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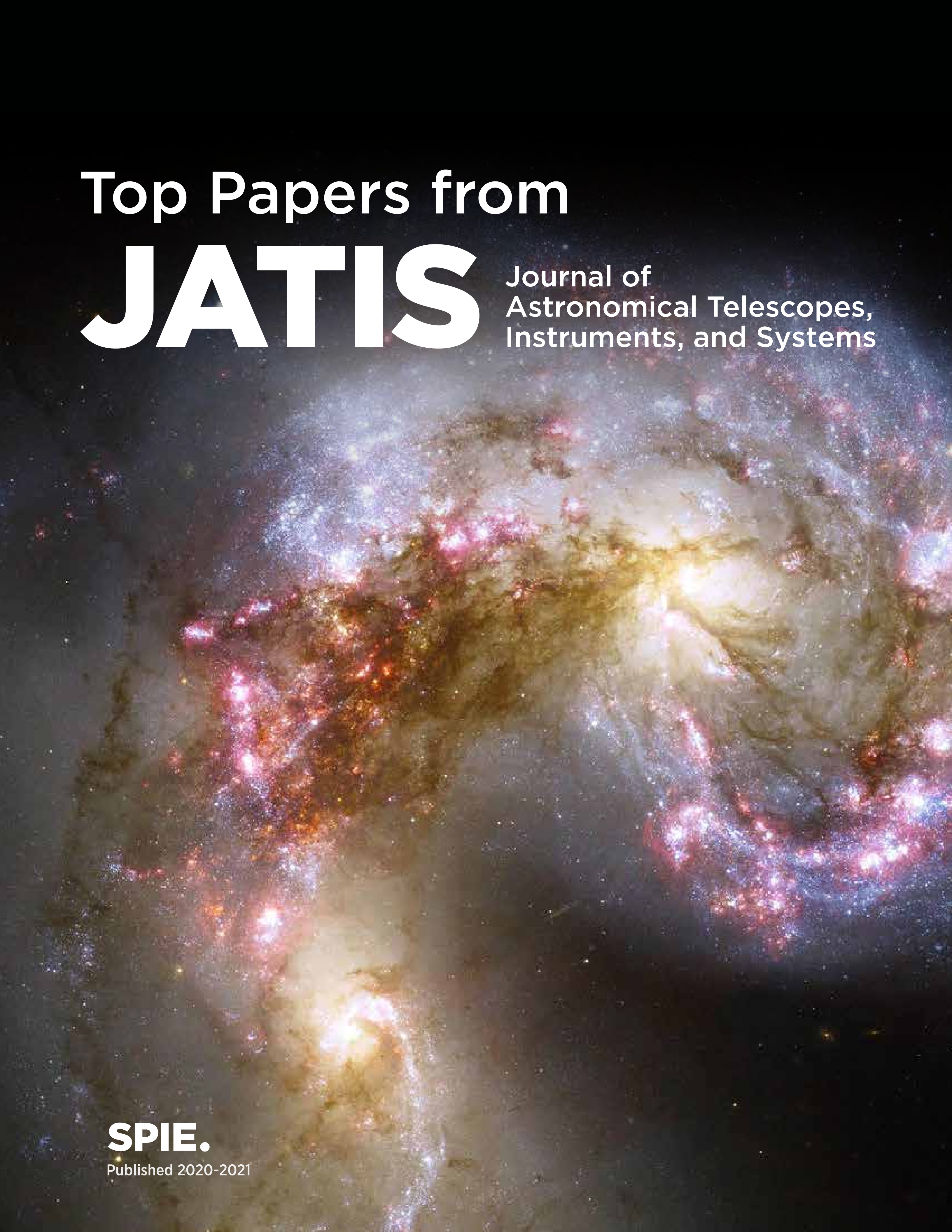

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Top Papers from JATIS

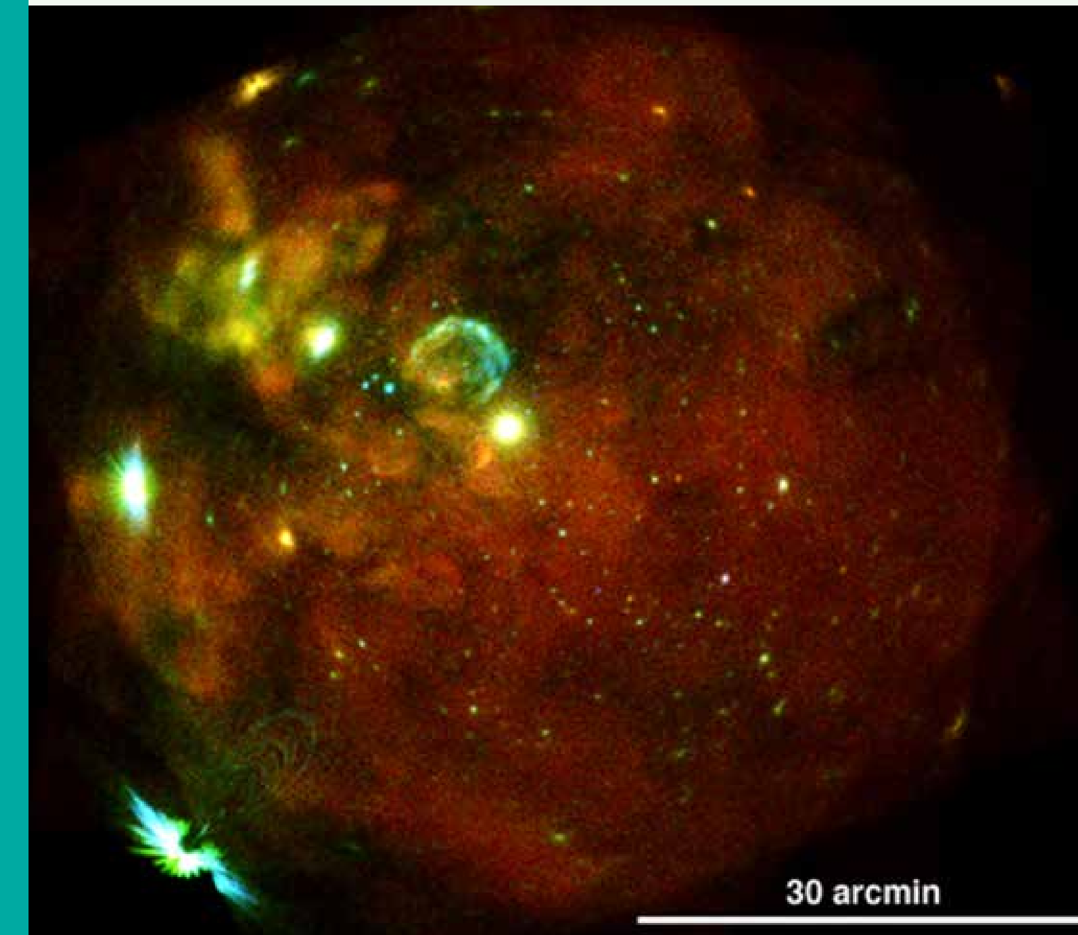
Journal of Astronomical Telescopes, Instruments, and Systems

