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Review

Emerging technology for astronomical optics metrology

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ABSTRACT

Next generation astronomical optics will enable science discoveries across all fields and impact the way we perceive the Universe in which we live. To build these systems, optical metrology tools have been developed that push the boundary of what is possible. We present a summary of a few key metrology technologies that we believe are critical for the coming generation of optical surfaces.

1. Introduction

Next generation space and ground based astronomical optics are bringing about exciting developments in our scientific understanding of the Universe in which we live. From solar science, exoplanet detection, to dark matter and first light investigations, the scientific community around the world is pushing the limits of our fundamental knowledge through astronomical optics. To build the next generation of telescopes, which will enable this work, new metrology methods and tools have been developed. We (see Vitae for brief description of the authors) believe that recognizing and highlighting some key emerging technology in this area will be beneficial for the scientific community.

1.1. Science motivation

Before discussing the recent developments in the field of astronomical optics metrology, we want to provide some motivation for why the tools were developed by discussing the exciting science that they are enabling. We hope that this will serve to put the technology in the larger context of how astronomy, fundamental science, and physics exist in a synergistic relationship with the optics community.

In the 2010 decadal survey report from the U.S. National Academies, *New Worlds, New Horizons in Astronomy and Astrophysics (NWNH)* [1], the most important science questions that should be addressed are identified and a prioritized listing of the major missions and facilities that are needed to realize the science goals is provided. Among the highest priority missions and facilities are the James Webb Space Telescope (JWST), the Wide Field Infrared Survey Telescope (WFIRST), the Large Synoptic Survey Telescope (LSST), and a Giant Segmented Mirror Telescope (GSMT). Each of these facilities, performing close to their theoretically achievable limits, will provide previously unobtainable observational capabilities, both in spatial resolution and sensitivity. Achieving this level of performance from these facilities requires cutting edge technology in both the fabrication and testing of the optical systems.

Three giant telescopes are under construction that should address the science goals identified in *NWNH* by a GSMT. They will explore the Universe with observations from mid-IR to near-UV wavelengths. The Giant Magellan Telescope (GMT), with an effective 24.5 m diameter primary mirror, will be located at the Las Campanas Observatory in Chile. The Thirty Meter Telescope (TMT) is currently planned for either Mauna Kea, in Hawaii, or the Canary Islands. The Extremely Large Telescope (ELT) is being built in Chile by the European Southern Observatory (ESO). Each of these observatories has challenging science and technical requirements that when met will enable these facilities to yield spectacular results.

The images we display in Fig. 1 are examples of how critical achieving the highest spatial resolution in the science images can be to realizing the science goals. To study the disks of debris and gas around distant stars from which planets form (e.g. Fig. 1(a)) and to image the exoplanets themselves (e.g. Fig. 1(b)) requires sub arc second spatial resolution and high contrast imaging. The ability to realize such images of the faint companions of the much brighter stars around which the planets orbit is enabled by adaptive optics systems.

NASA's 2.4 m Hubble Space Telescope (HST) revolutionized our ability to study the detailed structure of extremely distant galaxies. Observed behind foreground clusters of galaxies, the great mass of the foreground cluster amplifies and magnifies the images of the back ground galaxies. However, this "strong lensing" also distorts the images, see Fig. 2(a), requiring exquisite optics that enable the intrinsic properties of the galaxies to be well measured. NASA's 6.5 m JWST, scheduled for launch in October of 2018, will improve our ability to detect and study substructure in distant galaxies as shown in Fig. 2(b) because the optics

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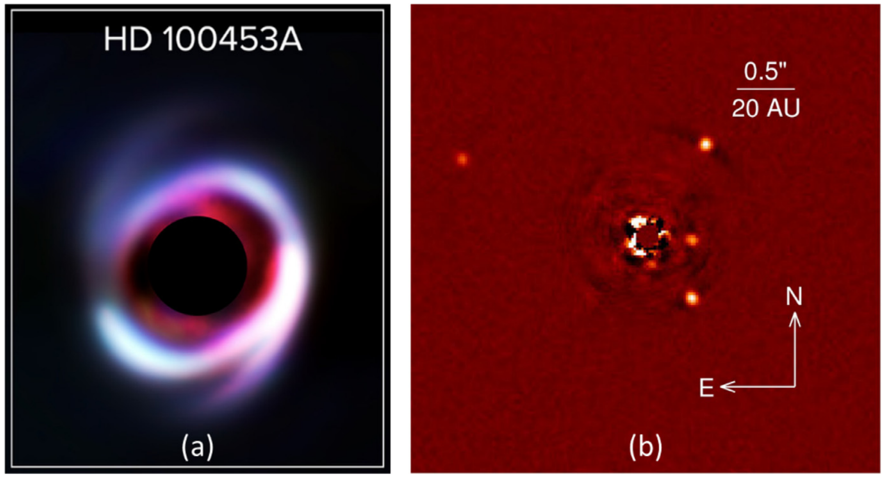

