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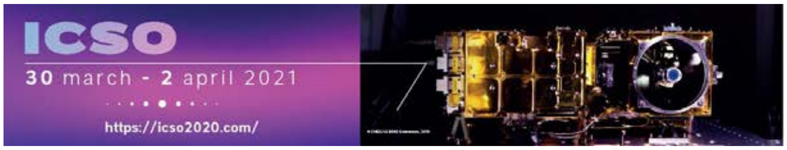

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Space Spectrograph Design for Calibration

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ABSTRACT

Recent societal demands in climate awareness call for rapid launch of space optical spectrographs, such as to be capable of putting state-of-the-art technology in short timeframe into orbit. As a consequence, it is of paramount importance to compress instruments' construction schedules down to the ultimately necessary need. Because calibration and characterization (C&C) partially takes place after full instrument assembly, it is de facto on the time-plan critical path, bearing antagonist requirements: measurement accuracy shall be guaranteed without jeopardizing the instrument delivery date. To solve this problem, Airbus has explored multiple paths in order to propose an instrument's "Design for Calibration": the method consists in integrating C&C at the very beginning of the instrument development in order to respond efficiently to the identified needs. First, all planned tests are exhaustively simulated and analyzed with tools validated before measurements, ensuring full control of the overall C&C throughout the entire lifecycle of the project. Next, Airbus strongly enforces its strategy of measuring relevant parameters as soon as they are accessible, hence providing early characterization out of the critical path. Then, the remaining parameters have been thoroughly analyzed to provide a lean optical ground support equipment (OGSE) architecture capable of responding to current challenges. Moreover, it enables full automation, enforcing its time-efficiency by minimizing overheads. Although rapidity is ensured, measurement accuracies are simultaneously kept compliant. Finally, this work presents also disruptive photonics hardware investigated by Airbus to provide calibration for relaxing design: optically filtered supercontinua and optical microcombs.

Keywords: design-to-calibration, space optical spectrographs, characterization, microcomb, Fabry-Perot filter, supercontinuum

1. INTRODUCTION

Recently, enormous social pressure has been applied to governments around the globe to immediately provide both monitoring and solutions to anthropogenic climate change. Given its prime importance in surveillance and data collection, the space segment of Earth observation must now tackle the current emergency by minimizing its development lifecycle while continuously providing state-of-the-art technology in orbit. Although launchers have embraced the challenge one decade ago, optical payloads intended for atmospheric spectrography still require innovative solutions to respond to the current need for speed.

Foreseeing this evolution, Airbus has already reoriented its optical payload development towards fast-tracking, i.e. ensuring system engineering intended for fast launch while proposing simultaneously innovative solutions for always better scientific product delivery [1][2]. Significant improvements have been achieved by developing new hardware capable of providing higher instrument performances, but also by changing its system engineering strategy to an agile

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organization enforcing speed as a requirement. Along these lines, calibration and characterization (C&C) has been identified as an important step where the room for improvement is gigantic.

Because verification, characterization and calibration are required in theory when the payload is assembled, it is therefore adding up to the instrument critical path. Consequently, Airbus has been thoroughly reorganizing these activities into “Design for Calibration”, where a holistic approach is undertaken from the early phase of the product development. C&C is therefore integrated to the system core from the beginning, hence enabling iterative optimizations both for performance and schedule. Innovations here involve both on-ground and in-orbit C&C organization, as both cross-influence the final instrument performance.

2. DESIGN FOR CALIBRATION PRINCIPLES AND EXAMPLES

2.1 C&C as part of the system during its full lifecycle

To overcome schedule issues, it is crucial to include C&C in the overall system from phase A and to iterate the C&C requirements over the entire system development. Both points are essential to achieve performant and on-schedule delivery: late inclusion leads to critical-path driving developments such as for the optical ground support equipment (OGSE), while frozen C&C requirements lead to time-detrimental redundancies and characterization non-compliances. This approach, embraced by Airbus, is inspired from both the agile product development and the non-redundancy philosophy advocated by leading standard calibration institutes [3].

Throughout development and integration, subsystems are characterized as early as possible and their measured performances are immediately propagated into the system, hence providing early deviation detection. Benefits are twofold: failure can be repaired quickly and the system can be reworked to adapt to an unavoidably deviating subsystem. Most importantly however, system performance verification can be eventually inferred from these subsystem values, hence removing the need for critical-pathed end-to-end tests.

