

ATOM: Optical Metrology for In-Orbit Monitoring of Deployable Satellite Reflectors

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ABSTRACT

Telecommunication satellites rely on large reflector antennas and broad frequency allocations to maximize connectivity. Next-generation Very High Throughput Satellites (VHTS) aim to extend operation into the Q/V bands (33–75 GHz) using deployable reflectors exceeding 5 m in diameter. Such structures cannot be manufactured monolithically and are susceptible to thermally induced deformations that alter reflector pointing.

To address this need, the Italian National Metrology Institute (INRiM), in collaboration with Thales Alenia Space Italia and within the ESA ARTES programme, has developed the ATtitude Optical Monitor (ATOM). ATOM measures the relative attitude between two remote targets over three angular degrees of freedom using an optical head combining passive and active components. Two lasers at different wavelengths are coupled into a single optical fiber and directed toward the targets; the reflected light is collected onto a CMOS camera for yaw and pitch measurements and onto a polarimeter for roll determination. Amplitude modulation of the lasers provides rejection of background solar radiation. Experimental characterization, including thermal-vacuum tests performed in INRiM's 30 m facility at 8 m distance between -20°C and $+60^{\circ}\text{C}$, demonstrates an accuracy of 10 arcsec on all three rotation axes at 10 Hz, with linear response over a $\pm 0.2^{\circ}$ field of view. ATOM has reached TRL 5–6 and is suited to rigid optical linking of spacecraft sub-assemblies, inter-satellite metrology, formation flying, and, after miniaturization, nanosatellite constellations.

Keywords: optical metrology, in-orbit monitoring, ATOM

1. INTRODUCTION

Telecommunication satellites represent a critical component of modern global communication infrastructures, enabling broadband connectivity, broadcasting services, and data relay over large geographical areas. The core elements of a typical telecommunications payload include travelling wave tube amplifiers (TWTs) for Radio-Frequency (RF) power amplification, Feed Horns (FHs) to generate the electromagnetic wavefront, and reflector antennas to collimate and direct the RF energy toward ground terminals. The overall performance and economic viability of a telecommunications satellite are strongly influenced by two parameters: the antenna aperture size and the available communication bandwidth. Larger reflectors improve the ability to focus RF energy into narrow beams, while broader frequency allocations increase communication capacity and reduce the number of RF amplification chains required to achieve a given throughput. Current High-Throughput Satellites (HTS) primarily operate in the Ka-band frequency range (27–40 GHz), with reflector diameters on the order of a few meters [1]. They employ multiple spot beams and frequency reuse strategies to increase throughput and reduce cost per unit of bandwidth [2]. Since the launch of Thaicom-4 in 2005, close to 100 HTS platforms have been deployed by major operators such as ViaSat, Intelsat and Eutelsat [3–5], with reconfigurable payloads that can adapt beam coverage and RF power distribution [6, 7]. Driven by the continuously growing demand for broadband connectivity, the next generation of platforms, which are referred to as Very High Throughput Satellites (VHTS), aims to significantly increase system capacity through two concurrent technological trends. The first trend is the extension of operational frequencies from the Ka band toward the Q/V bands (33–75 GHz), where larger spectral allocations are available. The second trend is the adoption of larger reflector antennas, with diameters potentially reaching 5 m or more. The combination of higher frequencies and larger apertures enables smaller spot beams and increased frequency reuse, reducing the cost per unit capacity and improving the overall efficiency of the satellite communication network.