Fig. 1. Science images enabled by adaptive optics systems: (a) A double-armed spiral image in a planet-forming disk around the young star HD100453 using a coronagraph and an extreme adaptive optics system (VLT/SPHERE) as reported in Wagner et al. [2]. This unusual disk structure is most likely driven by a stellar companion outside the disk or a massive planet within the disk. Image credit: K. Wagner (Univ. Arizona), (b) exoplanet detection around HR 8799 imaged with the LMIRCam of the Large Binocular Telescope [3]. Image credit: P. Hinz (Univ. Arizona).

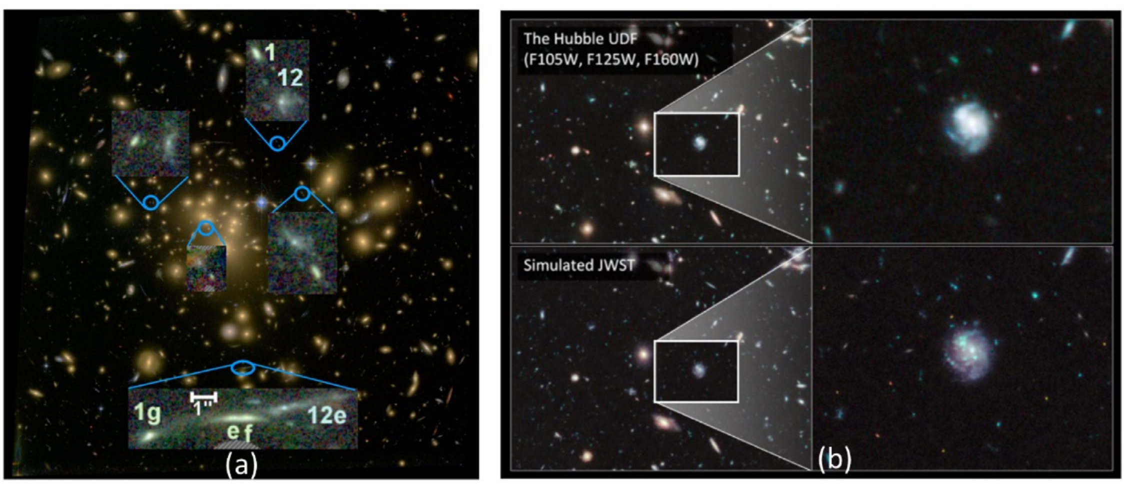

Fig. 2. Improving image quality through larger and more exquisite optics: (a) strong gravitational lensing distorts images in the Hubble Space Telescope (HST) [4], which contain information that the next generation of telescopes such as the James Webb Space Telescope (JWST) will resolve. Image credit: B. Frye (Univ. Arizona), (b) simulation of the improved resolution capabilities of the JWST compared to the HST [5]. Image credit: STSCI.

for the telescope will allow the theoretically achievable improvement in resolution provided by the larger primary mirror of JWST.

The giant ground based telescopes now being constructed: 25 m Giant Magellan Telescope (GMT), 30 m Thirty Meter Telescope (TMT), and 39 m ESO Extremely Large Telescope (ELT) will provide images of the highest spatial resolution, comparable or better to the interferometric imaging now being made, of bright targets, by the Large Binocular Telescope Observatory from Mount Graham in Arizona with its 23 m baseline. In Fig. 3(b), the exquisite 0.02″ image of Jupiter's moon IO reveals remarkable details of the surface, including hot spots from Io's volcanic activity. Images with this kind of spatial resolution, but with the full collecting area of the giant telescopes under construction, will be transformative to our study of the entire Universe, from exoplanets to the most distant galaxies.