Contents

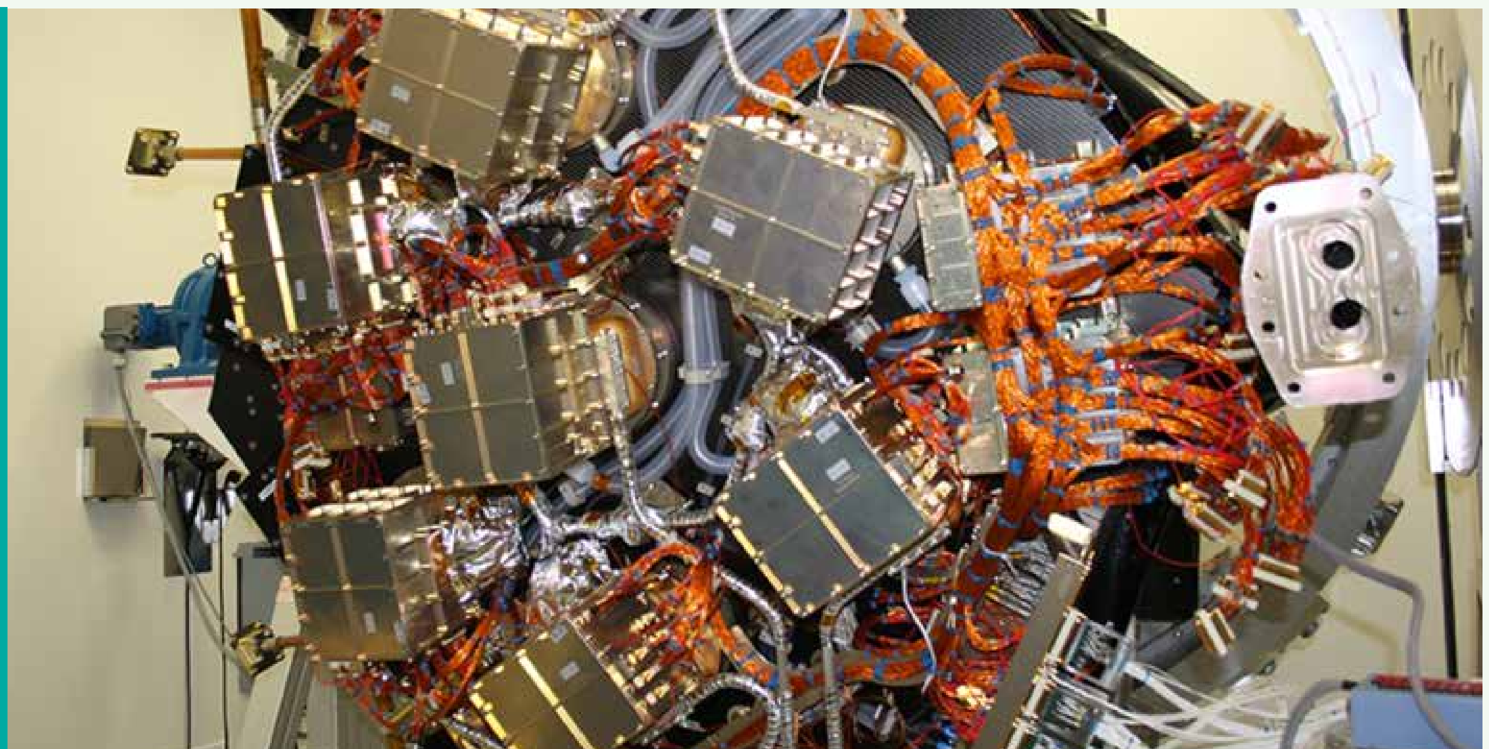
Candid cosmos: eROSITA cameras set a benchmark for astronomical imaging

SUMMARY

A team of scientists from Germany developed the cameras for an astronomical instrument built to perform all-sky surveys in the x-ray wavelength regime. In their recently published paper, they highlight the features of the cameras, a key part of a telescope called eROSITA, describing the hardware development and ground testing, and report the performance aboard the satellite, opening doors to a deeper understanding of our cosmos.



First light of the eROSITA X-ray telescope in space.



A team of scientists from the Max-Planck-Institut für extraterrestrische Physik, Germany, built an x-ray telescope called eROSITA consisting of an array of co-aligned focal plane cameras with one in the center and six surrounding it. Image credit: P. Friedrich, doi 10.1117/1.JATIS.7.2.025004

An overview and performance assessment of the seven cameras of eROSITA, a space x-ray telescope launched in 2019

Recently, the eROSITA (extended Roentgen Survey with an Imaging Telescope Array) x-ray telescope, an instrument developed by a team of scientists at Max-Planck-Institut für Extraterrestrische Physik (MPE), has gained attention among astronomers. The instrument performs an all-sky survey in the x-ray energy band of 0.2-8 kilo electron volts aboard the Spectrum-Roentgen-Gamma (SRG) satellite that was launched in 2019 from the Baikonur cosmodrome in Kazakhstan.

"The eROSITA has been designed to study the large-scale structure of the universe and test cosmological models, including dark energy, by detecting galaxy clusters with redshifts greater than 1, corresponding to a cosmological expansion faster than the speed of light," said Dr. Norbert Meidinger from MPE, a part of the team that developed the instrument. "We expect eROSITA to revolutionize our understanding of the evolution of supermassive black holes." The details of the developmental work have been published in SPIE's Journal of Astronomical Telescopes, Instruments, and Systems (JATIS).

eROSITA is not one telescope, but an array of seven identical, co-aligned telescopes, with each one composed of a mirror system and a focal-plane camera. The camera assembly, in turn, consists of the camera head, camera electronics, and filter wheel. The camera head is made up of the detector and its housing, a proton shield, and a heat pipe for detector cooling. The camera electronics include supply, control, and data acquisition electronics for detector operation. The filter wheel is mounted above the camera head and has four positions including an optical and UV blocking filter to reduce signal noise, a radioactive x-ray source for calibration, and a closed position that allows instrumental background measurements.

"It's exciting to read about these x-ray cameras that are in orbit and enabling a broad set of scientific investigations on a major astrophysics mission," says Megan Eckart of Lawrence Livermore National Laboratory, USA, who is the deputy editor of JATIS. "Dr. Meidinger and his team provide a clear description of the hardware development and ground testing, and wrap up the paper with a treat: first-light images from eROSITA and an assessment of onboard performance. Astrophysicists around the world will analyze data from these cameras for years to come."

The eROSITA telescope is well on its way to becoming a game changer for x-ray astronomy.

View the full article ›

Norbert Meidinger et al., "eROSITA camera array on the SRG satellite," *J. Astron. Telesc. Instrum. Syst.* **7**(2), 025004 (2021). doi 10.1117/1.JATIS.7.2.025004

Shining Infrared Light on the Origins of the Universe

Researchers provide a baseline concept of the new Origins Space Telescope, a mid- and far-infrared telescope with unprecedented sensitivity

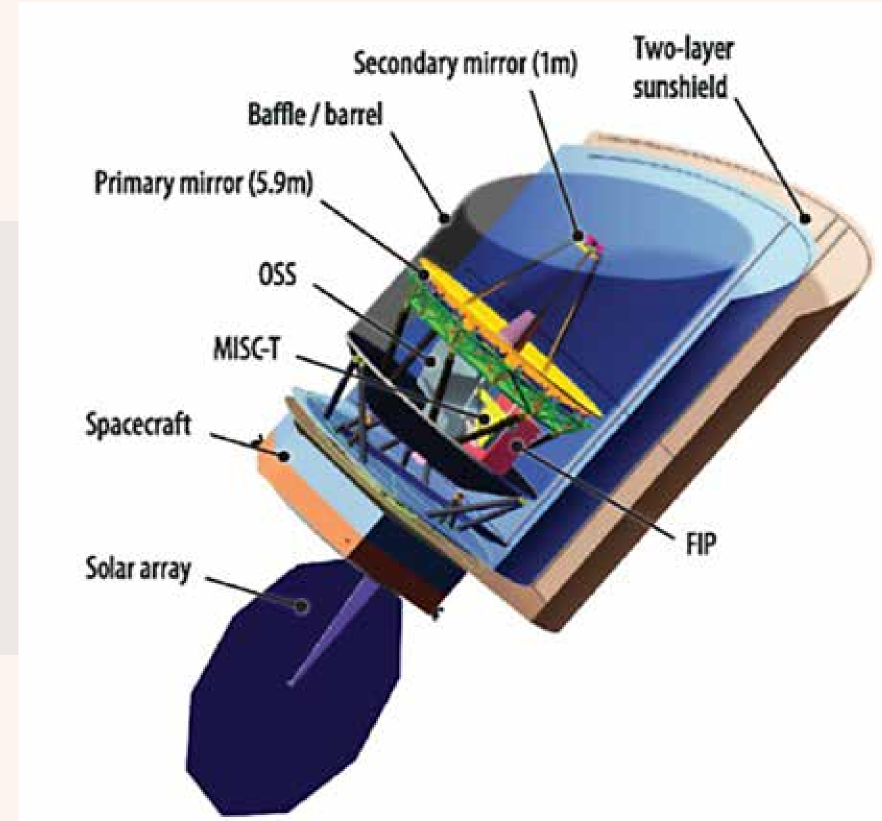
SUMMARY

In astronomy, far-infrared (IR) wavelengths are a gold mine of information about the early universe. However, current far-IR telescopes suffer from "confusion noise limit." This makes it difficult to distinguish between individual sources. Researchers now introduce the Origins Space Telescope, a mid- and far-IR telescope that can reach sensitivity limits as low as the natural astrophysical background and help us shed light on the mysteries surrounding the origin and evolution of our universe.

