The TANDEM project: a story

a personal venture and a technical assessment
by Alberto Buzzoni

Early concept and timeline

TANDEM began to take shape in my mind about year 2015, as the incepting activity on Space Situational Awareness (SSA) with the Cassini telescope in Loiano provided encouraging evidence of cutting-edge use of the telescope for tracking of "exotic" targets of anthropic origin, like demised deep-space spacecraft and rocket bodies at trans- and cis-lunar distances and along interplanetary routes.

The striking case of Gaia spacecraft detection (Buzzoni et al. 2016; see **Fig. 1**), 1.5 million km away at the Earth-Sun libration point L2, in Oct 2014, or the intriguing object WT1190F (Buzzoni et al. 2018), perhaps a debris related to the Apollo 10 lunar mission of the 70'ies, (re)-entered from beyond the Moon one year later, or again the 2017 Earth flyby of spacecraft OSIRIS-Rex on its route to asteroid Bennu (Buzzoni & Micheli 2018), raised wide interest both on the media and in the professional context dealing with Space Surveillance and Tracking (SST), in those years a quickly growing initiative in Italy and abroad, thanks to the auspices of ESA and the European Commission, the latter under grants EU-SST.

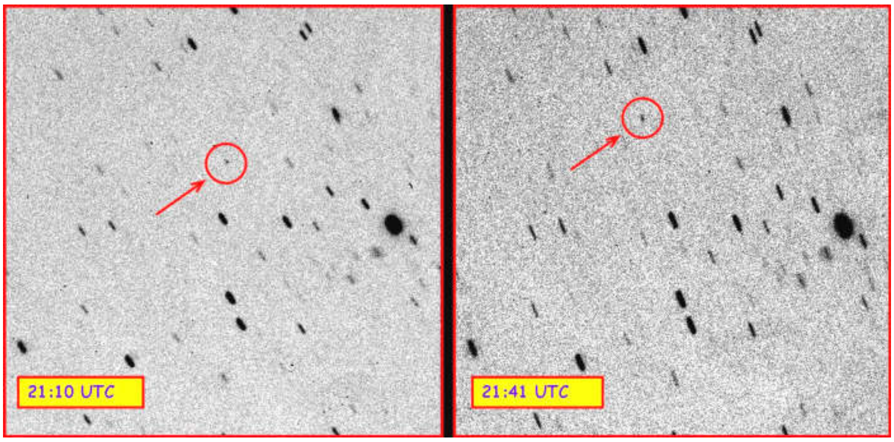


Figure 1 - The spacecraft Gaia, as detected in the night of Oct 17, 2014 from Loiano with the BFOSC camera of the Cassini telescope. The displayed field is 3×3 arcmin across.

A chance was envisaged, therefore, to lead again the Cassini telescope (see **Fig. 2**) to its fully competitive wide-field capability, only barely exploited until then due the limited CCD size of the available instrument BFOSC. By relying on the exquisite Ritchey-Chretien optical design, in fact, Cassini can offer a corrected field of view (FOV) of 72 arcmin projected on a 25 cm-wide spot on the image plane at the f/8 Cassegrain focus, with a platescale of 17 arcsec/mm. On the other hand, the efforts I set in place in those years, mainly in collaboration with Italo Foppiani at OAS, to intercept the full coma-corrected FOV with a monolithic mega-detector or a composite CCD/CMOS mosaic eventually proved to be unattainable both for financial and (especially) technological constraints.

As a matter of fact, actual micro-chip technology mostly constrained detectors size for astronomical use within 40 mm; if the full Cassini FOV (which spans some 1/60 of radians) were therefore to be projected on one of these chips, then an (equivalent) focal ratio about f/1.5 had to be required for the telescope, with a drastic focal reduction by a factor of 0.5x if applied at the Cassini's f/3 prime focus or an even more demanding 0.2x figure at the Cassegrain focus.

Figure 2 – A panoramic view of the "G.D. Cassini" telescope at the Loiano Observatory in its original configuration. In operation since year 1975, the telescope has a Ritchey-Chretien optical design and sports an f/3 primary mirror of 152 cm in diameter. An equivalent focal ratio f/8 is reached at the Cassegrain focus, currently equipped with the BFOSC CCD camera.

This overwhelming limitation, together with the intervened cut in the technical manpower support at the Loiano observatory, early in 2017, led me to aim at alternative ways still struggling however to grant the Cassini wide-field capabilities, though in a "surrogate" and somewhat unconventional approach. This change of paradigm actually led me to re-think the "new Cassini" concept as a composite instrument, consisting in fact of an assembly of different smaller telescopes to flank the main sensor on the same equatorial mount.

A challenging "fast" focal ratio of f/3 for the supplementary telescopes, as for the Cassini's primary mirror, and arguments of structural symmetry of the combo design, eventually suggested to accompany the main instrument with a service array of four smaller telescopes, each in the 30-40 cm aperture range. Though not reaching the full Cassini aperture, when combined, these telescopes could conveniently match the collecting area of a monolithic mirror of 60-80 cm in diameter sporting an even "faster" focal ratio of f/1.5. Most importantly, as a major added value of this choice, this new "synthetic" telescope could in principle supply an even wider FOV, up to 2-2.5 degrees across the sky.

With these milestones in mind, late in 2018 I commissioned a detailed feasibility study to the NCP Spacemind enterprise of Imola (BO), in order to carefully assess also the structural constraints for safely anchoring the (then-named) "new opto-mechanical system" at the Cassini mounting. Different concepts were explored for a "piggy-back" mounting fork at the main polar axis, as shown in **Fig. 3**. As a preferred solution, however, NCP's study eventually devised a fully original solution, with the telescope combo located at the base of the Cassini polar axis in the so-called "base mount fork" configuration. This final concept is displayed in **Fig. 4**.

The valuable input of the NCP preliminary study provided an important reference framework for further internal elaboration, concerning in particular the optical design of the telescopes and the appropriate match with the focus detector, in order to maximize the FOV extension.

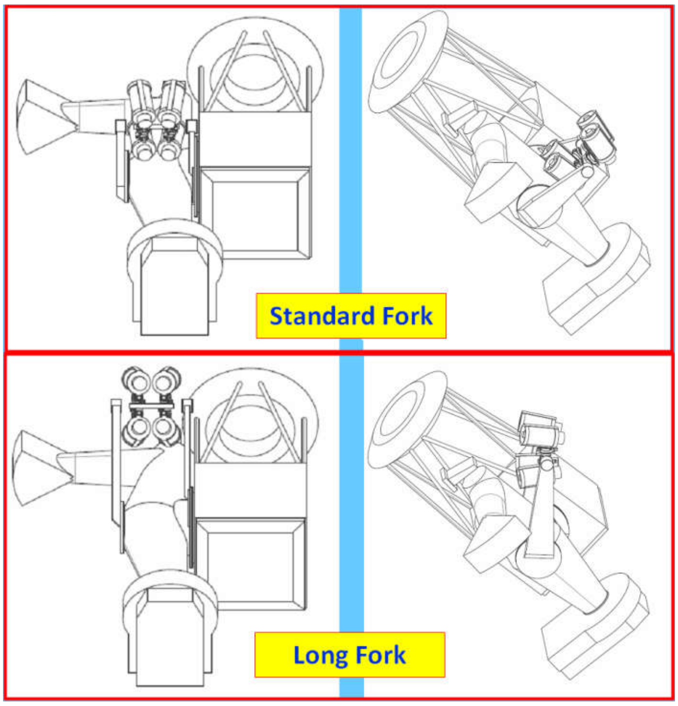


Figure 3 – Some of the structural concepts proposed by NCP in its 2018 study to anchor the new “combo telescopes” at the Cassini’s main mounting.