As an illustration, Table 2 shows an example of typical photodetection-related instrument parameters for which each tests is scheduled early as possible, minimizing the need for instrument-level verification. Here, only the ones subjected to time variations (RON, PRNU, DSNU, bad/dead pixel list, RTS, offset correction, stability) are measured end-to-end, hence minimizing schedule risks.

Table 2. Photodetection-related instrument parameters measurement plan optimized for early tests.

Parameters	Detector level	Detection chain-level	Instrument level
Dark current as a function of detector temperature	X		
Detector pixel-to-pixel dependent non-linearity response	X	X	
Saturation level exposure (full well capacity)	X	X	
Detector Read-out noise (RON)	X	X	X
Detector Pixel-to-pixel Response Non-Uniformity (PRNU)	X		X
Detector Pixel-to-pixel Dark Signal Non-Uniformity (DSNU)	X		X
Memory effect	X	X	
Pixel-to-pixel cross-talk calibration	X		

Detector bad and dead pixel list	X	X	X
Detector Random Telegraph Signal (RTS) pixel list	X		X
Electronics offset correction		X	X
Electronic conversion		X	
Electronics stability (Gain and offset variation) in time (short and long term)		X	X
Characterisation / quantification of binning and co-adding effects if any			Analysis only
Spectral Detection Efficiency	X		
Detector reflectivity	X		
Detector Polarisation Sensitivity	X		
Signal to Noise Ratio	X	X	
Lag		X	

Evidently, this approach requires a system performance model building before any measurement takes place: Airbus enforces it by proposing before the end of phase B1 complete mathematical models, for both system performance (for which calibration results are inputs) and C&C performances for radiometric, spectral, geometric, polarization and straylight C&C. Propagation is performed up to the product delivery level, here level 1B. Subsystem results subsequently populate the full-stack performance model, while C&C development results are being propagated to constantly monitor 2 main schedule detractors: OGSE and C&C campaign.

2.2 OGSE development

OGSE are specified as a flow-down from system requirements such as to provide the required accuracy for verification and C&C. As a consequence, they are often overspecified with their architecture being frozen early to enable eventual suppliers to cope with these overspecifications. To solve this, we propose a co-engineering of the OGSE along the early phases of the project, together with subsystem characterizations specifications and/or results: the OGSE architecture is then proposed as lean, where redundancies are systematically tracked and removed in order to simplify the OGSE design. Subsystem characterization tracking and propagation presented in section 2.1 supports this activity and are iteratively integrated into the full system to provide simple, yet performant OGSE.

One example of this lean organization is the removal of ground-based Sun beam simulators (SBS) to measure the solar goniometry onto the on-board solar diffuser. To be representative, such SBS must output 0.5° field divergence, over an exit pupil capable to cover entrance baffles, still with required output power typically in the range of 1/10 of solar irradiances. For typical instruments, the construction of such item has been proven cumbersome, with compliance rarely achieved, if at all: compromises must be found, resulting often in non-representative measurements, especially for illuminating a full baffle. To solve this, it is proposed to systematically provide solar goniometry in-orbit, during commissioning, such that full representativity at no cost and with reduced schedule penalty is achieved. With true solar irradiances, measurements are indeed faster and the whole baffle is covered, hence providing the required representative characterization.

2.3 C&C development and campaign time reduction

Schedule improvement is also achieved by agile C&C organization. An illustration is given in figure 1: although instrument spectral response function (ISRF) is initially intended to be measured from the nominal Earth port of spectrographs, simplification and rapidity are achieved by measuring it nominally through the Sun port, i.e benefiting from the on-board diffuser to cover the whole field and pupil at once. Additionally, by directly collimating the output of a multimode fiber onto the on-board diffuser, very little power is lost, resulting is higher signal-to-noise-ratio and hence faster measurements, enabling moreover any fiber in-coupled monochromatic source to be used.

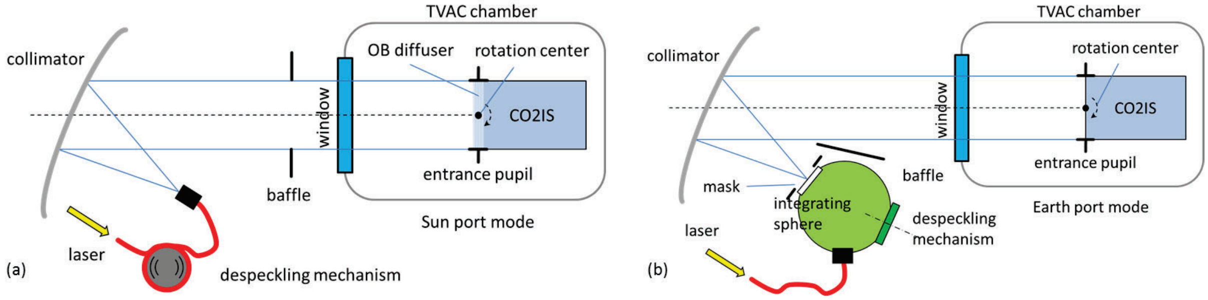

Figure 1. OGSE for fast and simple homogeneous-scene ISRF characterization on (a) Sun port, with potential double-check on (b) Earth port.