Since the early days of astronomy and the advent of the telescope, humans have been curious about understanding the universe, pondering questions related to its origins, such as how planets and galaxies formed, and how eventually life came to flourish on our planet. We know now that interstellar dust was one of the earliest forms of matter, originating from the material ejected by dying stars. Characterizing the composition of this dust has provided much insight into the process of star formation.

Interstellar dust is opaque to visible and ultraviolet light but emits radiation in the far-infrared (IR) region, corresponding to wavelengths in the range (30-600) μm. As a result, much effort has been dedicated to far-IR space missions, notably the Spitzer Space Telescope, the Infrared Space Observatory, the Cosmic Background Explorer, the Infrared Astronomical Satellite, and the Herschel Space Observatory. However, despite the remarkable achievements in far-IR astronomy, current far-IR telescopes continue to suffer from a nagging problem: the confusion noise limit. This refers to the limit beyond which no additional individual sources can be extracted from the image. The astrophysics community has wanted a far-IR space telescope that approaches the natural background sensitivity limits with a moderate to high spectral resolving power.

Now, in a new study published in the Journal of Astronomical Telescopes, Instruments, and Systems, an international research team led by Dr. David Leisawitz, an astrophysicist at NASA Goddard Space Flight Center, has unveiled the latest development on this front, namely the Origins Space Telescope (or Origins).



In a new study, an international research team presents Origins, a single-aperture cooled telescope with a record-high sensitivity that can help us answer some of the most profound questions on the origin and evolution of our universe. Figure credit: D. Leisawitz et al., doi 10.1117/1.JATIS.7.1.011002

A new-generation telescope with operating wavelengths in the mid- and far-IR regions, Origins boasts a sensitivity three orders of magnitude higher than that of the Herschel Space Observatory, the largest telescope to be in space so far. Origins aims to find answers to three important questions in astrophysics: (i) how do galaxies form stars, make heavy elements, and grow the supermassive black holes at their center? (ii) how do conditions suitable for life develop during the formation of planets? (iii) Do any of the planets orbiting the dwarf stars support life?

The measurement requirements and, therefore, the baseline mission design of Origins has been fine-tuned accordingly. For instance, the measurement requires an extremely high sensitivity, for which the telescope needs to be cooled down to temperatures below 6 K. Moreover, it needs to be large. Accordingly, the baseline design comprises a telescope 5.9 m in diameter that is cooled to 4.5 K using state-of-the-art cryocooler technology.

To allow for broadband sensitivity, Origins has been equipped with three measuring instruments, namely a Mid-IR Spectrometer and Camera Transit spectrometer for measuring the emission of transiting exoplanets in the wavelength range (2.8-20) μm with unprecedented precision, a far-IR imaging polarimeter to survey large angular areas at (50-250) μm, and The Origins Survey Spectrometer for making wide-area and deep spectroscopic surveys in the wavelength range (25-588) μm. Notably, Origins is a single-aperture telescope since a large improvement in the angular resolution compared to the Herschel telescope was not considered necessary.

The design of Origins focused on minimizing complexity and risk. The thermal architecture was borrowed from the Spitzer Space Telescope, while the cryocooling technology was inspired from the James Webb Space Telescope Technology, two highly successful space missions. It also requires very few deployments after launch.

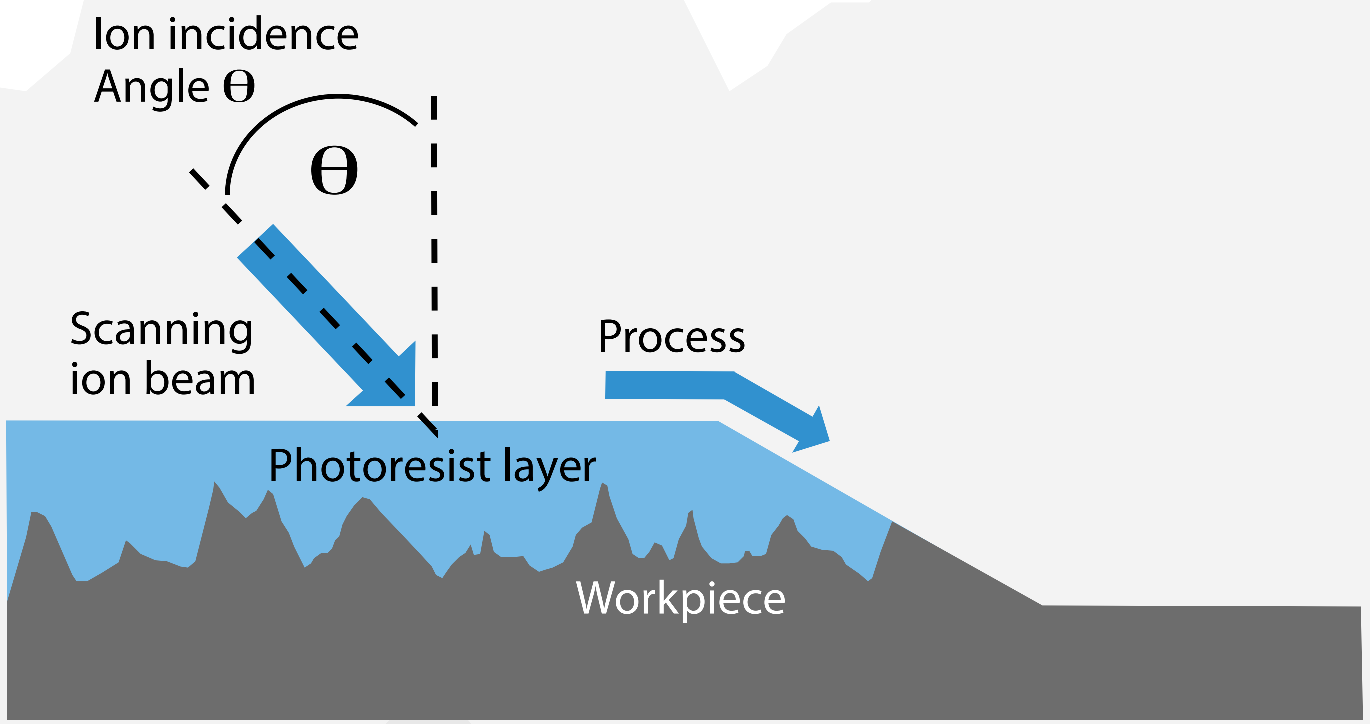
Origins has been designed to operate for a minimum of 5 years in an orbit around the L2 Lagrange point (equilibrium point for a small-mass object moving under the influence of two large celestial bodies) of the Sun-Earth system. The mission lifetime goal is 10 years, with a possibility of extension.

Could Origins help us answer the questions that have motivated humankind to peer into the depths of space since the dawn of astronomy? We're eager to find out.

View the full article ›

D. Leisawitz et al., "Origins Space Telescope: baseline mission concept," *J. of Astronomical Telescopes, Instruments, and Systems,* **7**(1), 011002 (2021), doi: 10.1117/1.JATIS.7.1.011002

Fabrication of Extremely Smooth Aluminum Mirrors to Permit Advanced Deep Space Imaging



A demonstration of how the ion beam planarization technique smooths out a surface. A beam of ions collides with the surface, thereby etching off the coated photoresist layer, and with it the overlying roughness from the aluminum mirror (here labelled as "workpiece"). The result is a significantly smoother aluminum surface as shown on the right. Figure credit: Melanie Ulitschkaety al. doi 10.1117/1.JATIS.6.1.014001

An ion beam to reduce fabrication marks on mirrors allows their application in the ultraviolet and visible regions of light

SUMMARY

Aluminum mirrors are cheap, lightweight, and easily scalable, making them an ideal candidate for space telescopes. Although current methods allow the fabrication of mirrors that are smooth enough for use in the infrared spectrum, smoother mirrors are needed for high-precision applications in the ultraviolet and visible spectra. Recently, a German research collaboration used a beam of charged particles to significantly smooth out imperfections left in mirrors by the fabrication process.