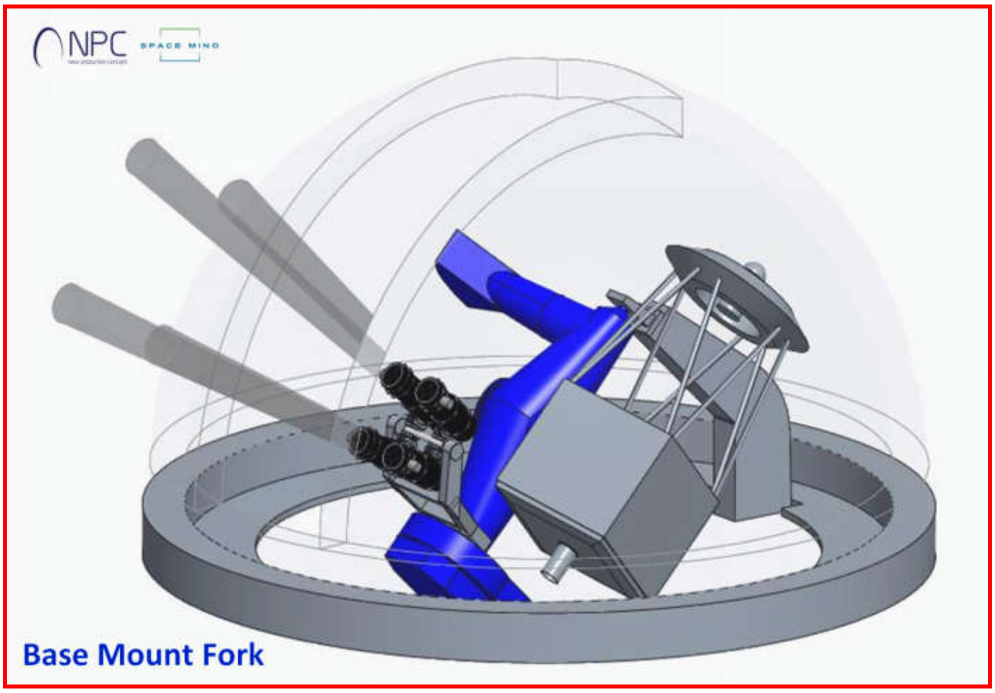


Figure 4 – The proposed structural concepts at the base of the polar axis eventually suggested by NCP to anchor the then-named “new opto-mechanical system” for Cassini.

Meanwhile, in an internal service mail of March 23, 2019, the anonymous “opto-mechanical system” for Cassini was dubbed, for the first time, “TANDEM”, standing for **T**elescope **A**rray e**N**abling **DE**bris **M**onitoring.

After successfully passing the scrutiny of the EU-SST Consortium, in order to assess the technical and strategic added value of TANDEM when integrated in the European Space Surveillance and Tracking network, in 2019 the new sensor was meant eligible by the European Commission for partial financial support in the framework of the Horizon 2020 Research and Innovation Programme, under Grant no. 952852-2-3SST2018-20.

The project TANDEM was officially included as a technological project of interest for INAF in 2020, by appearing in the "Piano Biennale degli Acquisti e Forniture" for 2020-21, under CUI F97220210583202000094 and CIG 9281288925. After completing the required administrative steps, in autumn 2021 an official Call for Tenders was issued for the instrument realization, with myself as a RUP. The intervening disruptive effect of COVID pandemic on the international markets prevented however the tender to be fulfilled at this first round and the call had to be re-issued again in spring 2022. Accordingly, the TANDEM realization was eventually assigned to ADS International, based in Annone Brianza (LC), which started to build the instrument in July 2022.

Instrument assembly

According to the approved ADS concept (see **Fig. 5** for a preliminary colourful rendering), TANDEM had to be anchored at the Cassini's declination axis flange on top of a rotating arm (in blue in the figure) in order the telescope combo to account for the possible 180^{o} pointing switch of Cassini, when manoeuvring from the "face-East" to "face-West" configuration.

Following the design requirements, month after month during winter 2022-23, TANDEM started to take shape at the ADS premises in Annone Brianza (see **Fig. 6**). By June 2023, the instrument was completed and in-house assembled for final Factory Acceptance Test. The latter was successfully passed on June 19, 2023 (see **Fig. 7**) making the instrument ready to be eventually moved to Loiano.

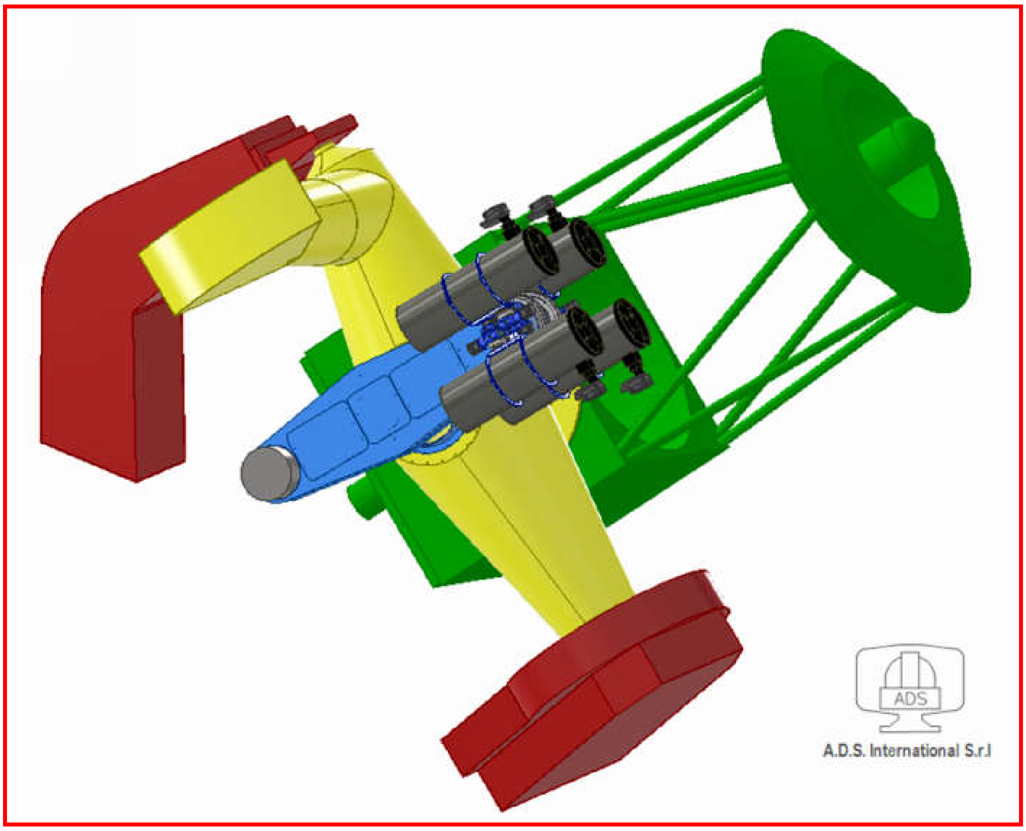


Figure 5 – The ADS concept for TANDEM, as approved for final assembly on summer 2022. Note in the sketch the four telescopes (in black) mounted on a rotating arm (in blue) anchored orthogonal to the Cassini polar axis (in yellow).

Figure 6 – A few milestones along TANDEM assembly. As a reference, top left is the final concept of the instrument, which began to take shape in spring 2023 with the acquisition of the four ORION telescopes (bottom left) and the manufacturing of the steering arm (top right) with the conic flange to anchor the instrument to the Cassini mount.