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However, the adoption of large reflectors and higher operating frequencies introduces significant technological challenges. Large antenna apertures require extended structural elements, typically in the form of deployable booms, to position the reflector at the appropriate distance from the spacecraft bus and the feed assembly. Reflectors with diameters of several meters cannot generally be manufactured as monolithic structures, and therefore rely on deployable architectures such as mesh reflectors or segmented antennas. Even when high-performance materials such as carbon-based composite isogrids are used to achieve high stiffness and low thermal expansion, thermal gradients and orbital temperature variations can induce deformations resulting in small but significant variations in the reflector pointing direction. The problem becomes particularly critical at Q/V-band wavelengths, which range approximately between 4 and 7 mm: at these wavelengths, even small deviations from the nominal geometry can degrade antenna gain and beam quality, reducing the ability of the system to focus RF energy into the intended coverage area. Accurate knowledge of both reflector orientation and surface shape therefore becomes essential, either as an input to an active control loop compensating for structural distortions, or, in systems without active control, as a means to update the spacecraft attitude or apply calibration corrections to the beam pointing model.

Optical metrology provides a particularly effective solution for these measurement needs. In this approach, information is exchanged between a reference system and a target via light. Optical methods offer several key advantages over traditional mechanical or contact-based sensors: being non-contact, they can measure delicate or complex structures without introducing deformations; the size of the optical instrument does not need to scale with the object, allowing efficient inspection of large deployed structures; and optical systems can achieve very high precision, difficult to attain with conventional sensors. Several optical metrology approaches have been developed for next-generation telecommunication satellites: photogrammetry has been applied to reconstruct the surface shape of a 5 m reflector with a resolution of approximately 50 μm [8]; collimation-based methods have been designed to monitor the attitude of remote instruments such as magnetometers [9, 10]; interferometric techniques have been employed in missions requiring extreme precision, including next-generation gravity studies [11]; angular interferometers have been used to measure mirror base angles with high accuracy, as demonstrated in the GAIA mission [12]; and more advanced instruments combine photogrammetry and interferometry to provide measurements of up to six degrees of freedom in a single system [13].

Within the ESA ARTES programme, the Italian National Metrology Institute (INRiM), in collaboration with Thales Alenia Space Italia, is developing an optical metrology system for in-orbit monitoring of large deployable antenna attitude. The proposed device, named ATOM (ATtitude Optical Monitor), measures the relative attitude between two remote targets over three angular degrees of freedom. A breadboard based on an arrangement of passive and active optical components in a rigid metal structure has been implemented. Light emitted by two lasers at different wavelengths, combined in a single optical fiber, is launched towards targets made of a mirror-polarizer assembly. The reflected light is collected by the optical system and directed onto a CMOS camera for yaw and pitch measurements and onto a polarimeter for roll angle determination. Dedicated strategies based on the amplitude modulation of the lasers for background light rejection are adopted, providing immunity to solar radiation. The system has been characterized in INRiM's 30 m vacuum facility at 8 m distance, over the $-20\text{ }^{\circ}\text{C}$ to $+60\text{ }^{\circ}\text{C}$ temperature range, achieving an accuracy of 10 arcsec on all three angular degrees of freedom at a sampling frequency of 10 Hz, with linear response over the full field of view of $\pm 0.2^{\circ}$. ATOM has reached a TRL between 5 and 6, and its accuracy, stability, and non-contact operation enable rigid optical linking of spacecraft sub-assemblies to a common reference frame such as a star-tracker; the concept is also extendable to inter-satellite metrology, formation-flying applications, and, after miniaturization, to nanosatellite constellations.

The remainder of the paper is organized as follows. Section 2 describes the ATOM measurement principle and optical system architecture. Section 3 presents the experimental facility and the thermal-vacuum test setup. Section 4 reports the characterization results, including accuracy, linearity, and thermal stability. Section 5 concludes the paper and outlines future developments.

2. SYSTEM DESCRIPTION

The ATOM instrument concept and its optical layout have been introduced in [14]. ATOM is designed around a single active optical head, referred to as the Active Unit (AU), together with a pair of purely reflective targets, the Passive Units PU1 and PU2. In the reference configuration for a single-spacecraft installation, PU1 is mechanically referenced to the star-tracker, while PU2 is solidly mounted on the reflector under monitoring; the same measurement scheme can be transposed to a formation of three cooperating platforms to establish a common, rigid optical reference across the constellation.