Optical mirrors, such as those used in deep space telescopes, consist of a substrate topped by a metallization layer that reflects light. While conventional mirrors use glass as a substrate, aluminum is used as a substrate in many specialized applications due to its high strength, low weight, low cost, and outstanding reflectivity. The reflectivity of aluminum ranges from from the infrared side of the optical spectrum all the way into the ultraviolet (UV) region.

Modern telescope mirrors need to be ultraprecise to efficiently collect light from and image deep space. For this, the mirror material needs to be extremely smooth. Currently, mirror surfaces are fabricated using a technique called single-point diamond turning (SPDT). But SPDT leaves marks on the surfaces of mirrors that range between 10 and 30 nm in roughness. While this roughness does not affect imaging using longer-wavelength light (infrared), the regular, periodic fabrication marks serve as a diffraction grating for shorter wavelength light. The light gets scattered through diffraction, reducing the efficacy of the mirrors and hampering long-distance imaging applications.

Now, a research collaboration between the Leibniz Institute of Surface Engineering and Technische Universität Dresden has suggested an improved fabrication method for smoother optical surfaces. The method, called ion beam planarization, uses a beam of charged particles (ions) to smooth out the periodic markings left by SPDT.

First, a well-documented photoactive organic substance, called photoresist, is coated on top of the aluminum surface to create an extremely smooth organic layer, which fills in the gaps in the aluminum roughness. The photoresist layer is baked post-coating to preserve the initial roughness of the surface. The post-baking temperature has to be optimized to avoid degradation of the photoresist layer.

Next, ions are accelerated in a nitrogen gas atmosphere and the resulting ion beam is directed at the photoresist-coated aluminum. As the ions collide with the sample, they etch away the surface. The smooth nature of the photoresist layer is transferred to the underlying aluminum layer as the reactive ions remove the photoresist layer. Adjusting the rate of ions allows for high precision etching and control in thickness. Once the rate of ions is optimized, this method flattens out the periodic marks left by SPDT, reducing their height by over 80%.

Finally, a second ion beam machining run is performed. The reflectivity of the aluminum surface is reduced after the first machining run. This is because the initial aluminum surface had a layer of aluminum oxide over it, which enhances its reflectivity. The second machining run is performed with oxygen as the process gas, which increases the thickness of the oxide layer and improves reflectivity. The second machining run also further smooths out the aluminum surface. The result is an ultrasmooth mirror with less than 3 nm in variability, suitable for sensitive applications in the visible and UV spectrum ranges.

The ion beam planarization technique can easily be extended to curved surfaces, making it extremely promising for the development of smooth, next-generation, deep space imaging mirrors. It also finds applicability in the broader field of optical surfaces, such as in beam steering, interferometry, and illumination.

View the full article ›

Melanie Ulitschka, Jens Bauer, Frank Frost, Thomas Arnold, "Ion beam planarization of optical aluminum surfaces," *J. of Astronomical Telescopes, Instruments, and Systems,* **6**(1), 014001 (2020) doi: 10.1117/1.JATIS.6.1.014001

A Look into the Front-End Firmware of Next-Generation Neutrino Telescopes

How precise neutrino observations were made from the depths of the Mediterranean Sea

Photograph of a digital optical module (DOM), which houses 31 photomultiplier tubes plus the front-end and readout circuitry.

Neutrinos are elusive subatomic particles that interact weakly with normal matter. As such, detecting neutrinos is difficult and requires large-scale structures known as neutrino telescopes. Unlike the more familiarly packaged optical telescope, a neutrino telescope consists of a huge array of photodetectors equally spaced over a vast volume. These photodetectors are used to sense special types of photons produced by collisions between neutrinos and ordinary matter.

KM3NeT, which stands for "Cubic Kilometre Neutrino Telescope," is a European research infrastructure that will house two next-generation neutrino telescopes placed deep in the Mediterranean Sea. The ARCA telescope, located 100 km from the southern tip of Italy, will be used to detect high-energy neutrinos coming from distant astrophysical bodies and events, including extremely energetic sources like supernovae, blazars, and pulsars. Its counterpart, the ORCA telescope, located 40 km off the coast of France, will be tailored to detect lower-energy neutrinos generated in Earth's atmosphere, helping physicists gain a better understanding of the particles themselves.

Both of these telescopes will consist of arrays of submerged digital optical modules (DOMs). Each DOM is essentially a glass sphere 43 cm in diameter containing 31 photomultiplier tubes and the necessary control and communication circuitry. These tubes convert Cherenkov photons produced by neutrino collisions into an electrical signal; by observing the timing of the signals generated at different detectors, it is possible to precisely determine the trajectory of an incident neutrino.

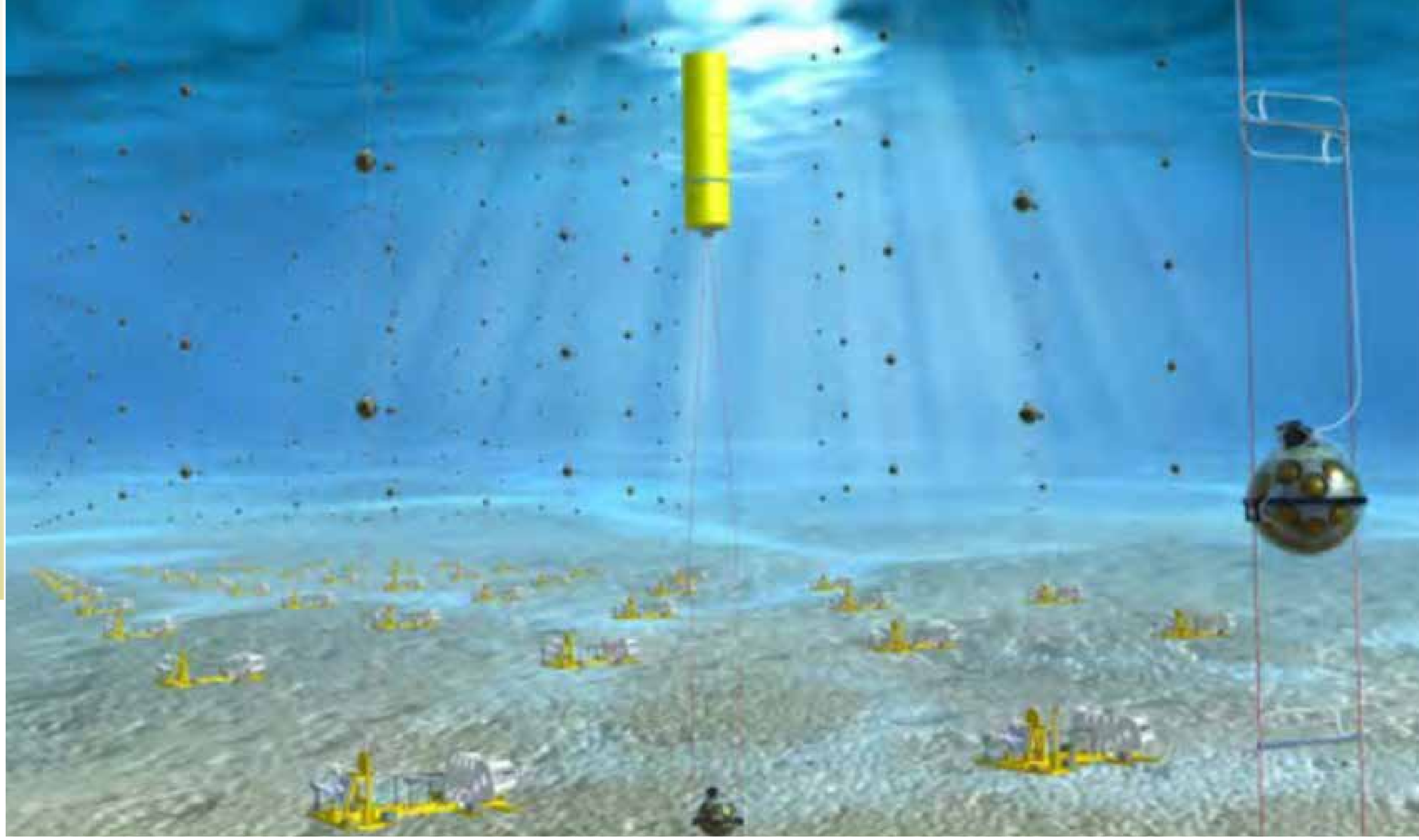
As straightforward as all of this may sound, digitizing, storing, pre-processing, and finally sending the data gathered by up to thousands of DOMs requires a carefully designed front end. Fortunately, the front-end firmware of the KM3NeT DOMs has been described in detail in a recent article published in SPIE's Journal of Astronomical Telescopes, Instruments, and Systems. Developed by a large international team of researchers, the front-end firmware of the DOMs had to be designed with many performance, energy, and flexibility constraints in mind.