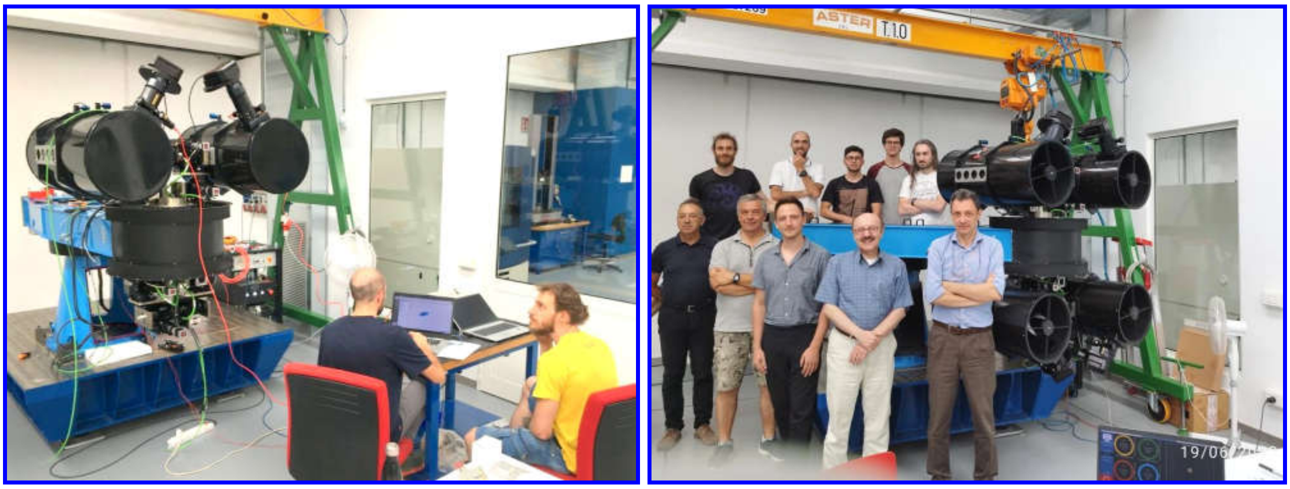


Figure 7 – The TANDEM final assembly (left) and the successful acceptance test at the ADS premises in Annone Brianza (right), on June 19, 2023. A "family picture" with the full ADS team involved in the project is shown, including Eng. Daniele Gallieni (ADS CEO) to my left in the picture.

The final installation at Cassini

The final installation of TANDEM at the OAS premises in Loiano quickly followed one week after the acceptance test, on Tuesday June 27, 2023. For transportation and mounting the instrument was partly disassembled leaving only a lighter structure of some 700 kg, essentially composed by the main steering arm and its counterweights, internal motors and electronics and with the conical flange to allow the Cassini anchoring.

The installation required a crane to raise the big piece over 12 meters high up to the observatory dome and gently drop the instrument inside, ready to be bolt down at the Cassini's declination flange (see **Fig. 8**). The operations proceeded quick and smooth leading to a safe installation of the TANDEM main steering arm at the Cassini original mount. The four ORION telescopes followed straight after (**Fig. 9**).

Figure 8 – Two views of the TANDEM final installation at the Loiano Observatory, on June 27, 2023. Left panel: TANDEM on its way to the Cassini dome, dangling from the crane. Right: inside the dome and close to its final anchoring to Cassini.

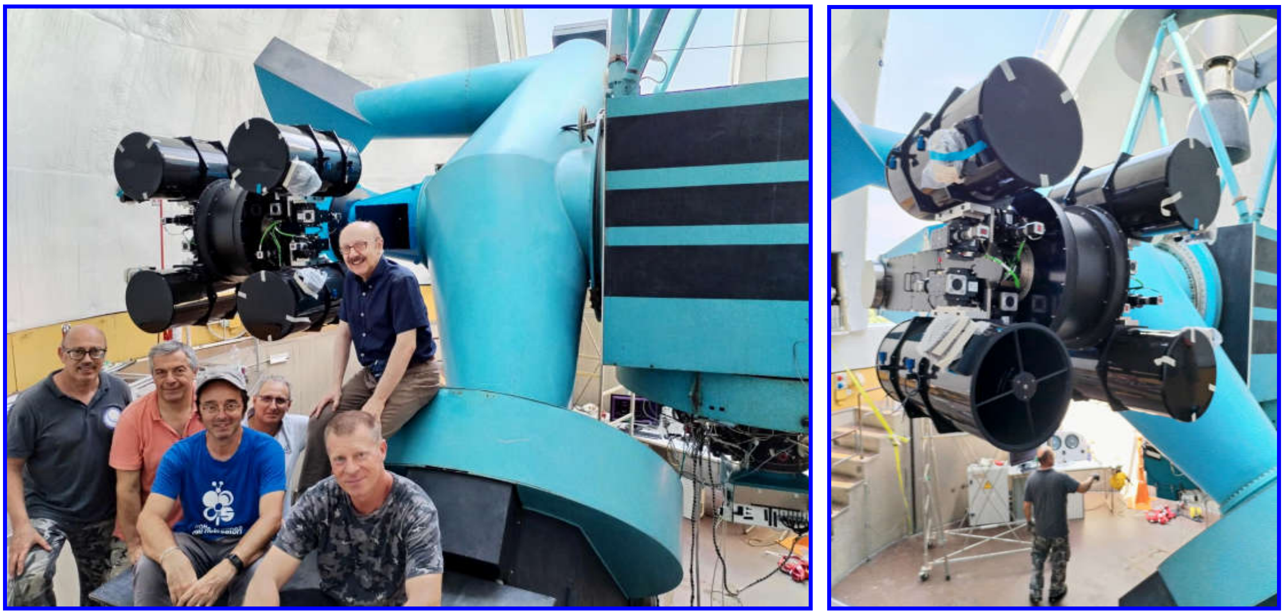


Figure 9 – A (finally) relaxed and smiling "family picture" of the INAF team (left), just after a successful ending of the TANDEM installation. From left to right: Roberto Gualandi, Roberto Di Luca, Albino Carbognani, Sergio Mariotti, Ivan Bruni (in front) and myself (behind). Right panel: TANDEM now flanks the Cassini main telescope.

TANDEM technical characteristics

Optical design

TANDEM consists of a battery of four customized AG14 f/3 Newtonian telescopes, built by ORION Ltd (UK), each with aperture 35 cm (see left panel in **Fig. 10**). Each telescope is equipped with a Moravian C4-16000 camera carrying a motorized and remotely controlled filter wheel.

The camera carries onboard a front-illuminated Grade 1 GSense 4040 (4096x4096 px) monochrome CMOS with electronic shutter. The CMOS pixel technology includes a microlens array (CMT), while the chip is sealed with D263T lids and anti-reflective coating on both sides. The detector is cooled down to 35^{o} C below ambient by means of a thermoelectric (Peltier) module. The spectral transmission curve of the GSense 4040 detector is shown in **Fig. 11**.

A 9 µm pixel size provides 17 Mpx imagery at 16 bit counting depth across a 2^{o}x2^{o} wide FOV fully corrected for coma aberration via a 4" Wynne corrector. The latter was *ad-hoc* manufactured by Tecnottica Consonni srl, in Calco (LC), on original optical concept by Emiliano Diolaiti at OAS (right panel in **Fig. 10**). The platescale at CMOS is 1.75 arcsec/px.

In addition to a "clear" (i.e. no filter) observing slot, a set of four BVR_cI_c filters (50 mm in diameter) is mounted on the five positions of each wheel, closely matching the Johnson-Cousins photometric system (**Fig. 12**).