A TRL 5 demonstrator has been assembled by integrating all active and passive optical elements onto a rigid metallic frame; the resulting breadboard is presented in Figure 1.

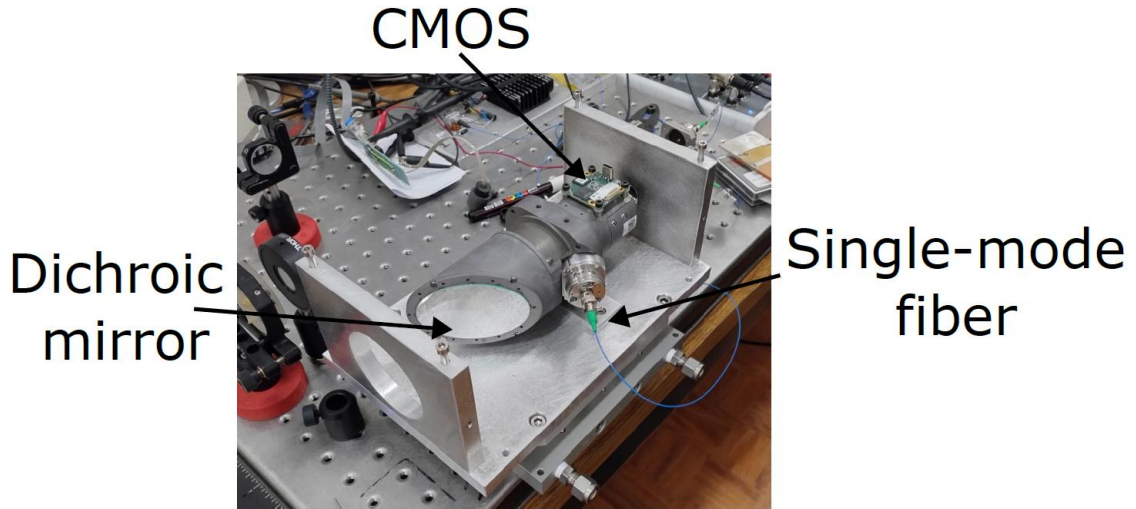


Figure 1. ATOM optical head.

Inside the AU, two laser diodes emit at two well-separated near-infrared wavelengths (Figure 2). Their outputs are coupled into one single-mode polarization maintaining fibre, whose end is collimated by a lens defining the ATOM optical axis. A dichroic mirror placed downstream of this collimator wavelength-separates the two beams into two orthogonal channels, each of which illuminates one of the Passive Units: PU1 sits in the same reference frame of the AU, whereas the second target, PU2 — the actual "target" in the remainder of this paper — is placed 8 m away. Both PUs are realized as a flat mirror with a wire-grid polarizer bonded to its front face.

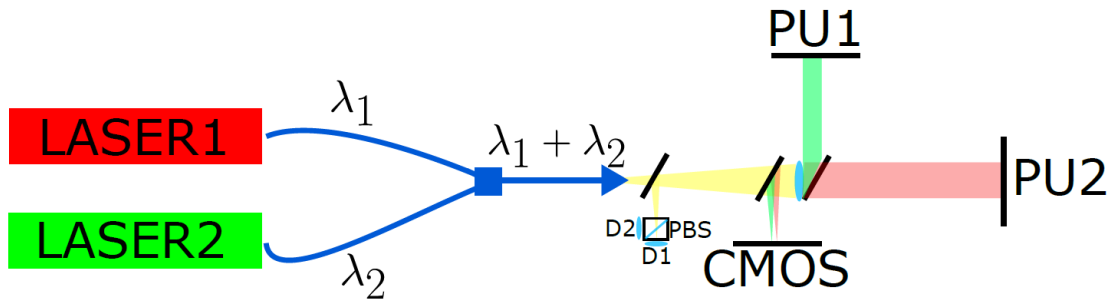


Figure 2. Representation of the optical path of the two laser beams having wavelengths λ_1 and λ_2 combined in a single-mode fiber.