Time-consuming systematic ISRF measurement during the C&C campaign can hence be performed fast, Earth port measurements being used for eventual partial double-checks, and/or for non-homogeneous scene illumination.

Such improvements are always paired with fully-automated OGSE designs, such that on-site human intervention is reduced to the strict minimum. This way, perturbations of the C&C campaign vicinity are minimized and remote operation is made possible, augmenting Airbus's expert monitoring and correction with little organization complexity.

2.4 Airbus facilities for system-integrated calibration

As demonstrated, "Design for Calibration" requires full integration of C&C processes into the spectrograph system from phase A onwards. Consequently, integrating its last component, the C&C facility itself, bears massive advantages: traffic jams with other missions is managed by Airbus itself, and the facility's characteristics can be iterated several times to provide both lean and rapid campaigns. Available equipment, vacuum chambers, cleanliness control, accommodation are then integrated into the system and harnessed to propose fast and efficient campaigns. Along these lines, Airbus proposes its optical laboratory originally build in 1987 in Taufkirchen to integrate, align, calibrate and characterize various equipment / subsystems / small to medium size optical instruments, such as:

- C&C of detectors from UV1 to TIR wavelength range in ambient and vacuum,
- Integration, alignment, verification, calibration and characterization of subsystems in ambient and vacuum.

The laboratories consists of 550 m² overall, where 160 m² are ISO5 clean rooms, 240 m² are ISO8 clean rooms hosting 4 thermal vacuum (TVAC) chambers and 150 m² are experimental study rooms. The 4 liquid N_2-provided, optically-windowed TVAC chambers are of dimensions:

- ⌀120 cm x 150 cm, 20 K to 373 K, for average-sized instrument test,
- ⌀80 cm x 120 cm 50 K to 373 K, optimized for detection chain C&C, as shown in figure 2,
- ⌀80 cm x 100 cm, 80 K to 373 K
- ⌀70 x 70 x 70cm³.

Controlling the full system development, from design definition to final C&C enables strong programmatic control by Airbus for typical space spectrograph projects, especially when fast-tracks are required.

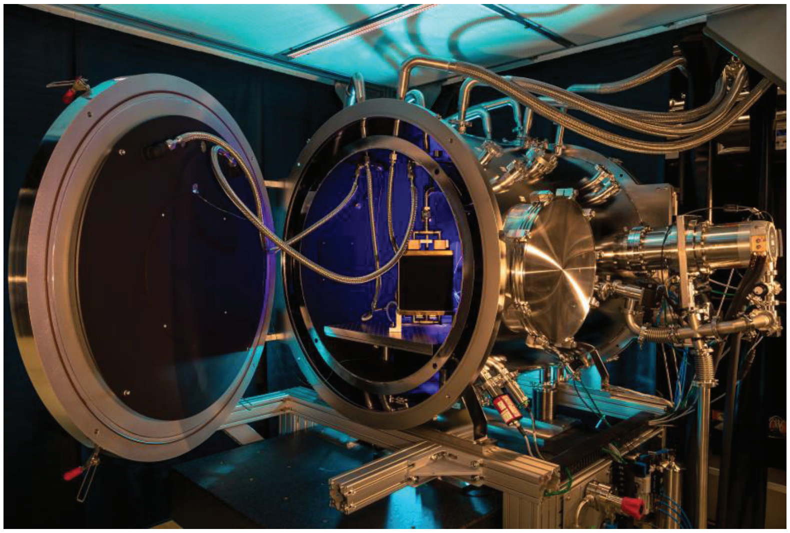

Figure 2. 80-cm diameter TVAC chamber at Airbus Taufkirchen facilities for on-site instrument test.