2. Emerging metrology

The science goals of the next generation telescopes are enabled in part by unique optical surfaces. Testing the optical surfaces requires precision, accuracy, and many times, new metrology methods. Each novel technology enables a critical aspect of the optical surface to be measured, and therefore fabricated. One reason the optical surfaces of the next generation telescopes are challenging to measure is because the science dictates more complex optical specifications. At the same time, the surfaces are also becoming more aspheric, and therefore require non-traditional test methods. In order to produce magnificent results while imaging through the Earth's atmosphere, improvements in the metrology for adaptive optics are also critical for enabling the science. A few key innovations in the field of metrology for astronomical optics will be presented to provide an overview of the technology in the hopes that the community may benefit from learning about the ideas and advances that others have produced.

2.1. Full spectrum measurement

Typical optical surface specifications may include peak-to-valley (PV), root-mean-square (RMS) surface errors, number of fringes across the aperture, or even Zernike term departures from nominal. However, for the highest quality, super-polished optical surfaces used for solar science, such as the Daniel K. Inouye Solar Telescope (DKIST), the traditional specification methods do not ensure low enough scattering, or high enough imaging performance, which is effected by spatial frequencies across the entire spectrum. The spatial frequencies present on the optical surface will directly map into the Point Spread Function (PSF)

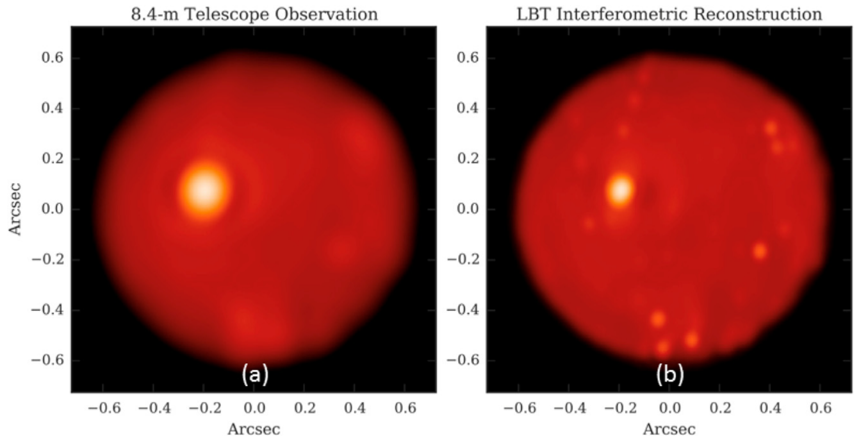

Fig. 3. Improvement in resolution results in better detection of volcanoes on the surface of Jupiter's moon Io: (a) single 8.4 m telescope image shows lower resolution compared to LBTI (b) with 90° of sky rotation [6,7]. This level of resolution obtained through interferometric imaging will be realized by the giant telescopes like GMT. Image credit: P. Hinz (Univ. Arizona) and Large Binocular Telescope Observatory (LBTO).