The optical paths are folded back on themselves. Each returning beam re-enters the dichroic mirror, is combined with the counterpart coming from the second target, and is then split twice by two beam splitters: one branch is imaged by the collimating lens onto a CMOS detector positioned at the focal plane of the main lens; the other reaches a polarimeter. Every returning beam therefore carries the three angular coordinates — pitch, yaw and roll — of the corresponding PU with respect to its local reference. Pitch and yaw are extracted from the transverse position of the focused spot on the CMOS: the centroid displacement, measured in pixels, is proportional to the angular tilt of the PU normal relative to the outgoing beam. The angular sensitivity, expressed in arcsec per pixel, is governed by the focal length of the collecting lens; the angular dynamic range is instead constrained by the lens clear aperture together with the size of the CMOS active area, although the latter is not a real limit and the size of the entrance lens is dominating the FOV of the apparatus.

Roll angles are recovered through a polarization-based scheme. The two outgoing beams are prepared in a well-defined linear polarization state, which defines the roll reference axis. On its way back, each beam is transmitted twice through the wire-grid polarizer attached to the target: if the transmission axis of the polarizer is rotated by θ with respect to the incoming

polarization (equivalent to a physical roll of the PU by θ), the polarization plane of the returning beam is rotated by the same amount. The returning light is then routed to the polarimeter, made of a polarizing beam splitter (PBS) followed by two photodiodes, D₁ and D₂, monitoring the two orthogonal PBS ports. The intensities read out by the two detectors are:

$$I_1 = I_0 \sin^2(\alpha) \quad I_2 = I_0 \cos^2(\alpha) \quad (1)$$

with I_0 the total optical power impinging on the PBS. The roll signal is then formed as the normalized difference:

$$S = \frac{I_1 - I_2}{I_1 + I_2} \quad (2)$$

which, being the ratio of two intensities acquired simultaneously, is intrinsically robust against fluctuations of the emitted laser power.

Since both wavelengths share the same detection chain, the AU implements a temporal-modulation scheme that separates the two laser signals in the time domain and, at the same time, subtracts optical background. Each acquisition cycle consists of three consecutive phases: in the first phase only laser A is on, in the second phase only laser B is on, and in the third phase both sources are off. The dark phase yields a periodic estimate of the background level (including stray sunlight), which is subtracted from the two illuminated phases before the pitch, yaw, and roll observables are computed. In this way, the two per-target measurements are isolated from each other and from the environmental background, ensuring immunity to solar illumination in orbit.

3. EXPERIMENTAL FACILITY

Characterization of ATOM requires an environment in which two conditions are simultaneously satisfied: pressure levels low enough to suppress the contribution of the refractive index of air along the 8 m propagation path, and a controlled thermal load applied to the instrument to reproduce its operative temperature range. A dedicated vacuum facility has therefore been assembled around a two-chamber layout. The Active Unit together with PU1 is installed inside a main chamber, while PU2 (referred to as the target) is placed inside a secondary chamber. A 200 mm diameter pipe joins the two volumes and preserves the optical continuity between the AU and the target, whose separation is set at 8 m. The main enclosure is a cylindrical vessel of 50 cm diameter and 50 cm length, which accommodates (in addition to the ATOM head and PU1) the thermal conditioning stage and the auxiliary hardware required by the measurement. The secondary enclosure has a rectangular footprint of 50 × 50 × 30 cm and houses PU2 (for the tests a 2-inch flat mirror mounted on a tip-tilt stage) together with the motorized tilt stage used to apply controlled angular perturbations, along with its ancillary devices. Optical viewports and vacuum feedthroughs are provided on both chambers for beam access and instrumentation cabling. Pumping brings the system to about 10⁻³ mbar in a few tens of minutes, a pressure sufficient to make negligible the variation of the refraction index. Two views of the facility are shown in Figures 3 and 4. The temperature of both the ATOM optical head and the passive units is regulated by an active thermal control system that spans the -20 °C to +60 °C interval, which brackets the qualification and functional test window of the instrument.