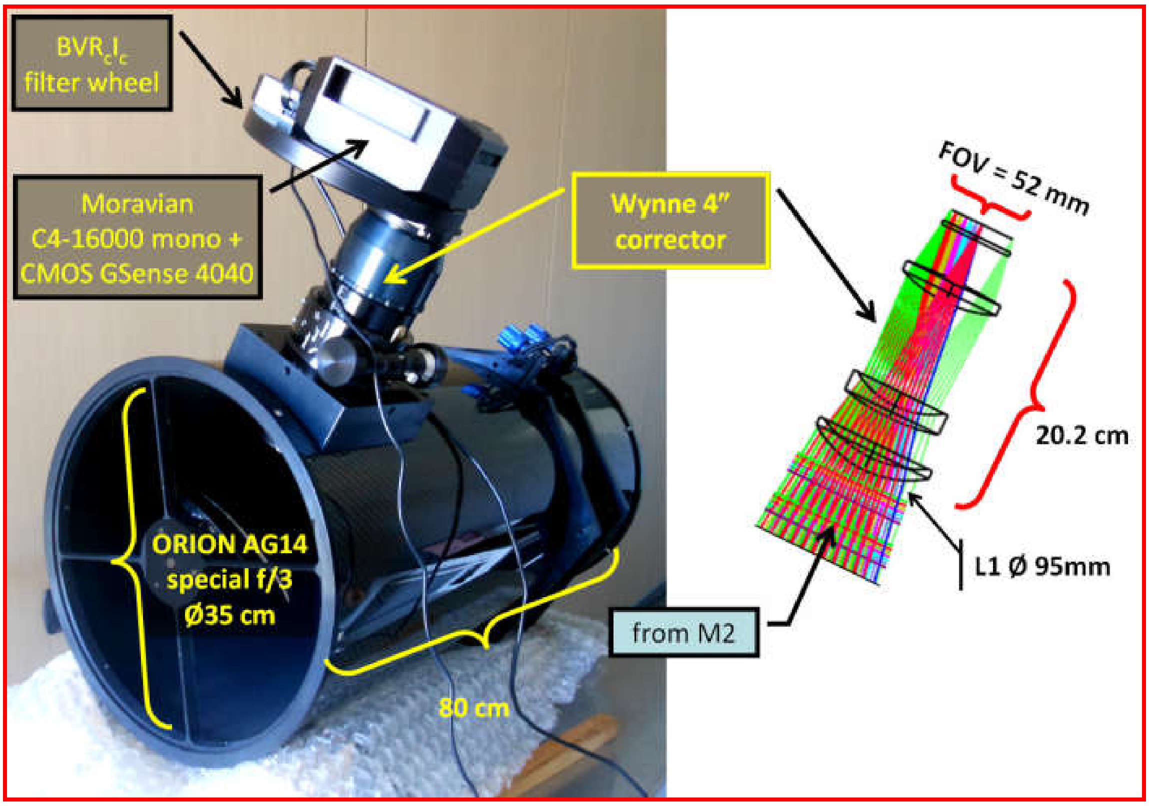


Figure 10 – The optical design of TANDEM telescopes. Each instrument is a customized ORION AG14 telescope with a 35 cm aperture diameter and Newtonian design (left panel), carried to a focal ratio f/3 and coupled with an *ad-hoc* 4" Wynne field corrector (right panel) manufactured by Tecnottica Consonni srl. Imagery is provided through a Moravian C4-16000 camera mounting a Johnson-Cousins BVRI filter wheel and a CMOS GSense 4040 (4096x4096 px with 9 µm pixel size).

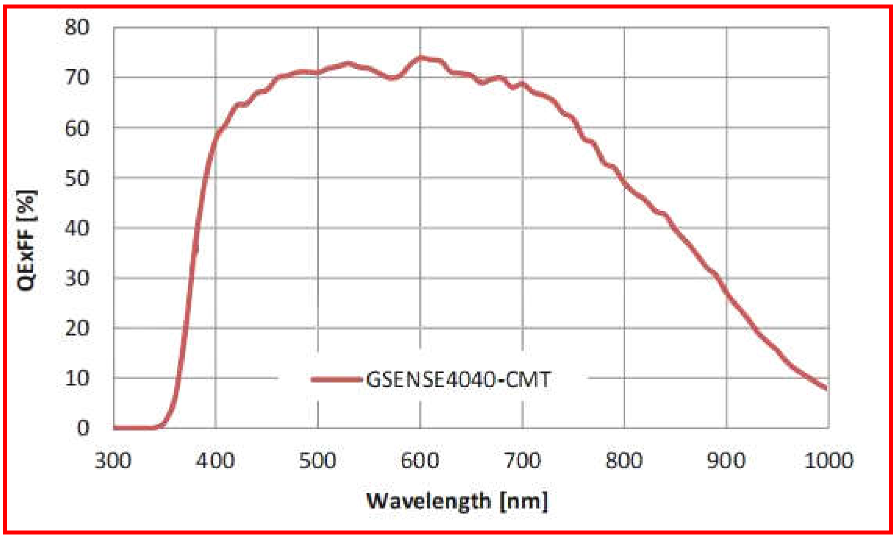


Figure 11 – The detector quantum efficiency (DQE) along wavelength of the front-illuminated Grade 1 GSense 4040 (4096x4096 px) monochrome CMOS onboard of the Moravian C4 camera.

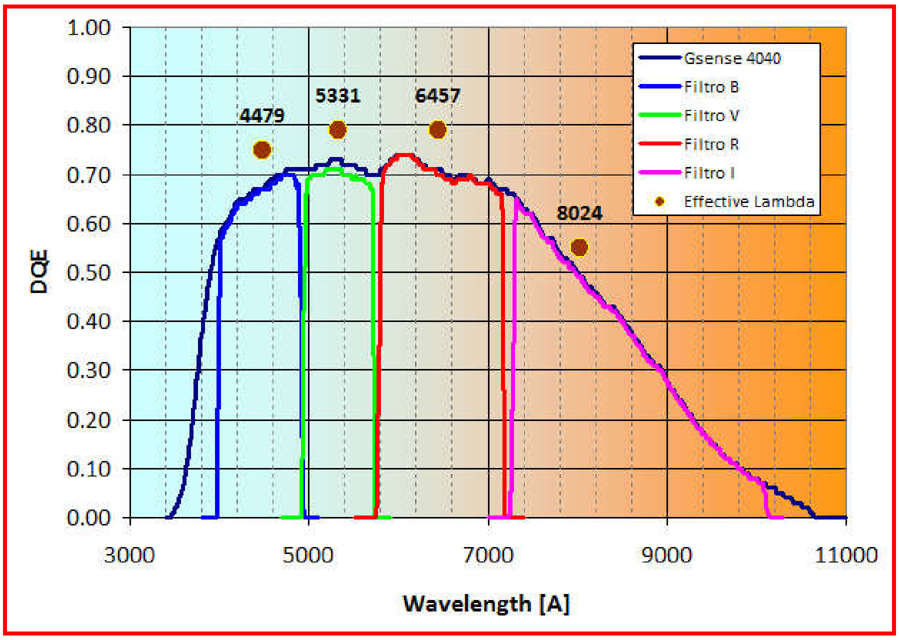
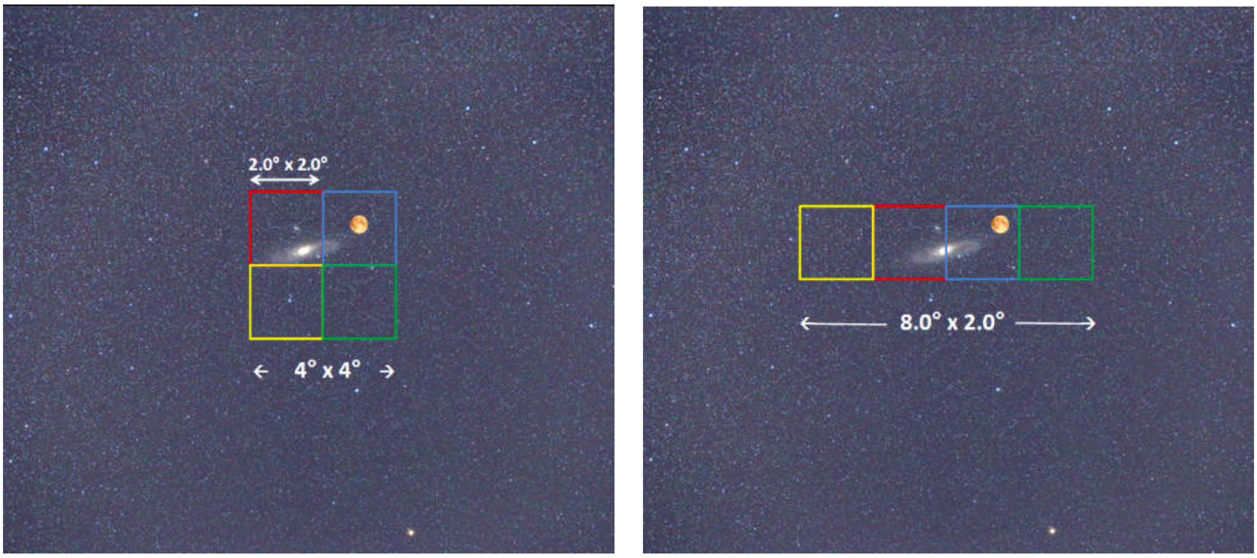


Figure 12 – The TANDEM photometric system includes a set of four BVR_cI_c filters. Effective wavelengths (dots and labels in the plot) fairly well reproduce the Johnson-Cousins system. As a common feature, note that the I_c band is in fact mainly constrained by the CMOS spectral transmission.