The platform on which the front-end firmware of each DOM is embedded is a field programmable gate array (FPGA), a type of circuit that can be programmed after fabrication depending on the user's needs. In the FPGA of each DOM are coded 31 time-to-digital converters (TDCs)—one for each photomultiplier tube. When the electric signal produced by a photomultiplier tube exceeds a predefined threshold, its associated TDC records the exact time the threshold was exceeded and for how long the signal remained over it. This is recorded as a "hit" and digitally stored. Ultimately, another part of the circuit, called the state machine, organizes all the hits generated by the TDCs, encodes them in a usable format, and transmits them to the shore through an optical cable for processing.

A remarkable aspect of the implemented TDCs is their resolution. "The most important element to reconstruct the particle trajectory from the Cherenkov photons is the arrival time of the light on the photomultiplier tubes," said Dr. David Calvo of the Instituto de Física Corpuscular at CSIC—Universitat de València in Spain, one of the corresponding authors of the article. "For KM3NeT, the relative arrival time should be known with an accuracy of 1 nanosecond, which provides an angular resolution of 0.1° for astrophysical events," he said. Although the resolution implemented in the TDCs is of exactly 1 nanosecond, it could be increased in theory up to 250 picoseconds through a few straightforward modifications.

Other attractive features of the implemented firmware are the multihit and high-rate veto capabilities. The multihit option allows the system to record hits longer than the inherent 255 nanosecond limit, often associated with unexpected long-duration physical phenomena, by "combining" multiple consecutive observations. Meanwhile, the high-rate veto feature allows the system to automatically detect when photons are coming from sources other than neutrinos, such as bioluminescence from deep-sea lifeforms. When this happens, the detectors temporarily stop recording to avoid storing and sending useless data.

The future of neutrino observation has never looked brighter!



Artist's representation of a deep-sea neutrino telescope, showing DOMs deployed in a 3D grid. Figures credit: Sebastiano Aiello et al., doi 10.1117/1. JATIS.7.1.016001

SUMMARY

The KM3Net will house two next-generation neutrino telescopes deep in the Mediterranean Sea. These will consist of a large 3D grid of thousands of digital optical modules (DOMs) to detect neutrino collisions with ordinary matter. In a recent article, scientists describe in detail the front-end firmware developed for the DOMs. High performance, reliability, and design flexibility make the developed firmware a solid foundation for the KM3NeT telescopes, paving the way for accurate neutrino observations.

View the full article ›

Sebastiano Aiello et al., "Architecture and performance of the KM3NeT front-end firmware," *J. of Astronomical Telescopes, Instruments, and Systems*, **7**(1), 016001 (2021) doi: 10.1117/1. JATIS.7.1.016001

Smart Calibration Procedure for **Fiber Positioners** in Multiobject Spectroscopy

Researchers devise a simple and accurate calibration protocol to help special telescopes image multiple stars and galaxies simultaneously

Recently, a novel approach for observing celestial objects far away in space has been gaining traction. This approach, called "multiobject spectrometry (MOS)," relies on the accurate positioning of small optical fibers right where the images of desired celestial targets would form on a telescope's focal plane. This strategy allows one to detect signals coming from hundreds of stars and galaxies simultaneously that enables huge and highly efficient surveys.

For MOS devices to work properly, it is essential to position and angle the optical fibers precisely on the telescope's focal surface (an imaginary surface on which initially parallel rays converge to a focus). To achieve this high degree of precision, scientists rely on mechanical systems known as "robotic fiber positioners," which are small robotic arms with two motorized rotational joints. Through a careful commanding of the motors, the robotic positioner maneuvers the fiber's end towards its correct location and angle on the focal surface.

However, there are many potential sources of error in the fiber positioning process. Considering that MOS telescopes can have hundreds and even thousands of fiber positioners, their calibration can be formidably non-trivial and extremely time-consuming. Therefore, a reliable and convenient way is needed to calibrate them as well as check their performance.

Against this backdrop, a new study by Luzius Kronig et al. from Ecole Polytechnique Fédérale de Lausanne, Switzerland, proposed an automatic procedure to characterize, calibrate, and validate robotic fiber positioners for MOS telescopes. Their approach and results were published in SPIE's Journal of Astronomical Telescopes, Instruments, and Systems.

The measurement setup required for their procedure is relatively straightforward and low-cost. It involves securing a fiber positioner on a V-shaped groove and feeding a laser beam through the fiber. The laser beam passes through a convex lens, creating a light cone that hits a diffuser screen placed one focal distance away from the lens. Two optical cameras then come into play. The first one is pointed directly at the plane of the convex lens and serves to measure the position of the fiber's end. The second camera is pointed at the diffuser screen and is used to infer the tilt of the incident light cone. In turn, this is used to precisely calculate the tilt of the fiber.

The researchers had to address the main sources of error in this measurement setup. They compensated for the distortion of the cameras by imaging a checkerboard pattern and calculating a correction vector for each pixel. Afterwards, they used a simple iterative procedure to ensure that the diffuser screen was placed precisely one focal length away from the concave lens. Finally, they used a high-precision roundness calibration cylinder to determine the absolute angle of the V-shaped groove, which is used as a reference for determining the absolute tilt of the positioner. Multiple experiments proved that this calibration setup leads to precise and highly consistent results. Errors in the absolute fiber tilt were below one hundredth of a degree, while position errors were below five micrometers.

SUMMARY

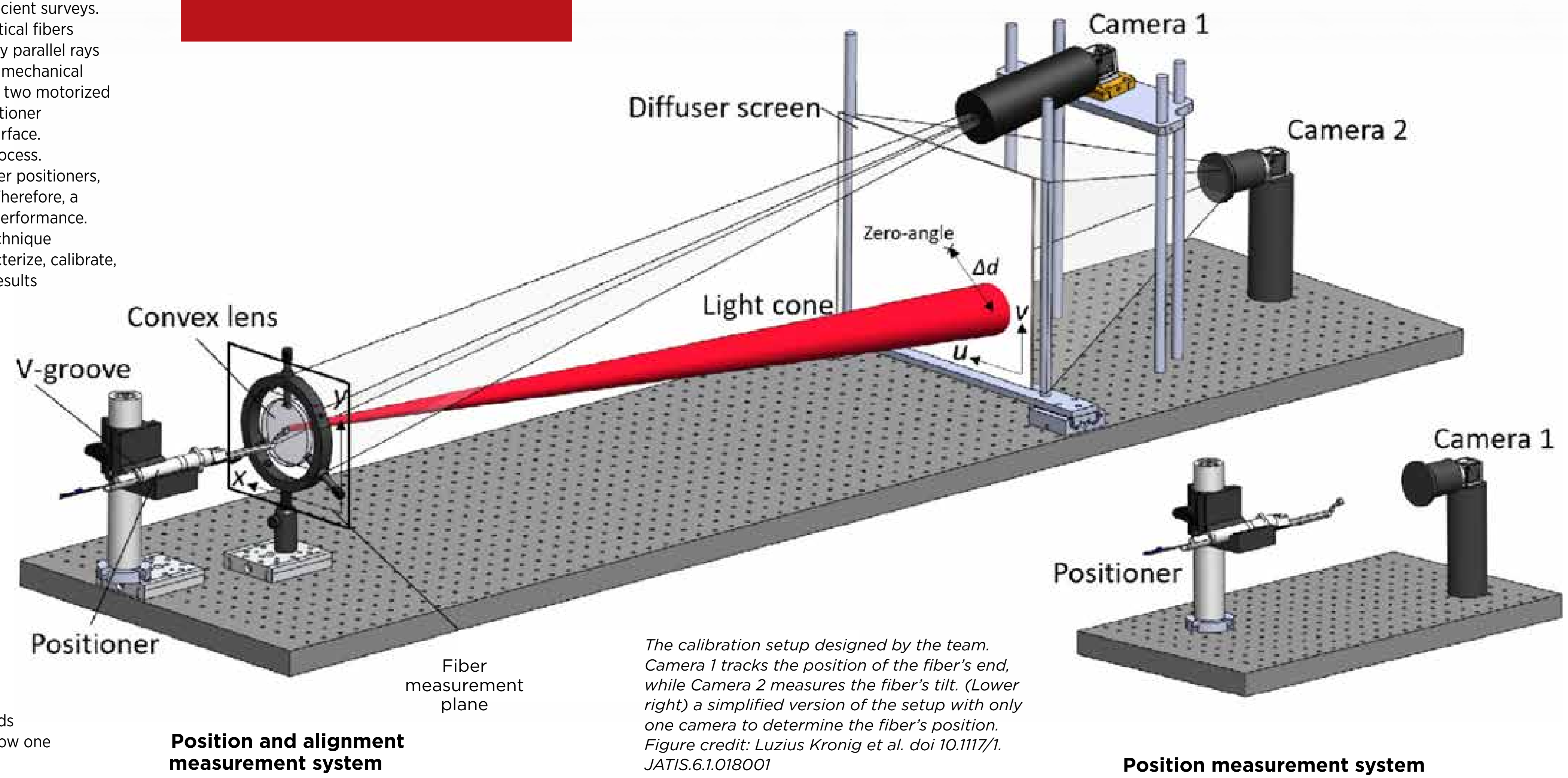
Multiobject spectroscopy (MOS) is an emerging approach that uses multiple optical fibers to observe hundreds of stars and galaxies simultaneously. These fibers need to be precisely positioned using robotic fiber positioners. However, the calibration of these positioners can take extremely long. In a new study, scientists from Switzerland present a simple yet highly accurate procedure to automatically characterize, calibrate, and assess the performance of these fiber positioners, paving the way for efficient MOS-based astronomy.

