendulum Rotary Scanner Concept (top), ACE-FTS Interferometer Showing Scan Arm in Yellow (bottom)

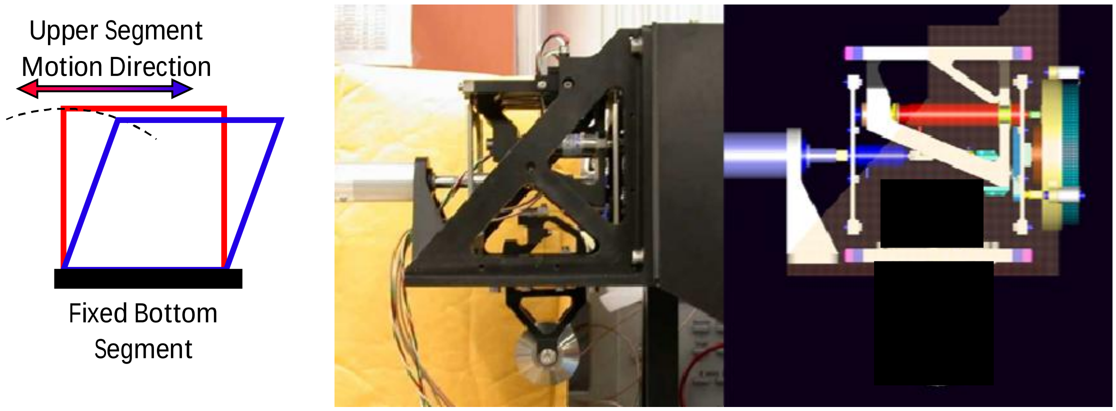

Fig. 3. Parallelogram Type Scanner

The second common architecture, the parallelogram scanner also referred to as a porch-swing in the CrIS literature typically controls a single mirror movement and thus was used in smaller spectral resolution instruments. The parallelogram mechanism is easiest implemented using a flat mirror since the motion theoretically induces no rotation and the reflection height is independent of the up/down transverse motion of the carriage. This is the approach used in CrIS. When the use of a cube corner mirror is desired, a second parallelogram is attached to the first one such that the sag motion oppose and the cube height is maintained through the scan. This results in a quasi-pure linear translation but a more complex mechanical arrangement. The motion can also be doubled for the same flex blade effort given that the two stages split the work in half. This architecture can use a cube corner as the mirror since it will not create beam shear during motion. It is the approach implemented in IASI. The use of cube corner can then compensated for the slight rotation encountered during the scan whereas the flat mirror system is ideally combined with a dynamical alignment system for maximising performance. In all cases, the parallelogram architecture results in a more complex and heavy interferometer as this system is separate from the optical bench holding all interferometer components together.

The legacy metrology system can be used as long as these scanners are operated at relatively high speed typically higher than 1 kHz fringe rate. However in the case of the CrIS interferometer which also requires dynamic alignment of its mirror throughout the scan, a more complex metrology system must measure the Optical Path Length (OPL) in multiple locations in the aperture to ensure it is constant across the science beam.

II. Metrology System Adaptation for Imaging FTS Configurations.

The shift from monopixel FTS system to array detectors is viewed by many in the field as the logical evolution of the FTS technology. As the cost of detector arrays drops (especially in the IR) and on-board processing electronics allows manipulation and downlink of GB size data cubes, imagery is steadily gaining ground in prospective FTS missions (MTG/IRS, PREMIER/IRLS, PCW/PHEOS). The division of the FTS FOV into much smaller detector elements often calls for longer integration time over the scene in order to maintain acceptable SNR on individual spatial element. Also the readout speed of array detectors often calls for a readout rate below the good old kHz lower speed limitation of former metrology systems. Hence, new approaches have been developed in which the speed servo has been dropped in favour of position servo in which the command calls for a linear increase. This typically marks the end of a simple analog servos and one must shift to a digital servos implemented in micro-controller or FPGA driven by a high speed clock which also dictate the rate at which the laser fringe signals are digitised. This digital approach allows for more complex processing of the metrology fringe and the possibility to perform step-scanning of the stroke without any degradation of the feedback signals which remains at a very high rate (> 1 kHz). The precision at which a longitudinal mirror position can be retrieved depends on the quality of the metrology electronics, the laser wavelength, its stability and the quality of the algorithm used to retrieve the position. Today’s commercial systems routinely achieve resolution below the nm level although at these scales everything moves so much that it becomes hard to obtain stable or noise free readings of optics separated by large distances. The correction on a drive mechanism must then implement some form of assumptions on what perturbation really needs to be corrected. Also, at these scales, the geometrical difference between the metrology beam and the science beam (beam waist, position within aperture, wavelength) sheds some additional doubt on the true value of the retrieved optical position. Nevertheless, nanometer-level precision is sufficient for many visible band observations.