Figure 3. Overview of the experimental facility: the main vacuum chamber connected via the 8 m optical pipe to the secondary chamber.

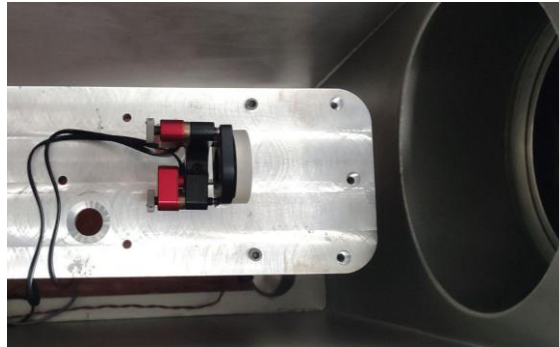


Figure 4. The motorized target flat mirror mounted on a tip-tilt optomechanical stand in the vacuum chamber connected to the 8m far main chamber by an evacuated 20 cm diameter pipe.

4. RESULTS

ATOM is currently undergoing a testing campaign whose primary objective is to establish a calibration curve linking the attitude of the target to the position of the focused laser spot. Calibration of the ATOM attitude readout is performed by motorizing the PU2 using pico-motor piezo-actuators. The PU2 is installed inside the vacuum chamber at the far end of the 8 m vacuum pipeline, with its rear face treated to be reflective so that its attitude could be independently monitored by an Elcomat 3000 autocollimator located outside the chamber. The laser beam emitted by the ATOM head is reflected by the front mirror of the target and subsequently focused by the main lens onto the CMOS camera mounted at the focal plane of the optical head. The centroid of the resulting spot is then extracted, in pixel units, through dedicated image-analysis software, allowing its correlation with the target attitude to be determined. The attitude angle is decomposed into pitch and yaw components. As shown in Figure 5, a linear calibration curve provides a satisfactory description of both axes, yielding calibration coefficients of 3.47 arcsec/pixel for yaw and 3.78 arcsec/pixel for pitch. The residuals with respect to the linear fit remain below 3 pixels—corresponding to less than 10 arcsec given the coefficients above—which confirms that a first-order calibration is adequate to meet ATOM performance requirements. Nevertheless, adopting a higher-order polynomial fit would further reduce the residuals. The field of view (FOV) of the ATOM optical head—defined as the two-dimensional region in the pitch–yaw plane bounded by the target angles beyond which the back-reflected beam no longer traverses the main lens—extends over approximately $\pm 0.2^\circ$ ($\approx \pm 700$ arcsec). Figure 6 presents the map of the linear-fit residuals across the entire FOV. The residuals remain below 10 arcsec throughout, demonstrating that ATOM preserves its linear response

up to the boundary of the FOV, where the incoming beam becomes partially clipped. The persistence of a linear angle-to-spot-position relationship even in this regime further attests to the robustness of the Center-of-Mass algorithm.