However, the researchers did not stop there. They designed a series of detailed mathematical models describing a general fiber positioner, including aspects such as the nonlinearity arising from using reduction gears, and the alignment and wobbling of the positioner's rotation axes. By combining the calibration setup and these models, the researchers developed a procedure involving various repeated measurements to calibrate and assess the performance of the positioner. This allowed them to evaluate various metrics, such as measurement repeatability, roundness of the axes, and hysteresis.

Overall, the experimental results paint a bright future for the proposed characterization and calibration strategy. With any luck, MOS technology could pave the way to a new era of astronomy.

View the full article ›

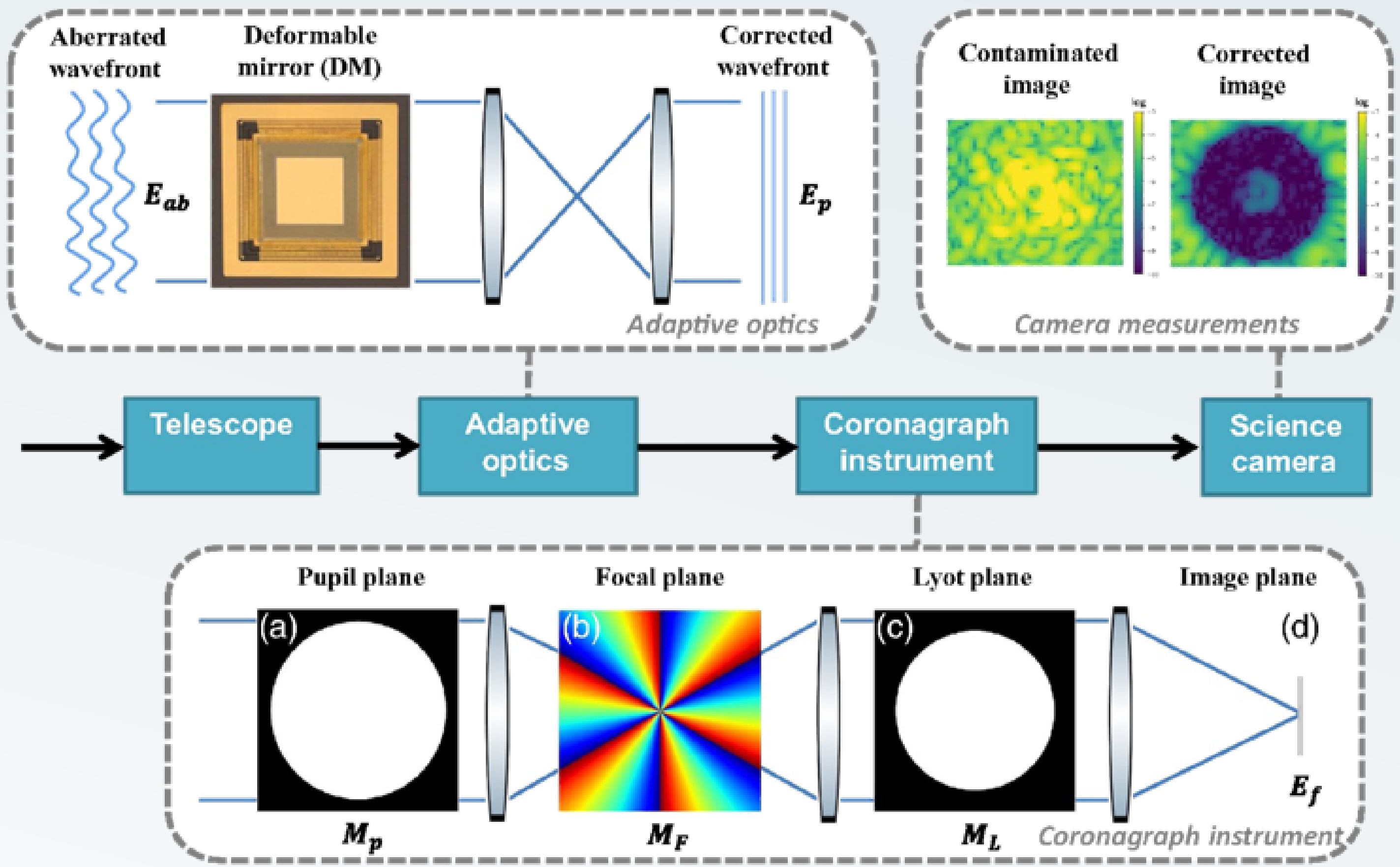
Luzius Kronig, Philipp Hörler, Stefane Caseiro, Loïc Grossen, Ricardo Araujo, Jean-Paul Kneib, Mohamed Bouri, "Optical test procedure for characterization and calibration of robotic fiber positioners for multiobject spectrographs," *J. of Astronomical Telescopes, Instruments, and Systems,* **6**(1), 018001 (2020), doi: 10.1117/1.JATIS.6.1.018001



The calibration setup designed by the team. Camera 1 tracks the position of the fiber's end, while Camera 2 measures the fiber's tilt. (Lower right) a simplified version of the setup with only one camera to determine the fiber's position. Figure credit: Luzius Kronig et al. doi 10.1117/1.JATIS.6.1.018001

Optimizing for Fast, High-Contrast Imaging with Adaptive Optics for Space Telescopes

Researchers provide an approach for a quicker sensing and correction of distortions in light signals from faint astronomical objects



A schematic representation of a space telescope fitted with adaptive optics and a vortex coronagraph. This layout is almost exactly the same as the one simulated by the researchers in their study, except they used an extra deformable mirror. Figure credit: He Sun et al., doi 10.1117/1.JATIS.6.1.019001

The search for faraway Earth-like exoplanets, which could possibly contain traces of life, is at the forefront of astronomical research. In this regard, large space telescopes are a promising tool for providing insights into these planets. Since the signals from these exoplanets are usually very faint and are often obscured by starlight, these telescopes are equipped with a coronagraph, which suppresses the stronger background from starlight. Additionally, the telescopes also use a technology called "adaptive optics" (AO) which corrects for distortions in the signal by deforming a mirror (called a "deformable mirror") to compensate for the distortion.