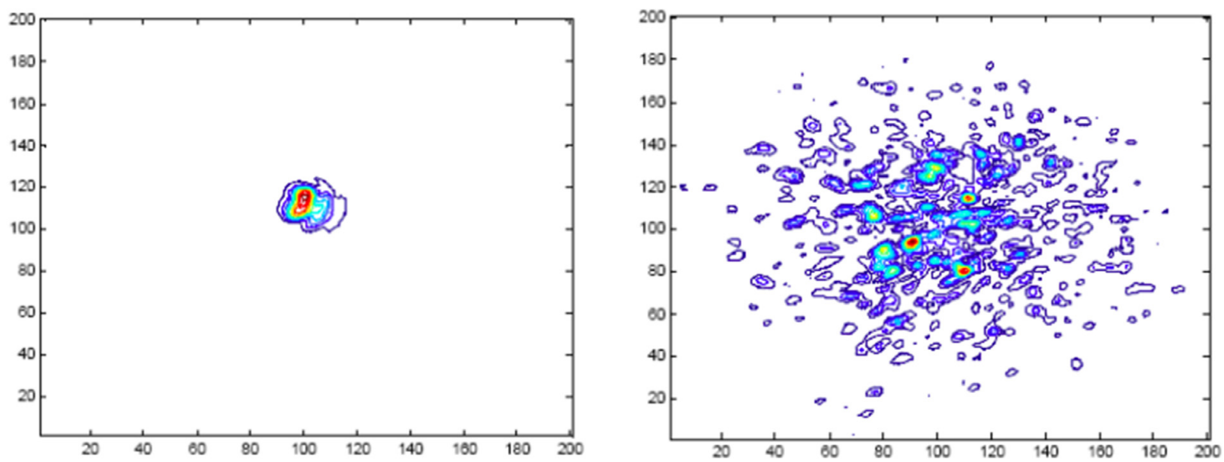

Fig. 4. Autocollimation measurements of two identically specified optical systems, on the left having a much smaller spot due to fewer mid-spatial frequency errors [8]. Note that the exposure time for the image on the right is 50 times longer than the image on the left. This means mid-spatial frequency errors also increase measurement time because the system is not as efficient. Axes are in units of pixels. Image credit: R. Parks.

of the surface. The PSF is computed by taking a Fourier transform of the exit pupil, which for a single surface is the aperture. When we have an ideal circular aperture and no aberrations, the Airy disk is formed, but given errors on the surface in the mid-spatial frequency regime, the side lobes of the airy disk become more pronounced. More power from the central lobe is spread into the sides, causing a serious degradation of the image. Shown in Fig. 4 is an example of the loss in PSF quality when mid-spatial frequency errors are present in an optical system [8]. To control the significant errors due to mid-spatial frequencies, modern surfaces are specified with a power spectral density (PSD) or Structure Function [9,10], which is a metric across the full spatial frequency spectrum that defines the amount of residual error for a given frequency in the surface's aperture. In this way, all critical spatial frequencies are controlled and the PSF is well formed.

In order to measure and test the optical surface across the low-to-mid-to-high spatial frequency regime, new test methods to fill in the gaps between traditional test methods were developed. Specifically, the mid-to-high-spatial frequency regime was in particular need. Typical test methods such as interferometers [11], or low spatial resolution profilometry [12], cover the low-to-mid-spatial frequencies, while micro-roughness measurements from white light interferometers are able to measure high-spatial frequencies very accurately [13]. The mid-to-high-spatial regime, which is becoming critical to control for modern polishing methods [14, 15], is not as readily measurable.

A slope measuring test using deflectometry and an additional auxiliary lens called Slope-measuring Portable Optical Test System (SPOTS) enabled the mid-to-high-spatial frequencies to be measured on the DKIST mirror. The concept of SPOTS is based on deflectometry, a reverse Hartmann test, which uses a display screen (e.g. LCD) and imaging camera to measure surfaces with nanometer level surface accuracy [16]. By displaying a known pattern on the screen and measuring how the pattern changes due to the reflection off the surface under test with the camera, deflectometry captures the local slope information of the surface. An integration step is then required to reconstruct the surface height information. In the case of DKIST metrology, SPOTS bridged the gap in the PSD data between the interferometer and the micro-roughness measurements [17]. Fig. 5 shows the full spatial frequency coverage that was achieved on the DKIST mirror with the multiple metrology tools [18]. With significant calibration and careful error control, SPOTS measures mid-to-high spatial frequencies with nanometer RMS level accuracy [19].

Further methods of measuring mid-to-high spatial frequencies also involve using high resolution optical profilometry. Optical profilometry tools also measure slope, but cover the spatial dimension by scanning the device on mechanical stages. The device measures the local slope of the surface, and records over time as it is moved across the entire aperture. Many samples are taken as the device is scanned, leading to very high spatial resolution. To measure the local slope, a light source illu-