3. PHOTONIC SOLUTIONS FOR IN-ORBIT CALIBRATION TO RELAX DESIGN CONSTRAINTS

While “Design to Calibration” clearly favors risk and schedule w.r.t. to C&C activities and their potential impact on projects, Airbus proposes simultaneously “In-Orbit Calibration to Relax Design”: C&C hardware and procedures that favor instrument design by minimizing the need for complex solutions to achieve compliance. Two novel compact and performant hardware providing complete knowledge of the ISRF in-orbit are proposed, based on 2 recent photonic innovations: supercontinua and microcombs. For both, simultaneous monochromatic lines are being generated and scanned such as to rapidly cover the whole instrument bands and to provide multispectral inputs. As for standard monochromatic sources such as laser diodes, the instrument response to these stimuli is channeled down for level 2 post-processing.

Both solutions are compact and, importantly, generate multilines from a single single-mode fiber output, hence enabling a simple mechanical and optical accommodation, confirming its relevance for on-board accommodation. With regular knowledge of the ISRF in-orbit, requirements on its by-design stability are relaxed, consequently providing more freedom for system architecture.

3.1 Supercontinuum white light filtered with Fabry-Perot cavities

The first innovation exploits the recent commercialization of stabilized supercontinuum lasers, i.e. pulsed fiber laser pumping non-linear fibers that stretches pulses until producing a supercontinuum, or white light. Unlike its incandescent counterpart, this broadband light does not stem from blackbody but is directly generated in a fiber, hence making it directly available at fiber output. This source has been envisaged as both white light and monochromatic (after spectral filtering) in the context of MetImage [4]. To be used for in-orbit calibration this source is subsequently filtered using a fiber Fabry-Perot cavity, where light propagates in a gapped fiber, both facing fiber facets constituting the reflectors of the resonator.

Figure 3 (b) shows the results of a commercially available supercontinuum source being filtered by a Micron Optics FFP filter, depicted in figure 3 (a), as measured in Airbus laboratories. By properly adjusting spacing distance, 2 nm free spectral range (FSR) is achieved. One fiber being movable thanks to a piezo element, all lines can be simultaneously scanned, hence providing the required spectral scanning for instrument ISRF characterization.

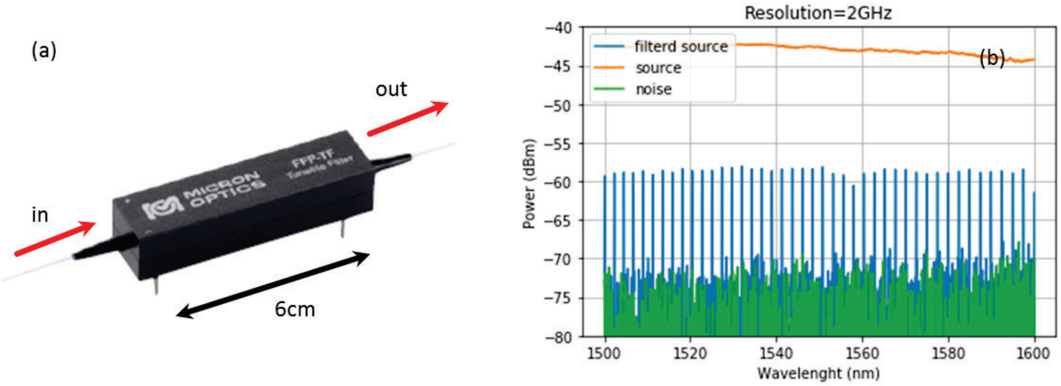

Figure 3. (a) Micron Optics FFP fiber Fabry-Perot tunable filter. (b) Generation of multiple simultaneous monochromatic lines by Fabry-Perot filtering a supercontinuum source.

3.2 Si_3N_4 microchip-based optical frequency microcombs

An even more promising implementation utilizes high Q-factor Si_3N_4 ring resonators commercialized by LIGENTEC SA. With careful tailoring of the dispersion, they can generate optical frequency combs at similar mode spacings, based on the approach first discovered in 2007 [5] and named microcombs. Here, a continuous laser resonantly pumps the 95-µm-diameter ring resonator: when exceeding a certain power threshold, a 4-wave mixing process generates sidebands that populate adjacent longitudinal mode. This process can cascade and produce a microcomb that exceeds 300 nm. Figure 4 shows such a comb with 500 GHz FSR, obtained recently in our laboratory.