Pointing capabilities and optimization

Due to its structural properties, TANDEM shares part of the Cassini pointing capabilities in a sort of mega-binoculars. In particular, the fixed anchoring of the TANDEM steering arm at the Cassini declination-axis flange, makes the telescope combo to share the hour angle (and correspondingly the celestial Right Ascension, RA) with Cassini. On the contrary, Declination pointing may be decoupled, as TANDEM can move the four telescopes according to its own declination axis, which is onboard the steering arm and allows the telescope set to cover the full range from Dec -30^o to +90^o on sky. In addition, and most importantly, one has to consider that each of the TANDEM telescopes is allowed a supplementary and independent steering by ±10^o around the common pointing direction (both RA and Dec) by means of individual tilt/spin actuators onboard.

This relevant characteristic allows the observer to "trade-off" angular and sensitivity performances, as he/she can either use TANDEM at its best magnitude sensitivity by converging the four telescopes on the same 2°x2° FOV or, in alternative, fully exploit the wider angular coverage on sky by steering each telescope in a different direction such as to mosaic four adjacent fields, covering a 4°x4° FOV, or simultaneously targeting four sparse fields up to 20° apart for up to 16 square deg. A number of pre-defined pointing patterns is made available by the system (see **Fig. 13**) and other user-defined configurations can, in case, be easily implemented.



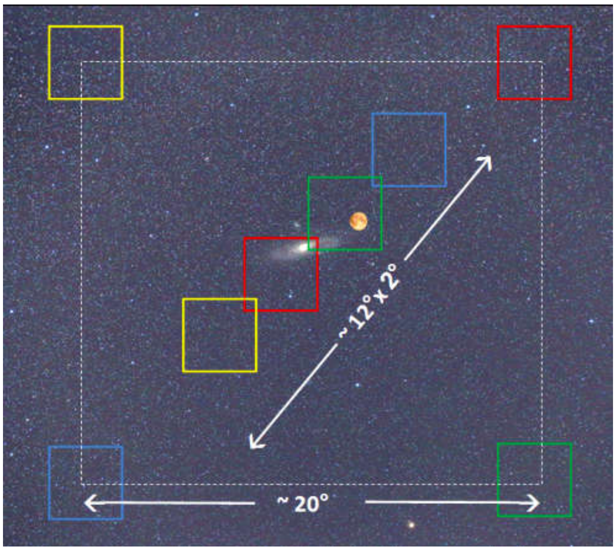


Figure 13 – Some of the pre-defined pointing patterns for the four TANDEM telescopes (each marked with a different colour). As a reference, the celestial region around the Andromeda Galaxy M31 has been displayed, together with a Full Moon sketch. Note in particular, here below, two very extended "sparse-field" options, one along a diagonal direction spanning a 12°x2° FOV and the other consisting of four independent pointings each 20° apart.

Due to the limited aperture of the dome shutter, a possible inconvenient could arise in case of very wide pointing configurations, like for instance the four sparse fields 20° apart (see lower panel of **Fig. 13**). In order to prevent the dome shutter to introduce any vignetting or definitely block the view of some of the telescopes, according to the user-defined sky pattern, the TANDEM control system will automatically re-assign the telescopes to each field such as to properly display an overall "convergent" pointing pattern such as to minimize the FOR across the dome shutter. An example is shown in **Fig. 14,** while the resulting FOR cross section through the dome shutter is sketched in **Fig. 15**.

In case we want to maximize TANDEM sensitivity, then the four telescopes can be pointed to the same 2°x2° wide FOV, as in **Fig. 16**. In this observing mode, TANDEM maximizes its collecting area, by reaching the aperture of a single monolithic telescope of 70 cm in diameter and f/1.5 in focal ratio. Compared to previous "sparse" configurations, in this "collimated" mode TANDEM imagery attains a 0.75 deeper magnitude limit (at given S/N ratio or exposure time).

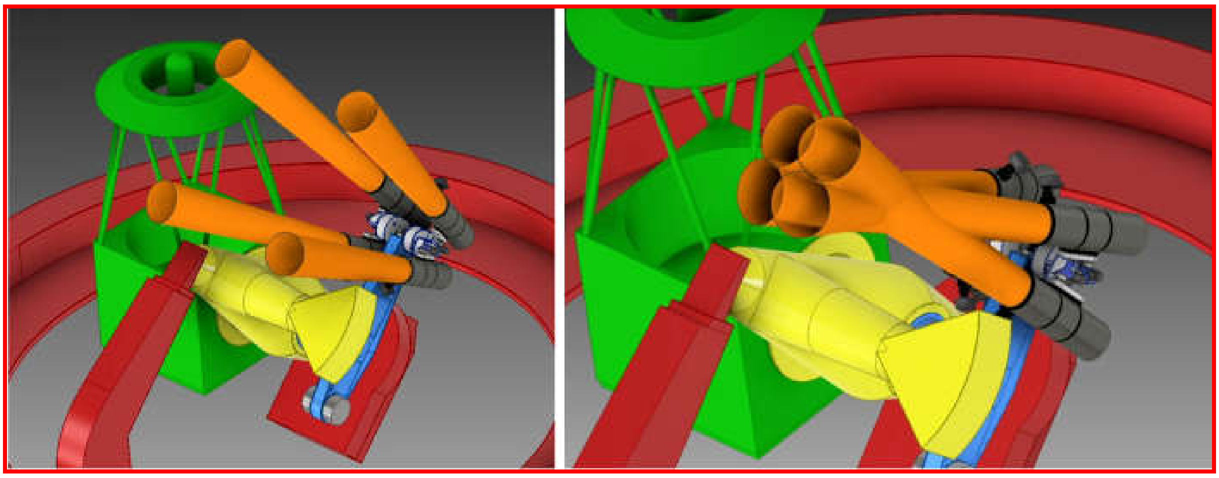


Figure 14 – The same pointing is compared before (left) and after (right) TANDEM optimization. Note in the right panel that the four telescopes are automatically re-assigned to each field such as to obtain a converging pointing pattern that minimizes the cross section through the dome shutter.

Figure 15 – The optimized pointing procedure to match the dome shutter aperture in case of wide-angle FOR configurations.

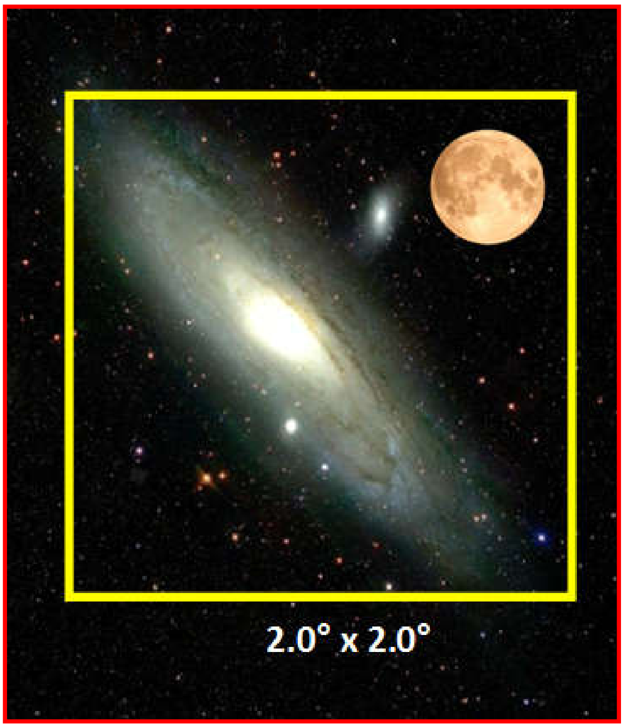


Figure 16 – The covered FOV of TANDEM in "collimated" configuration, with the four telescopes pointing the same $2^{o}x2^{o}$ field. Again, the celestial region around the Andromeda Galaxy M31 has been displayed for an illustrative reference, together with a Full Moon sketch. Though with a smaller FOV, this configuration allows the observer to maximize TANDEM sensitivity, reaching a 0.75 deeper magnitude limit compared to one single telescope imagery.