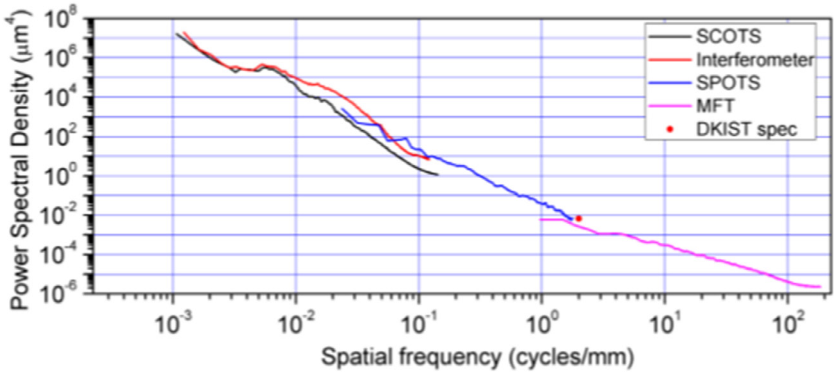

Fig. 5. Overlaid PSD plots from all four DKIST metrology systems where the PSD spec is derived from a Bidirectional Reflectance Distribution Function (BRDF) using the Rayleigh-Rice formula for super smooth surfaces [18]. The SCOTS (described in Section 2.2) and SPOTS metrology are deflectometry based, while the Microfinish Topographer (MFT) [13] and interferometer are interferometric methods. Image credit: D.W. Kim.

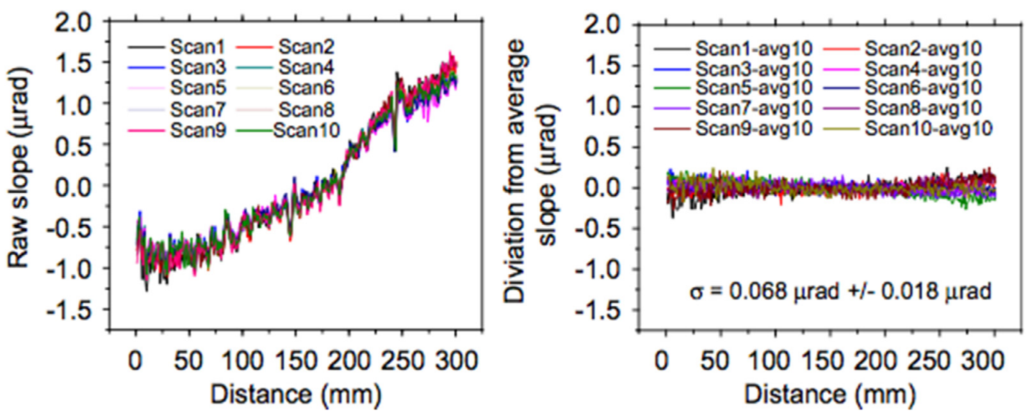

Fig. 6. Ten measurements of the same surface with the raw slopes on left, and the deviation from the averaged profile on the right. We see a sub-microradian slope accuracy [20]. Image credit: J. Qian.

minates a small area on the surface and the reflection is monitored. The change in the reflected angle is used to calculate the local slope value. With these instruments, sub-microradian slope accuracy is achievable, which results in height errors on the order of nanometers RMS [20], as shown in Fig. 6. Once again, in order to obtain high accuracy mid-spatial frequency data, calibration of the instrument is paramount [21].

Controlling the full spectrum of spatial frequency errors enables higher quality surfaces to be manufactured, which ensures that the science goals of the experiment are met successfully. New developments in this field continue to improve the accuracy of each tool and the range of spatial frequencies that it is able to measure. However, not all surfaces require such a super-polished finish, and the challenges faced in manufacturing are encountered in other areas.

2.2. Non-Null testing

Astronomical optics are starting to utilize aspheric surface shapes to enable better performance and off-axis designs. With the departure from spherical surfaces, the test methods must accommodate a larger departure from a spherical wavefront. The dynamic range of modern optical test methods must be sufficient to test such aspheric surfaces, especially during the manufacturing stage. Traditional interferometric methods utilizing null tests are designed to match a single surface shape. This means that as the surface is polished a null test cannot be used because the shape is not close enough to the final desired result. Furthermore, it is impractical to design many null tests to cover the whole polishing process. In contrast, a non-null test method is able to measure the in-process surface as it converges because of its dynamic range. For modern aspheric surfaces, the in-process metrology is critical to guide the fabrication procedure. With such tests, we can efficiently converge on the desired optical surface. Therefore, large dynamic range, non-null test methods have been developed to guide the fabrication of the next generation of optical surfaces for astronomy.