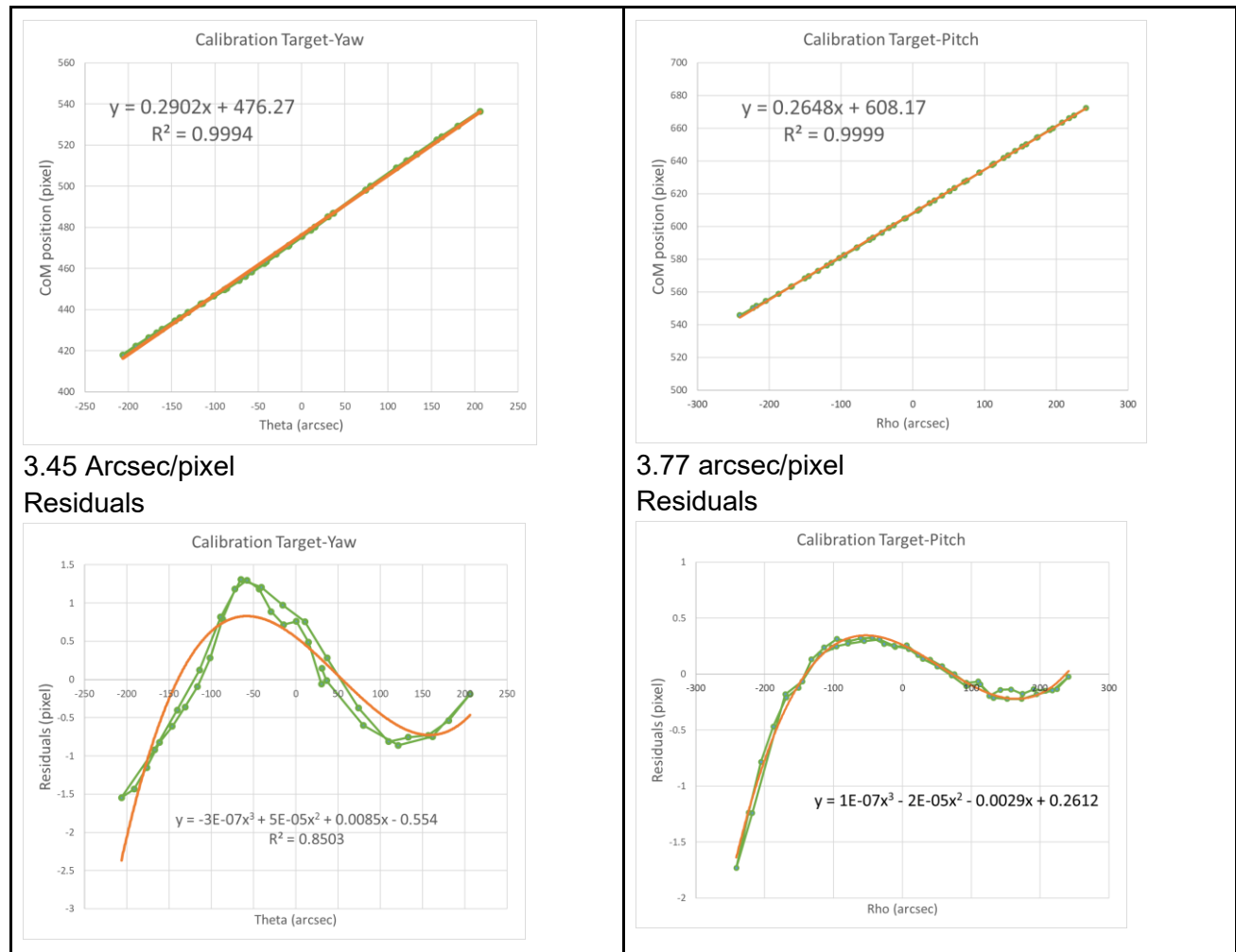


Figure 5. Top: calibration lines for the Yaw and Pitch DoF. Bottom: residuals from the regression line representing the calibration curve.