The use of AO is fairly common in ground-based telescopes, since they often need to correct for the distortions in light signals caused by atmospheric turbulence. However, the transfer of this technology to space telescopes is far from straightforward. This is because the image contrast requirement in space telescopes is much higher compared to that for ground telescopes. This rules out using a separate sensor for measuring the signal distortion (commonly used in ground telescopes) as it introduces "noncommon-path errors," characterized by persistent speckles in the image. While improved technologies have been proposed for light field sensing, they have focused mainly on estimating the distortion-corrected light field. However, acquiring images is also an important aspect of space missions. Since the signals from distant objects are faint, sensing them can take a long time. Reducing this time to make more time for scientific observations, such as detecting an astronomical object from the images, is, therefore, equally important.

A new study by researchers from Princeton University and California Institute of Technology, USA, has now addressed this issue in a new model for space-based AO. This model improves the sensing using optimized deformable mirror probing commands and considerably reduces the time of camera exposure and, in turn, image acquisition. Their results are published in the Journal of Astronomical Telescopes, Instruments, and Systems.

The team demonstrated their approach and its results with a simulation of a space-based AO system equipped with a vortex coronagraph (used for imaging very faint objects near a bright star) and tested for five different sensing approaches based on camera exposure policies, including the benchmark. The simulation results showed that a policy based on the benchmark probe but an adaptive exposure time provided the fastest convergence to the desired high contrast.

Hopefully, this new technique is a step towards uncovering the mysteries hiding behind the glare of the stars!

SUMMARY

To properly image faint exoplanets among brighter stars, space telescopes need to correct for distortion in their signals. While this can be achieved by using adaptive optics (AO) and is commonly used in ground telescopes, the contrast required in space telescopes is much higher, making the image acquisition and distortion correction time-consuming. Now, researchers from the US present an optimized model for a space-based AO system that significantly speeds up image capture and distortion correction.

View the full article ›

He Sun, N. Jeremy Kasdin, Robert Vanderbei, "Efficient wavefront sensing for space-based adaptive optics," *J. of Astronomical Telescopes, Instruments, and Systems,* **6**(1), 019001 (2020) doi: 10.1117/1.JATIS.6.1.019001

Advancing Primary Mirrors for Space Telescopes Capable of Observing Earth-like Planets

Review article summarizes the outcomes of a six-year project by NASA to mature key technologies for exoplanet astrophysics

SUMMARY

Observing planets beyond the solar system is a challenging task and requires huge leaps in telescope technology. In a review article, optical physicist Dr. H. Philip Stahl summarizes the findings of NASA's Advanced Mirror Technology Development project, whose objective was to develop key technologies to improve the primary mirrors of large-aperture space telescopes. The results of this project bring us closer to telescopes truly capable of imaging distant Earth-like planets.

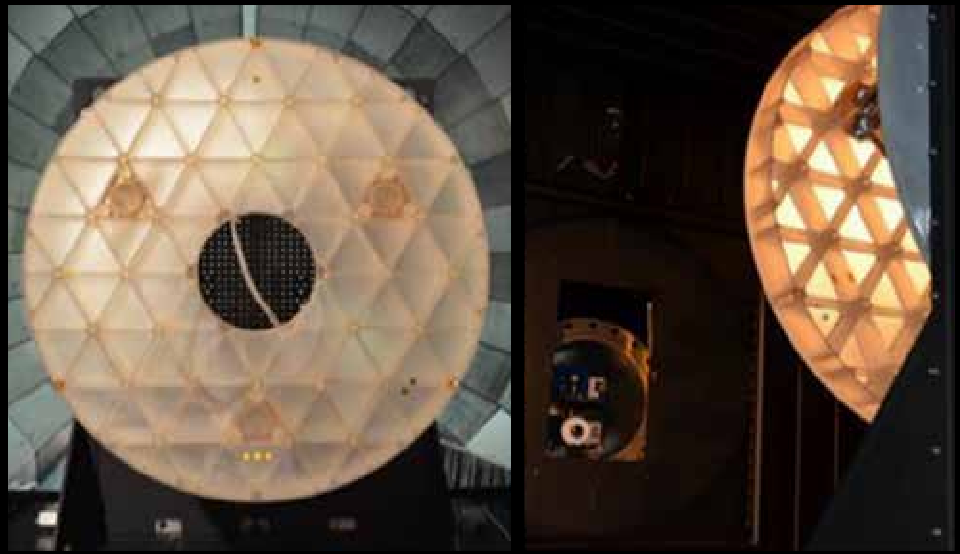
Are we alone in the Universe? Humans have probably been asking this question for eons. It, therefore, comes as no surprise that one of the most rapidly growing fields in astrophysics is the study of planets outside our solar system. Unfortunately, observing these exoplanets is quite challenging, especially so for rocky planets located in the habitable zone of distant stars. This is because light coming from the planet's parent star produces a strong glare on the telescope, obscuring the planet. Additionally, there are other sources of noise and error stemming from imperfect fabrication and harsh operating conditions of telescope components.

Put simply, exoplanet astrophysics currently requires some major leaps in telescope technologies if we are to ever observe Earth-like planets with more clarity. On this front, NASA and its partners have been working on some of the major challenges involved. One example is NASA's Advanced Mirror Technology Development (AMTD), a six-year project that began in 2012 with the aim of maturing critical technologies required to enable 4-meter (or larger) primary mirror (the main light-capturing surface of a telescope) assemblies for space telescopes.

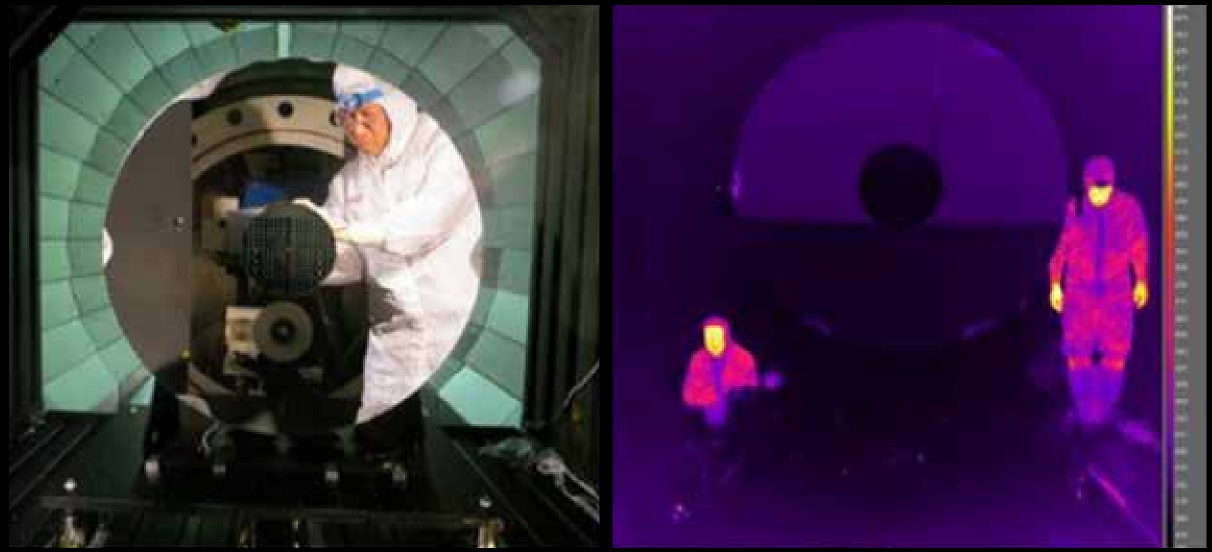
In an article published in SPIE's Journal of Astronomical Telescopes, Instruments, and Systems, Dr. H. Philip Stahl, Senior Optical Physicist at NASA Marshall Space Flight Center, USA, has summarized the methodologies and results of the AMTD project. The project was a remarkable collaboration between a Science Advisory Team and a Systems Engineering Team. While the science team provided expert advice in exoplanet astrophysics, the engineering team provided expertise in the design, fabrication, and testing of telescopes.

The AMTD researchers focused on six key technologies to build the primary mirror assembly for large-aperture ultraviolet, optical, and infrared (UVOIR) space telescopes. First, they used a fabrication process called "stack and fuse" to produce ultra-stiff, ultra-stable, but relatively lightweight mirror substrates. This helped reduce certain observation errors and made them viable for missions with a limited payload. Next, the AMTD worked on the design and fabrication of the mirror's support systems, which ensure that the mirror survives launch and can operate in orbit without suffering deformations. The AMTD team used special software tools to model and evaluate many substrate and support designs.