Pointing and tracking accuracy

An accurate study of TANDEM mechanical structure has been carried out by ADS by means of the Siemens software package FEMAP/NASTRAN for finite elements analysis (FEM). An example of the FEM diagnostic maps is shown in **Fig. 17**. In particular, the expected impact of mechanical torque and structural deformations while manoeuvring has been assessed.

The system response to mechanical solicitations displays a prevailing frequency (eigenvalue) of 13.1 Hz, during the steering arm manoeuvres, but secondary higher-frequency oscillations up to 30.4 Hz may also appear as induced by the smaller moving components of TANDEM. As expected, the declination axis is the most solicited part of the system all the way.

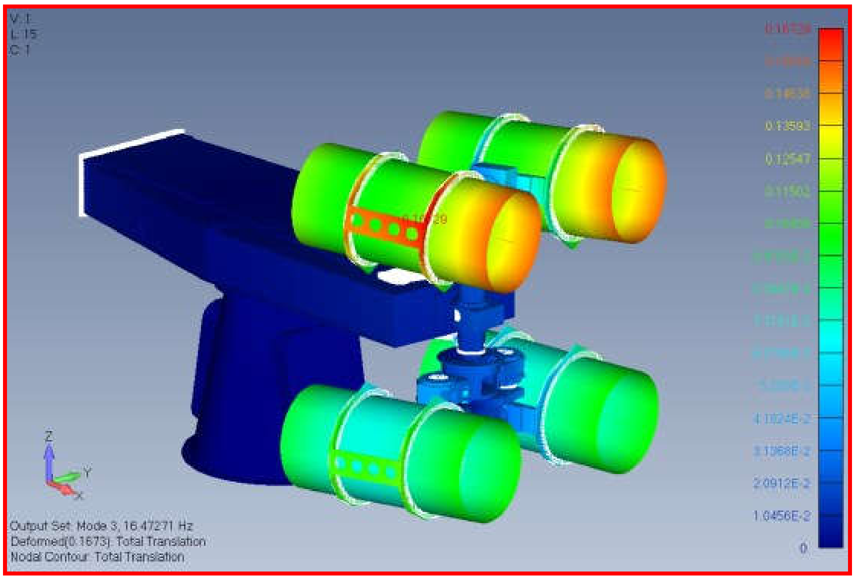


Figure 17 – The illustrative case of FEM analysis for the TANDEM structure when telescopes keep moving around their declination axis. In this case, a system eigenvalue of 16.5 Hz is the prevailing one.

A gravity static analysis has also been modelled, in order to characterize the expected torque forces on the telescopes in consequence of the load change according to the different pointing configurations. This figure provides important clues on the maximum exposure time allowed by sideral tracking to maintain a point-source image within one pixel. A full range of $\pm 90^{o}$ in hour angle around the meridian line has been explored by FEMAP/NASTRAN, by assuming the four telescopes (T1, T2, T3, T4) to head either at the celestial equator or at the pole (that is at Dec 0^{o} or $+90^{o}$, respectively). The results for the equatorial pointing (the most stressing case) are summarized in **Fig. 18.**

For this case, relative offsets up to 5 arcmin are to be expected between the individual telescopes, with the same nominal pointing, when inclined at extreme hour angles. This figure drastically improves, however, when looking around the meridian, as shown in the figure. As these relative offsets are in fact inherent to the system, they can directly be recovered by means of a pre-computed deviation matrix which is implemented into the TANDEM pointing model.

According to the FEM analysis, TANDEM mechanical stiffness can safely maintain any point source within one pixel on the image plane for up to 2.2 minutes at equatorial pointing and up to 9.6 minutes for polar pointing. Exposures in this range are expected to preserve optimum quality of optical imagery. Larger integration times can be considered, of course, providing to stack short-exposure sequences.

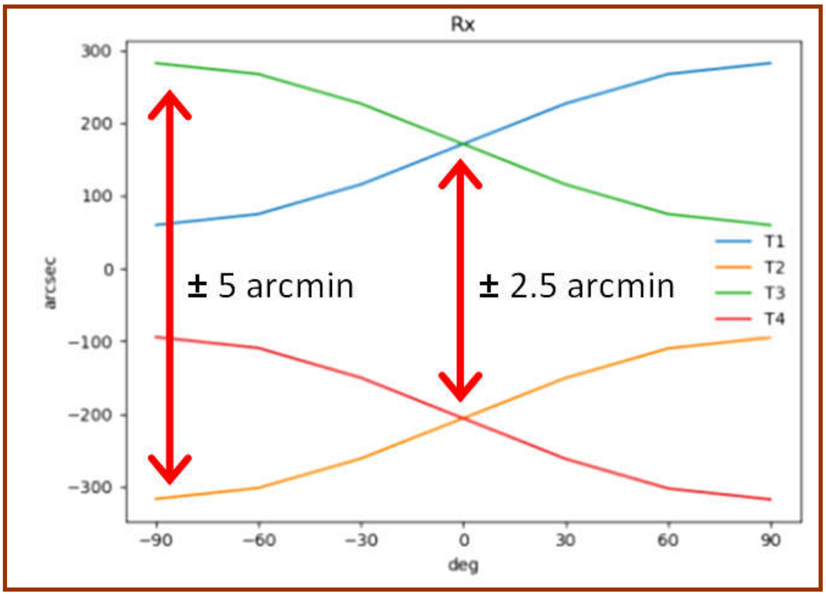


Figure 18 – The relative pointing offset with changing the hour angle (x-axis) due to gravity effect (y-axis) among the four TANDEM telescopes (named T1, T2, T3, T4 in the plot) according to the FEM analysis. In this scenario, telescopes were all (nominally) pointing the celestial equator. Note that a maximum deviation about ±5 arcmin affects the actual pointing at extreme hour angles. This figure allows us to constrain the maximum exposure time (2.2 minutes in this case) to restrain the effect of mechanical deviations within one pixel on the image.

First observing feedback

Short after installation, the OAS/ADS joint team spent the night of June 28, 2023 for the very first commissioning tests on sky. Somewhat unexpectedly, yet at its first "switch on" TANDEM woke up in fully good shape and the first light was obtained straight in the night of June 28, with an iconic image of the crescent Moon taken in blue light with the amazingly shortest exposure time allowed by the electronic shutter of the GSense 4040 CMOS, namely just 0.00002 sec (!) (see **Fig. 19**).

Further tests were performed the following night with a trichromy combination of V-R-I images of a crowded Milky Way field in Cygnus, around star P Cyg. The nice result is shown in **Fig. 20**, with a zooming on the Crescent Nebula NGC 6888 and on an anonymous asterism which allowed us a first estimate of a magnitude limit of V~18 reached by TANDEM in a 2 min integration time.