Progress in the field of non-null interferometry is a natural step from the null interferometric methods because it leverages a vast knowledge base of how interferometers operate, and can be produced. In general, interferometry provides extremely accurate surface measurements because it leverages the wavelength of light as its measurement scale by creating interference between two coherent beams. The interference pattern generated by the test beam and the reference beam contains the surface height information in the form of phase differences caused by a difference in the optical path length (OPL) of the two beams. However, retrace errors, where the light coming from the interferometer returns by a different path (varying OPL), create a significant problem. One method of mitigating such effects is to calibrate the system using a virtual interferometer and optimization algorithm [22]. This involves a model of the interferometric test, which can then be used to model the errors and optimize out the uncertainties. Experimental results indicate that this method can achieve a measurement repeatability of $\lambda/20$ PV for significant alignment errors in the test part.

Other more non-traditional methods of making surface measurements are also being developed to meet the demands of freeform optical surfaces and other non-conventional optics in the field of X-ray mirrors. One such method uses an X-ray near-field speckle scanning technique to characterize optical surface slopes with sub-microradian RMS accuracy [23]. In this method, a monochromatic, partially coherent, X-ray beam is passed through a random medium and then reflected off the surface under test. A speckle pattern is observed in reflection off the test optic

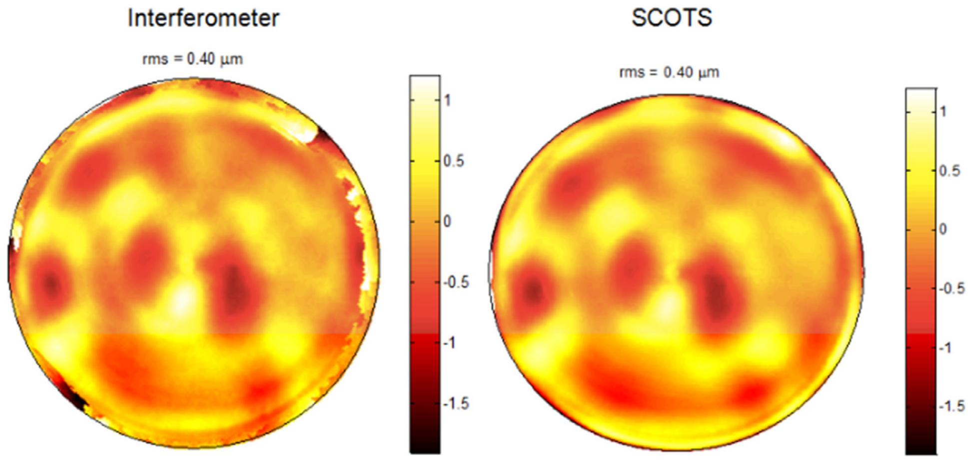

Fig. 7. Comparison between measurement results of 8.4 m diameter GMT off-axis primary segment mirror from SCOTS, a non-null deflectometry system, and a tradition interferometer. We see edge errors in the interferometric map due to high slopes, while the non-null test was able to accurately measure the edges [24]. Image credit: P. Su.

and is used to uniquely identify and then determine the local surface slope. The random medium is translated transversely to the beam in order to reconstruct the 2-dimensional surface slope.

Deflectometry is another non-null test method that achieves a high dynamic range. As such, it has been used with great success during the polishing stages on the GMT [24] and DKIST primary [25]. During the early stage of polishing on the GMT primary segment, an interferometric test could not resolve features near the edge of the surface due to high slopes as shown in Fig. 7. With a non-null deflectometry test called Software Configurable Optical Test System (SCOTS), the edge values of the mirror were measured and polishing continued in an efficient manner.

2.3. Grinding stage metrology

To efficiently manufacture the aspheric freeform optical surfaces found in the next generation astronomical optics telescopes, developments in the grinding stage metrology have been made. By guiding the high removal process of grinding through accurate metrology tools, a desired surface shape is obtained rapidly, saving manufacturing time and reducing costs. Measuring a surface that is still being ground is significantly different from polished surface metrology due to the surface roughness, and rapidly changing surface profile. Scattering from the surface prevents tools that rely on a specular reflection from working, while a contact profilometry measurement takes too much time to be useful after each grinding step. Therefore, new metrology tools are being developed to overcome these challenges and enable efficient surface measurements of ground surfaces.