The third key technology was the realization of mirrors with an extremely smooth surface. This helped minimize mid- and high-spatial frequency errors, which can arise from temperature-induced deformations, irregular surface roughness from polishing, and low thermal stability of the mirror's mount. The fourth and fifth key technologies were improving segment edges and segment-to-segment gap phasing ("segment" refers to the building blocks of a specific class of telescope mirrors, which comprise many small mirrors arranged in 3D to produce the same image as a larger, standalone mirror). While these two technologies proved particularly challenging to advance, the AMTD project did celebrate some small victories.



Schott 1.2-m ELZM.



Harris 1.5-m ULE (coated for emissivity)

Photographs of two smaller-scale model mirrors being tested in a thermovacuum chamber. The performance of these mirrors was carefully assessed by the AMTD team to validate integrated teslescope models. Figure credit: H. Philip Stahl, doi 10.1117/1.JATIS.6.2.025001

Last, the sixth key technology addressed the validation of integrated models of space telescopes. The researchers first developed ideal models for a pair of smaller-scale mirrors that were then fabricated. Following this, more realistic models of these as-built mirrors were obtained using X-ray computed tomography. Finally, the performance of the mirrors was tested in a highly specialized thermovacuum environment.

Overall, the AMTD project has undoubtedly advanced the state-of-the-art for large UVOIR space telescope mirrors. Hopefully, further efforts in this area will yield answers to the fundamental questions in astrophysics, such as how stars are organized within galaxies, how galaxies interact with the intergalactic medium, and how planets form and evolve. With any luck, we could soon observe Earth-like exoplanets in more detail, and, perhaps, find evidence of extraterrestrial life!

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H. Philip Stahl, "Advanced ultraviolet, optical, and infrared mirror technology development for very large space telescopes," *J. of Astronomical Telescopes, Instruments, and Systems,* **6**(2), 025001 (2020), doi: 10.1117/1.JATIS.6.2.025001

Calibration is Key:

A Second Look at the Gemini Planet Imager Calibration

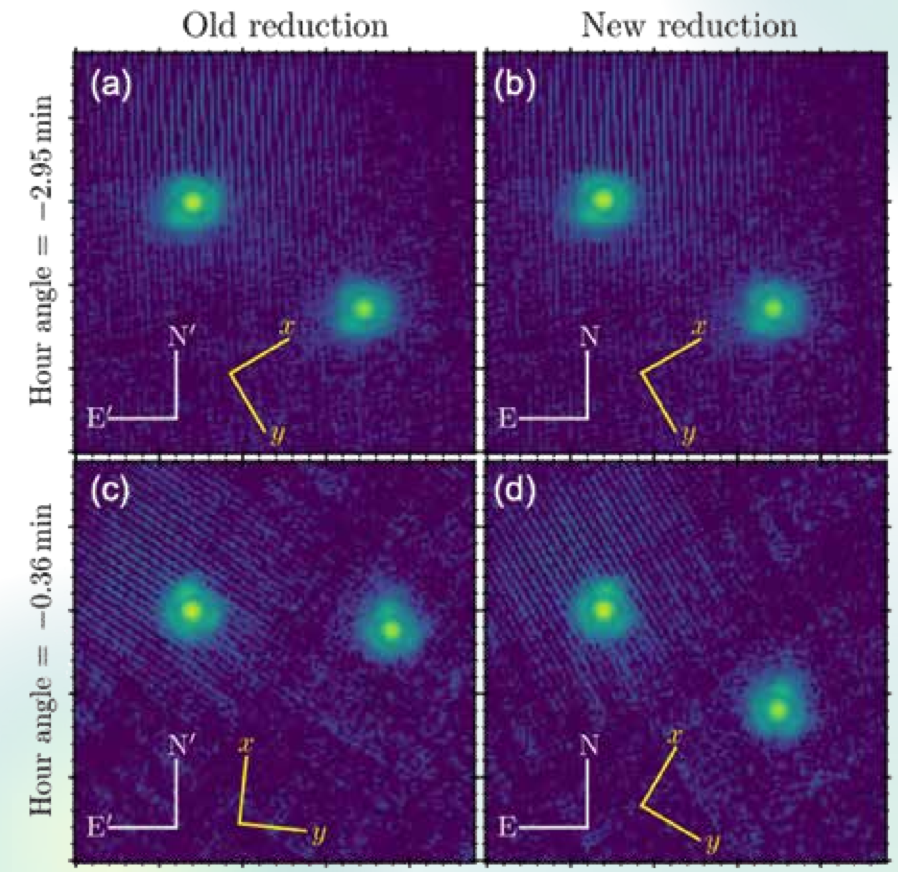
Researchers identify and correct issues in the astrometric calibration of the Gemini Planet Imager, yielding precise position measurements of exoplanets.

Currently housed at the Gemini South Observatory in Chile is the Gemini Planet Imager (GPI), a sophisticated instrument designed to resolve and image planets and other bodies in the vicinity of young stars. The GPI can image these through high contrast at small angular separations, providing a window into the darkest and deepest regions of space.

In addition to imaging, the GPI can be used to map the orbits of brown dwarfs and exoplanets. Like many other high-contrast imaging systems, the GPI requires highly accurate astrometry, which is the precise measurement of the positions and movements of stars and other celestial bodies over time. The GPI uses an integral field spectrograph (IFS) and polarimeter to collect image data of faint exoplanets next to nearby host stars and can measure their location to a precision of approximately a 700th of a pixel!

SUMMARY

The Gemini Planet Imager is an instrument designed to image and measure the positions and orbits of exoplanets. While it has been extensively used, scientists realized that there were issues with its calibration. By adjusting the data reduction pipeline, they corrected and improved the calibration of the GPI. The calibration was then used to retrospectively determine the correct positions of all the exoplanets that have been measured using the GPI to date.



An example of the corrections to the data reduction pipeline of the Gemini Planet Imager. The figure demonstrates that the correction is significant only for observations at low angles (images (c) and (d)). Figure credit: Robert J. De Rosa et al., doi 10.1117/1.JATIS.6.1.015006

For this precise position data to be practically useful and comparable to other telescope systems, it needs to be converted from pixels into an absolute on-sky separation and position angle, which requires an accurate astrometric calibration of the instrument. However, over time, researchers came to realize that the calibration might contain some issues and systematic biases, particularly when determining the true north angle. As a result, a collaborative team of researchers from 33 scientific institutions conducted a careful, thorough reassessment of the GPI's astrometric calibration. The work, which includes cross checks of the GPI data reduction pipeline, analyzing, and comparing the performance of several Gemini Observatory systems, and a complete reanalysis of all of the astrometric calibration targets observed with GPI retrospectively, has been published in the Journal of Astronomical Telescopes, Instruments and Systems.

The researchers found several issues with the GPI data reduction pipeline (DRP), which transforms the raw spectrograph data the GPI collects into science-ready, calibrated data structures.

The calibration consisted of a plate scale that converts pixels to arcseconds, and an offset to the north angle. The largest discrepancy was observed for the north offset angle, which was recorded as −0.10 ± 0.13 deg in the original erroneous calibration and was now found to range from 0.17 ± 0.14 deg to 0.45 ± 0.11 deg, depending on the date. Such differences can lead to largely different position measurements, particularly at low zenith angles.

The plate scale of the instrument did not show much discrepancy with the original calibration, although it incurred a larger uncertainty. In addition to the corrections to the data reduction pipeline that affected the astrometric calibration and subsequent measurements, the scientific team also corrected issues in data storage, where the header containing critical information was sometimes erroneous, as well as modeling any issues from image rotation.

The authors are hopeful that their work can serve as "a guideline for future instruments with very narrow fields of view, which will require a careful and thoughtful calibration strategy to reduce and mitigate any biases and unwanted effects."

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Robert J. De Rosa et al., "Revised astrometric calibration of the Gemini Planet Imager," *J. of Astronomical Telescopes, Instruments, and Systems*, **6**(1), 015006 (2020), doi: 10.1117/1.JATIS.6.1.015006