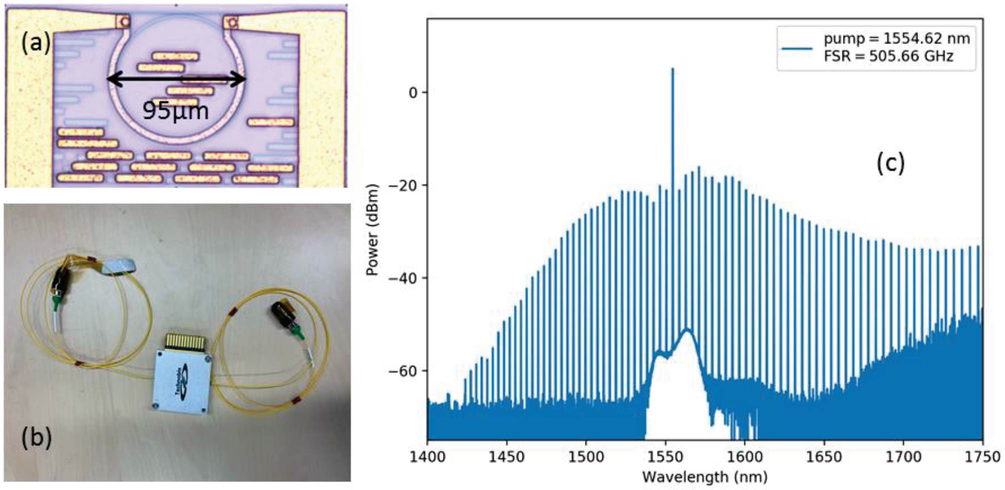

Figure 4. (a) Si_3N_4 microresonator micrograph. (b) Packaged and fiber-connectorized resonator. (c) Generation of approximatively 100 microcomb lines by 4-wave-mixing in Si_3N_4 microcomb.

The required simultaneous multiline scanning is achieved with a current-driven microheater integrated on top of the resonator by LIGENTEC SA. Using thermo-optical effect, optical modes of the resonator shifts and thus the frequency comb lines move. Simultaneously, the pump laser frequency is detuned to follow the pump resonance that generates the microcomb. Figure 5 (a) shows such a comb being thermally scanned over more than 1 full FSR, as detailed in figure 5 (b), therefore proving the principle of ISRF measurement with simultaneous multilines. Preliminary results have also shown that the stability of the generated microcomb is compliant with standard requirements, making this technology a solid contributor to an in-orbit calibration strategy.

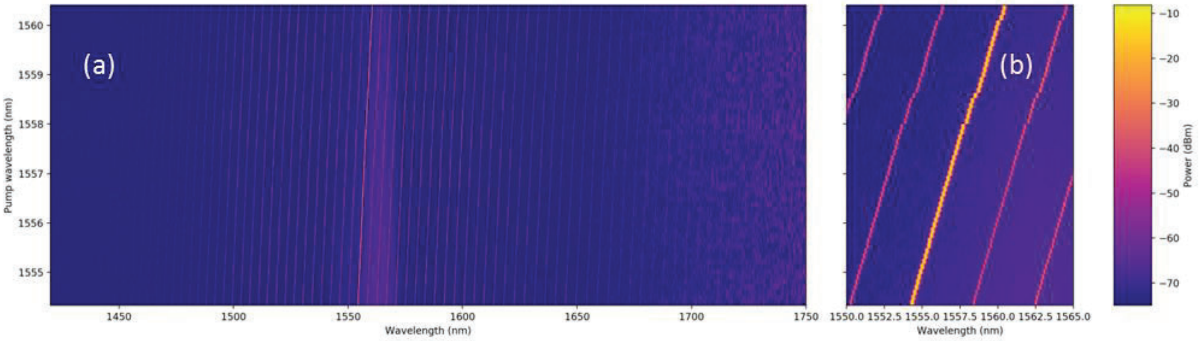

Figure 5. (a) Full-FSR tuning of a microcomb with integrated microheater; (b) Zoom on the pump and the 2 next sidebands.

4. CONCLUSION

With the presented work, Airbus proposes innovative methodology and hardware for two complementary goals: “Design for Calibration” and in-orbit calibration to relax design constraints. The former aggregates various improvements aimed at providing lean OGSE and C&C campaign, aiming at better instrument schedule control without any performance verification degradation. Simultaneously, the latter proposes innovative photonics hardware to strongly extend in-orbit ISRF knowledge such as to relax its stability requirements. Both items de-risk already complex instruments, as far as C&C is concerned. Given its massively beneficial impact, Airbus currently investigates deeper all aspects presented here; particularly promising improvements are foreseen for microcombs, where broadband and fully integrated solutions are already emerging from research laboratories.

With this, plus many other optimizations, Airbus has proven the possibility to embrace current needs with regards to what space segments have to deliver for better Earth atmospheric observations.

ACKNOWLEDGEMENTS

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