Steps towards deterministic generation of optical surfaces in the grinding stage are made possible not just by metrology of the surface being fabricated, but also the machines under computer control that are moving the grinding tool. One example of this calibration is at the Large Optical Generator, which is being used in the fabrication of the GMT mirror segments. The LOG is a giant gantry type numerically controlled machine that holds and maneuvers the tools used for grinding. Using commercially available laser trackers, the absolute position of the tool head, or cutting point, may be measured with 10 μm RMS error over the 5 m by 1 m working area [26]. A laser tracker operates by outputting a collimated laser beam that is returned to the device with a user positioned retroreflector. Using a time-of-flight (or interferometric) calculation and angular encoders in the laser tracker, the 3D coordinates of the retroreflector are computed. When the retroreflector is moved across the object being measured, we create a 3D point cloud of data describing the object. Another use of laser trackers is during the loose abrasive grinding stage, where in conjunction with Distance Measuring Interferometers (DMI), they are able to characterize the surface of the GMT mirror segments, shown in Fig. 8, with 2 μm RMS error across the entire surface [27].

On the recently completed DKIST mirror, scanning long-wave infrared deflectometry enabled a faster grinding stage by using an IR source and detector [17], shown in Fig. 9. Such a long working wavelength enables this test to measure surfaces with micrometer level roughness [28], guiding an efficient grinding stage process to converge on the desired profile more quickly than before.

After obtaining a desirable fine-ground surface, the lengthy process of polishing starts. To guide this important step, and to provide a final verification, high accuracy metrology tools are needed.

2.4. Sub-Aperture stitching metrology

As a companion to the non-null tests, a sub-aperture test using a null method has recently become an exciting resource for measuring the next generation of astronomical optics. Sub-aperture tests enable steep convex surfaces, usually found on secondary mirrors, to be measured. Traditional null and non-null tests cannot feasibly measure over large convex (or flat) apertures because the instrument to test the optic would be larger than the surface under test. Therefore, a sub-aperture stitching method is critical for the next generation of astronomical optics. In this method, small sections of the full aperture are measured individually such that the full surface is covered by many overlapping measurements and then stitched back together for a full aperture result. By having common features in each measurement, an algorithm that aligns each data set can be used to reconstruct the surface. To generate the multiple sub-aperture measurements, the system measurement geometry is changed by translating and rotating the surface under test, metrology tool, or both. By monitoring and recording the orientation of the system for each measurement, a full surface reconstruction is possible.

By definition, the sub-aperture test does not attempt to measure the full surface at once, but the aperture over which it measures may be changed to suit the instrument. One example is the implementation of an elliptical sub-aperture stitching technique [29]. Another method of annular regions has also been employed [30]. Typically, circular apertures are used and a local near-null test is achieved at each section on the surface under test. To generate the local nulls, a Computer Generated Hologram (CGH) may be used in conjunction with a reference sphere to achieve a reference arm of high quality and correct the wavefront that reflects off of the surface [31]. With careful calibration and alignment, sub-aperture stitching can achieve RMS wavefront errors on the order of 25 nm.

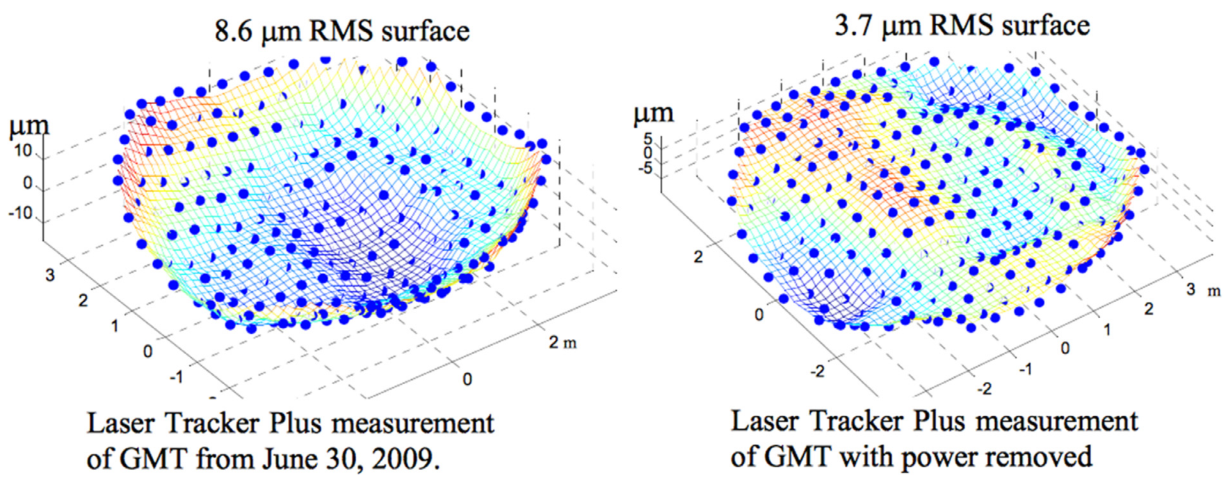

Fig. 8. Using the laser tracker system to measure the GMT surface at the end of the loose abrasive grinding stage [27]. Image credit: T. Zobrist.