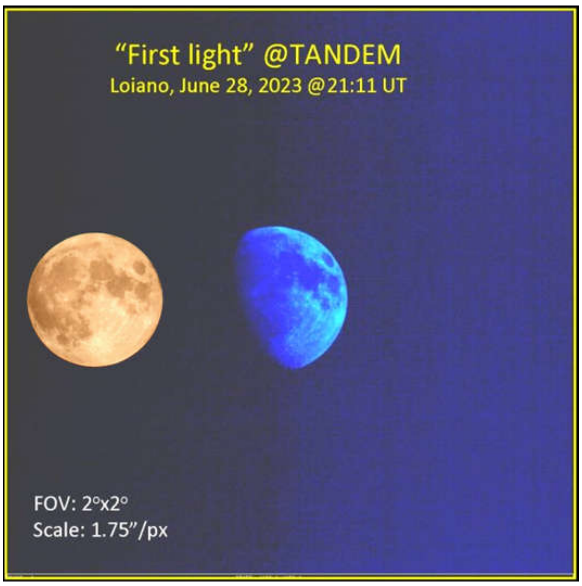


Figure 19 – The "first light" of TANDEM, just after the preliminary focussing operations. A gorgeous image of a "blue" crescent Moon (actually taken with the B filter), as seen by the telescope T2 of the combo, with the shortest exposure time allowed by the electronic shutter onboard the GSense 4040 CMOS, namely just 0.00002 sec. The full 2°x2° FOV is shown in the frame, with the inset of an artificial "red" Moon (to the left), just to compare with its expected size according to the nominal optical characteristic of the ORION telescope.

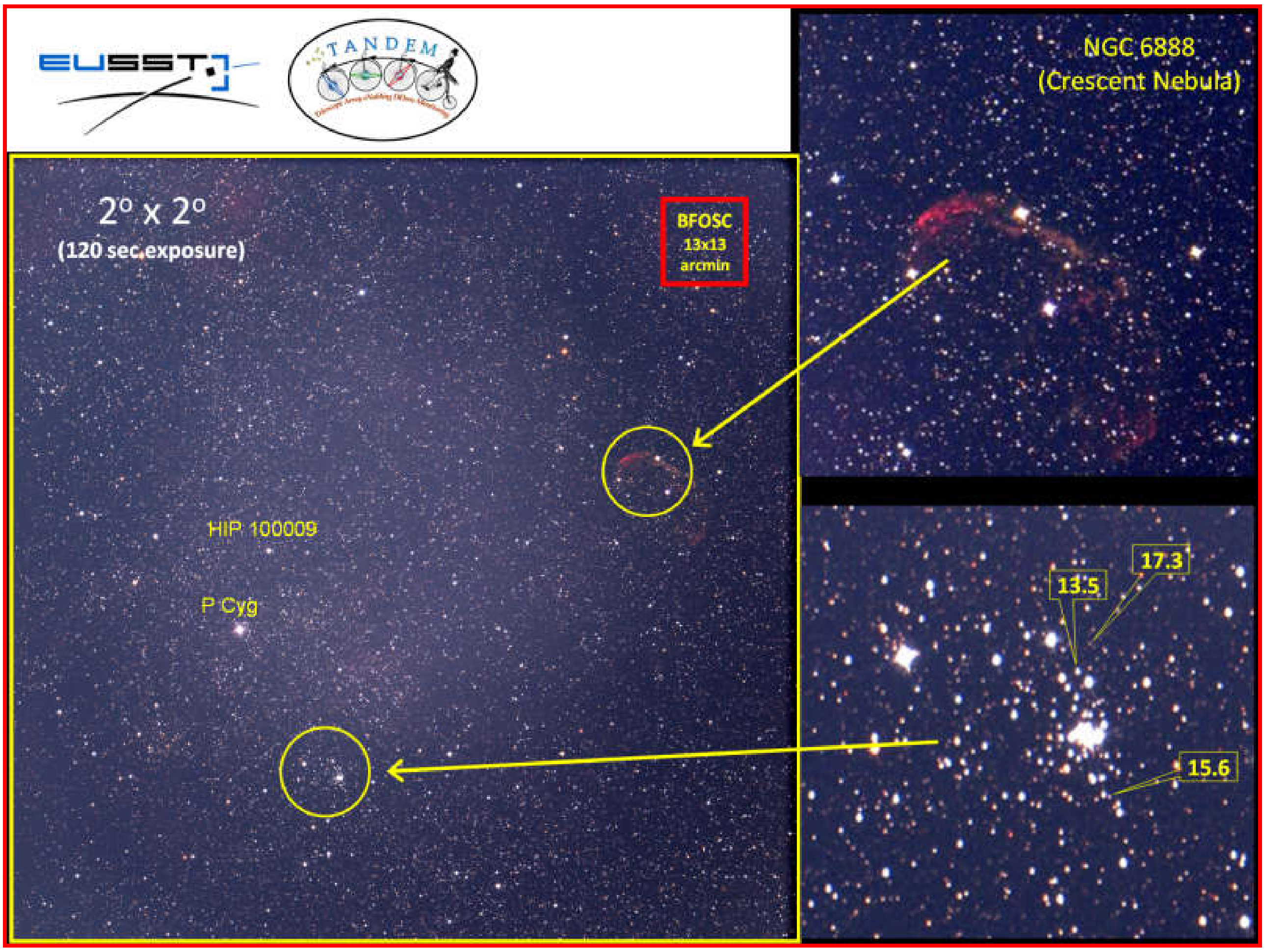


Figure 20 – A crowded Milky Way field in Cygnus imaged by TANDEM along the night of June 29, 2023 in thrichromy (by combining V-R-I filters) Two zooming insets are displayed around NGC 6888 (the Crescent Nebula) and around an anonymous clump of stars with measured magnitude, as labelled. Stars as faint as V~17.3 were clearly detected, with the frame reaching a limiting magnitude of V~18 for the faintest still recognizable objects. As a reference, the red square top right in the full frame displays the FOV currently available to Cassini through the BFOSC CCD camera (i.e. 13x13 arcmin).

Just to inaugurate the SST activity of TANDEM, a nice surprise also appeared when looking at the field around the planetary nebula M57, in Lyra. As shown in **Fig. 21**, in fact, a bright space debris was trailing across the field. To a further check, the object was identified as an exhausted booster of Ariane V rocket (COSPAR ID 2016-069E, NORAD 41863) left in orbit after delivery of a GPS satellite Galileo 15, on Nov 17, 2016.

According to the preliminary observing tests, a first empirical relationship can be derived for the V-band magnitude limit attained by one individual telescope with increasing exposure time, such as $\mathbf{V_{lim} \approx 1.25\ log(t)+15.40}$ providing to express the exposure time (t) in seconds. In case TANDEM is operated in "collimated" mode, then a 0.75 deeper limit can be reached by the tuned telescopes, so that the corresponding relation becomes $\mathbf{V_{lim} \approx 1.25\ log(t)+16.15}$. **Fig. 22** is a graphical display of both relations.