III. Outlook for Future Systems

Recently ABB has developed a new purely transitional dual level flexure-based scanner that can be mounted around the mirror in order to leave a clear aperture in the centre. This system is based on a 12 flexure design which can be over constrained if not assembled properly. This compact mechanism was initially developed for SITELLE [2] a visible astronomical imaging FTS to be installed at the Canada-France-Hawaii telescope in 2015. It is used with a flat mirror and incorporates dynamic alignment (tip-tilt) capabilities. Unlike the classical parallelogram, this mechanism provides a similar angular stiffness in any orientation which is ideal when the gravity vector changes during operation. Indeed, while the parallelogram behave well in space, its mechanical arrangement is prone to misalignment under torsion on the upper stage applied in the vertical axis. The new mechanism has three sets of flex blades located at 120 degree interval around the moving cylinder. It does not suffer from the up/down motion of the parallelogram and will typically exhibit lower residual tilt through the scan. It can be used with a flat mirror or cube corner mirror and uses a limited space in periphery of the optics that can be centred inside the tube. This mechanism is an extension of very early mechanisms used successfully in space on several Nimbus satellites and thermal emission spectrometers (TES) on Mars missions and uses the same technology elements, modelling tools and manufacturing technique as the CrIS, ACE and TANSO-FTS sensor.

Fig. 4. Frictionless uni-axial linear scanner

More recently Canada was invited to contribute to the SAFARI instrument of the prospect ESA/JAXA SPICA mission. The Canadian contribution under study is the supply of the Imaging FTS scan mechanism and its metrology system. While this application targets relatively long wavelengths (> 30 um) some significant challenges are brought by the exceptionally high sensitivity of the observatory and the 4 Kelvin operation. These require improvements over legacy systems both on the mechanism and the metrology side. This mechanism shall use a novel scanning approach based on magnetic bearings. This approach which on the earth bears some levitation challenges is viewed as ideal for a zero gravity operation as the moving mass becomes essentially free floating. Once the mass is set in motion in the right direction by the actuator only subtle trajectory corrections are required on the magnetic bearings to keep the moving mass scanning in the right direction. In other words, the moving mirror orbit is modified slightly to generate a constant displacement with the rest of the spacecraft. This is truly the holy grail of frictionless scanning mechanisms and one that is bound to achieve a very long lifetime. ABB is currently studying the implementation of this sub-system in Canada and is engaged in discussions with Belgian delegates to combine their strength in magnetic bearings with that of Canada in FTS scan mechanisms. This effort builds on the previous steps done in the Netherlands [3]. Results of this study are expected in March 2015 and Technology Readiness Level improvement activities are expected to begin on prototype sub-assemblies in 2015.

Further out in the future, prospect missions in astronomical optical interferometry calls for metrology systems operating over still longer distances. Gravitational wave detection or aperture synthesis mission proposals demands highest possible position precision over hundreds of meters if not kilometres of distances. The quest for higher precision measurement systems is heading toward the use of frequency comb lasers which can break through the limitation of today's best metrology systems. ABB is involved in collaborative projects with the group of Dr. Jerôme Genest at Université Laval which specializes in the use of frequency combs systems for sensor applications. Merged with high power lasers these have the potential to gain orders of magnitude in detection precision as well as operate over very large distances.

The field of longitudinal scan mechanisms is also bound to evolve toward longer stroke systems in space. This evolution will likely be achieved by the use of free flyer or formation flying spacecraft equipped with multi-stage positioning mechanisms. The technology of the magnetic bearings studied for SAFARI project to offer proximity “free floater” scans is viewed as a logical complement to these future facilities.

IV. Summary

The use of interferometers in space is not showing any decline in the foreseeable future as confirmed by the advanced weather sounders in the works by leading space nations. Other earth observation payloads such as those used for greenhouse gas measurement are also considered to be turned into operational missions for generations to come. These systems will build on heritage technologies to reduce the risk as their spectral requirement do not call for significant performance improvements over past systems and their approval assumes low development risks. The SPICA/SAFARI opportunity calls for the use of new technologies set to bring the field to new levels of performance. Canadian scientists have stated their official interest in this mission and making it one of the highest priority projects for space astronomy beyond JWST. They are asking the Canadian Space Agency to provide hardware contributions to the mission in order to secure observing time on the telescope. The FTS scan mechanism and metrology system is the current prime candidate for a Canadian contribution for SAFARI.

REFERENCES

[1] K. I. K. Roussan, “High Resolution Infrared Spectroscopy of Allene -D4”, Thesis (PH.D.)--THE PENNSYLVANIA STATE UNIVERSITY, Dissertation Abstracts International, Volume: 44-01, 1983.

[2] F.Grandmont et al., “Final design of SITELLE, a wide-field imaging Fourier transform spectrometer for the Canada-France-Hawaii telescope” *Proceeding of the SPIE*, Astronomical Telescope & Instrumentation, 2012.

[3] T.C. van den Dool et al., “SPICA/SAFARI Cryogenic Magnetic bearing FTS Mechanism” *ICSO proceedings*, 2010.