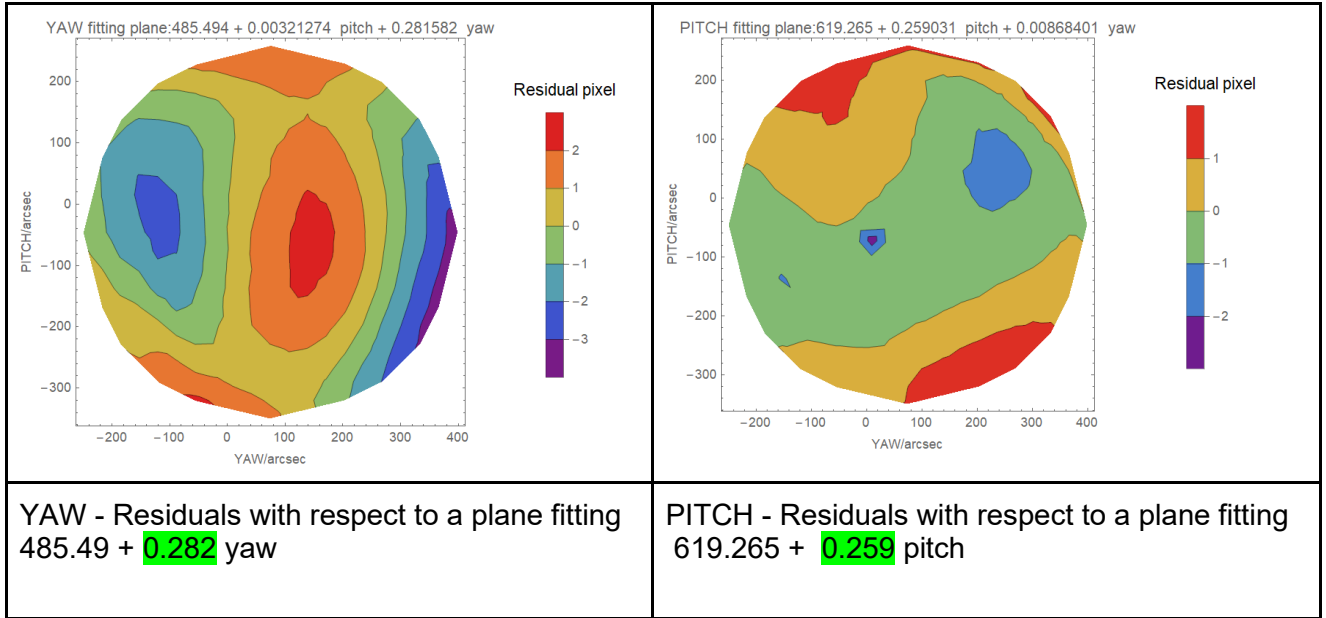


Figure 6. Maps of the residuals on the Yaw-Pitch plane over the FOV. The residuals are below the required accuracy of 10 arcsec over the whole FOV.

5. CONCLUSIONS

This work has presented ATOM, a compact opto-mechanical instrument realized at INRiM under the ESA ARTES programme for the simultaneous determination of pitch, yaw and roll between an optical head and a set of remote passive targets. The measurement is performed non-contact over separations of several meters, and the three angular observables are estimated in parallel through a combination of focal-plane centroiding and polarimetric detection. Testing at 8 m has demonstrated an angular accuracy on the order of 10 arcsec sustained at a 10 Hz readout rate, in line with the specifications defined by the ARTES call.

Building on the current breadboard, several upgrade directions are being considered to broaden the instrument's domain of applicability. The extension of ATOM from a purely angular sensor to a combined attitude-and-range meter is the most immediate one: this can be obtained by replacing one of the existing laser sources with a fast-modulated emitter and by pairing it with a high-bandwidth detector, so that time-of-flight or phase-shift ranging can be added to the current angular pipeline without altering the optical layout. A parallel line of activity will focus on the miniaturization of the active unit, to produce a version compatible with the volume and mass envelopes of nano- and micro-satellite platforms; a compact ATOM would enable relative-attitude and, in perspective, relative-position monitoring within formation-flying missions, where precise inter-satellite metrology is required.

The activity described in this paper has been carried out in the framework of ESA ARTES contract AO/1-9742/19/NL/NR. The instrument is protected by Italian Patent Application 102023000012324 and additional protections are established under PCT filing PCT/IB2024/055898 and U.S. patent submission 19/492,831.

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