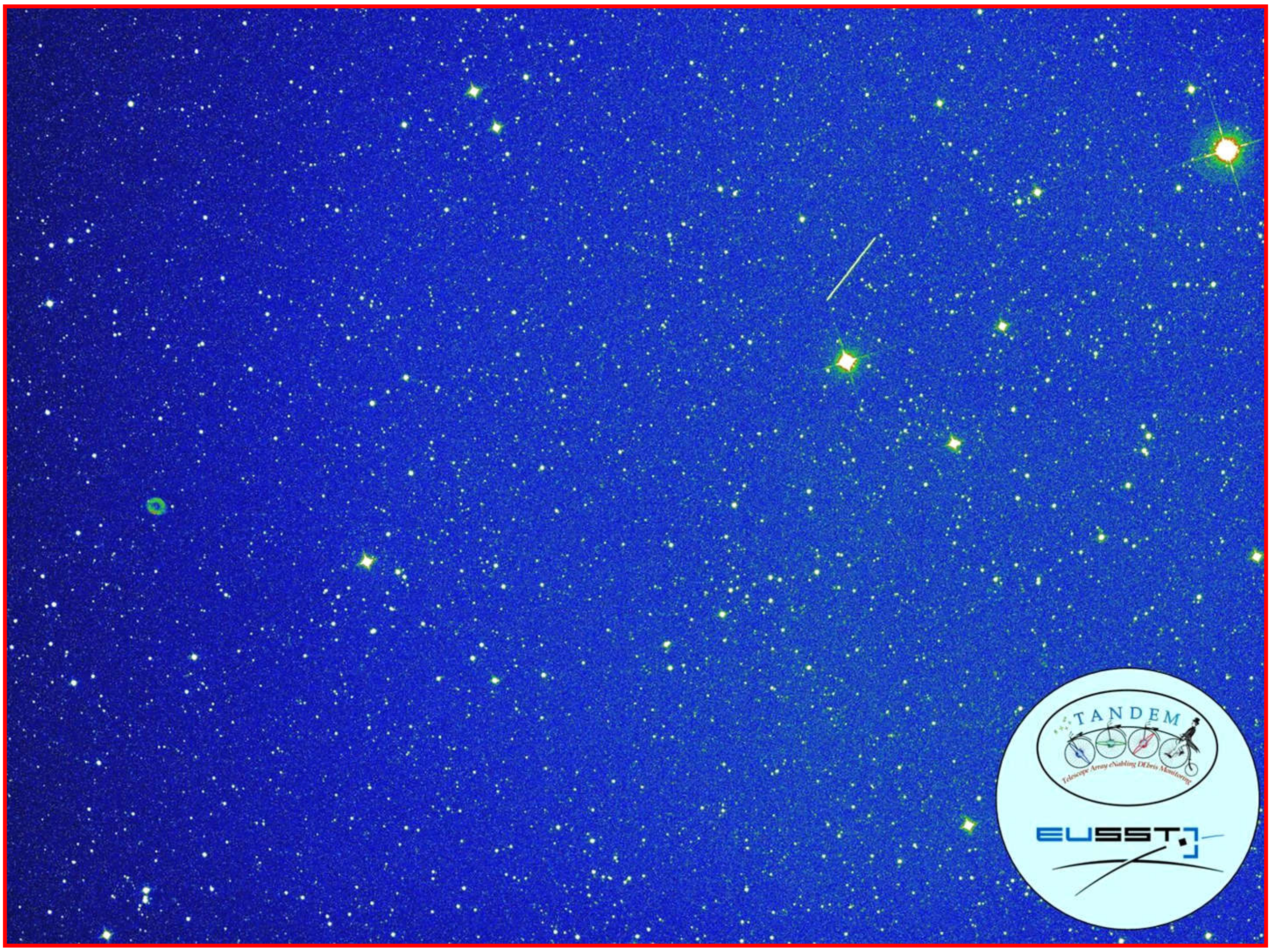


Figure 21 – A field around the gorgeous planetary nebula M57, in Lyra (the small green donut to the left of the frame), in a 10 sec exposure of June 29, 2023. Note the bright trail in the upper right corner of the image, left by a space debris then identified with the Ariane 5 rocket booster (NORAD 41863) which delivered in MEO orbit the GPS satellite Galileo 15, in 2016.

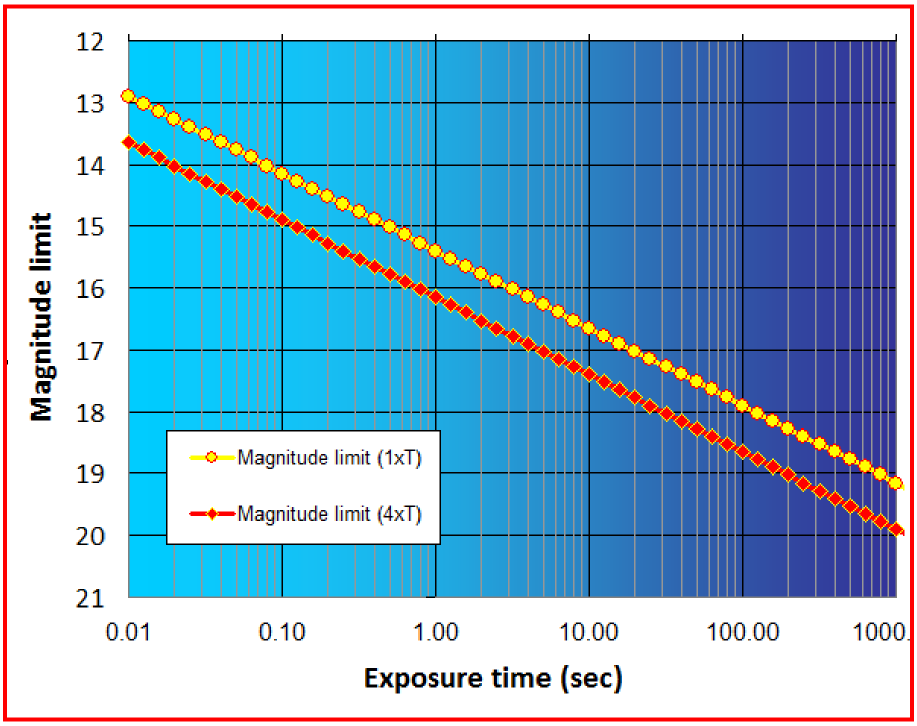


Figure 22 – The stellar magnitude limit reached by each TANDEM telescope (1xT, yellow line) and by the full combo in "collimated" mode (4xT, red line) with increasing exposure time. A sideral tracking is assumed such as to integrate the target on the same pixels.

Beyond SST: envisaged science cases for TANDEM

In addition to specific SST purposes, TANDEM may find useful future applications in a more direct astronomical context. After all, a further alternative spelling of the official acronym may also sound like "**T**elescope **A**rray **N**ot only for **DE**bris **M**onitoring"...

Among the many envisaged fields of interest, that could usefully take advantage of TANDEM special capabilities, the following cutting-edge science cases (a not necessarily exhaustive list) could be mentioned for their relevance:

- ✓ Search for optical counterparts of GRB and FRB events and gravitational wave (GW) flashes
- ✓ Search for exo-planets with the occultation method
- ✓ OSETI (search for interstellar laser signals) surveys, with hyper-fast photometry
- ✓ Search for Main Belt, NEO and PHA (Potentially Hazardous Asteroids) objects
- ✓ Search for "interstellar intruders" (comets and asteroids like 1I/'Oumuamua or 2I/Borisov)
- ✓ Study of meteoric impacts on the Moon
- ✓ Study of stellar streams in the Galaxy (and other archeo-astronomy applications)
- ✓ Wide-field survey of extragalactic star clusters and variable stars in Local Group galaxies
- ✓ Study of serendipitous celestial transients

Though within the framework of the due institutional activity for SST/SSA services, a fraction of TANDEM observing time along the current commissioning period (2023-25) may be available for external collaborations with our science group upon suitable MoU conditions to be negotiated.

In conclusion, and maybe as the most important lesson to be learned in our story, I remained assured that TANDEM successful completion, along the eight years from its early vision to its final realization, only stem as a result of a combined effort and a fruitful interplay among people (scientists and technicians) with the widest range of professional expertise and human input. And, let me say, I'we been extremely lucky in these circumstances with all my friends at OAS, who took active part in this venture. I want therefore to mention here (in almost alphabetical order):

- ✧ **Ivan Bruni, Antonio De Blasi, Silvia Galleti and Roberto Gualandi** – for their always proactive technical support and competence at the telescope
- ✧ **Albino Carbognani** – for his tireless managing of EU-SST operational services and data quality check
- ✧ **Andrea Comastri** - the OAS Director, for supporting since the beginning this perilous venture
- ✧ **Fausto Cortecchia, Emiliano Diolaiti, Matteo Lombini and Laura Schreiber** – for their generous advisorship on the so many opto-mechanical and technical challenges along the way
- ✧ **Roberto Di Luca** – for his always synergic and often resolutive IT support
- ✧ **Italo Foppiani and Fabrizio Bonoli** – for feeding my pervasive curiosity at the beginning of this story and giving me (sometimes even unconsciously) the right clues to go ahead with this project
- ✧ **Antonio Semola and Annalia Piccioni** – for their legal and administrative skills
- ✧ **Giovanna Stirpe** – the General Manager of the Loiano Observatory, for her always enthusiastic help and valuable contribution to the EU-SST initiatives at OAS

Bologna, August 01, 2023