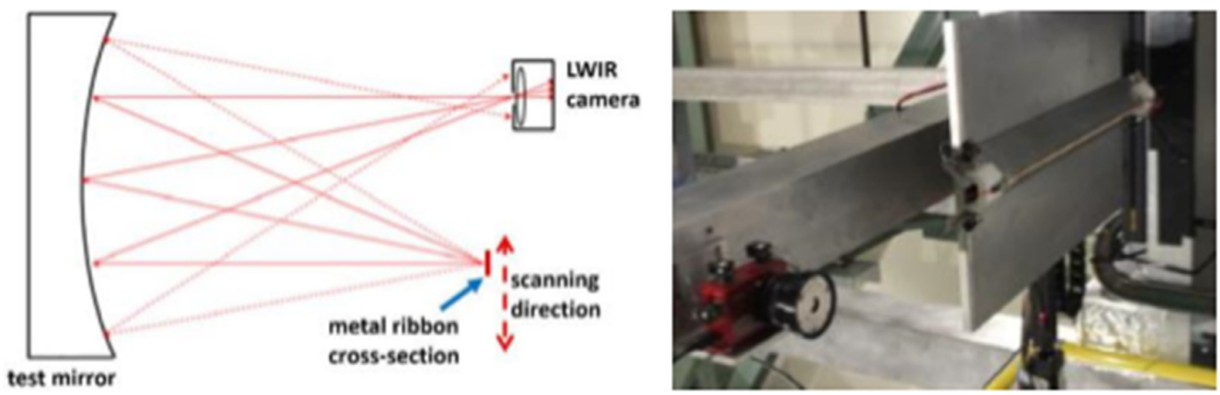

Fig. 9. Overview of the Scanning Long-wave Optical Test System (SLOTS) used for grinding stage metrology (left) and the hardware implementation of the system (right) [18].

Sub-aperture testing is particularly useful when testing large steep convex spheres. Most Cassegrain-type astronomical telescopes utilize such a surface for the secondary mirror to obtain a compact optical system. Measuring surfaces with a small R/# (ratio of the radius of curvature to the diameter) pose significant challenges that can practically only be solved using sub-aperture stitching. Specialized stitching algorithms have been developed to handle such steep surfaces, which generate unique errors when reconstructing the full aperture [32]. Shown in Fig. 10 is an experimental setup used to test a large steep convex optic, where the optic and interferometer are mounted on precision numerically controlled machines. In this setup, the test optic is rotated while the interferometer is translated such that measurements across the full aperture are collected by the interferometer.

Continuing to develop new procedures and algorithms used in sub-aperture tests will reduce the errors in the fabrication of large steep convex surfaces, increase the efficiency of producing these mirrors, and overall enable the next generation of astronomical telescopes to be built. A sub-aperture measurement is an effective way to test large convex surfaces, and will continue to be an indispensable part of the metrology toolbox for many years. The technology in sub-aperture stitching also benefits greatly from the field of null interferometric testing because that is typically the metrology tool used to perform each sub-aperture measurement.

2.5. High accuracy null tests

Along with the need for metrology methods with the ability to measure a wide variety of surfaces, sometimes in non-null configurations, there is also a need for the highest accuracy and utmost precision available in optical testing. This requirement is satisfied by the cutting edge of null tests, typically employed as the final step in fabrication as a performance verification. A null test is able to achieve the highest level of accuracy because it only yields a correct result when the mirror surface is exactly the shape designed for the test.

Fig. 10. Sub-aperture stitching measurement made of a large steep convex surface [32]. Image credit: S. Chen.

The on-going GMT project uses an interferometric null test as its final performance verification for each mirror segment. A vibration insensi-

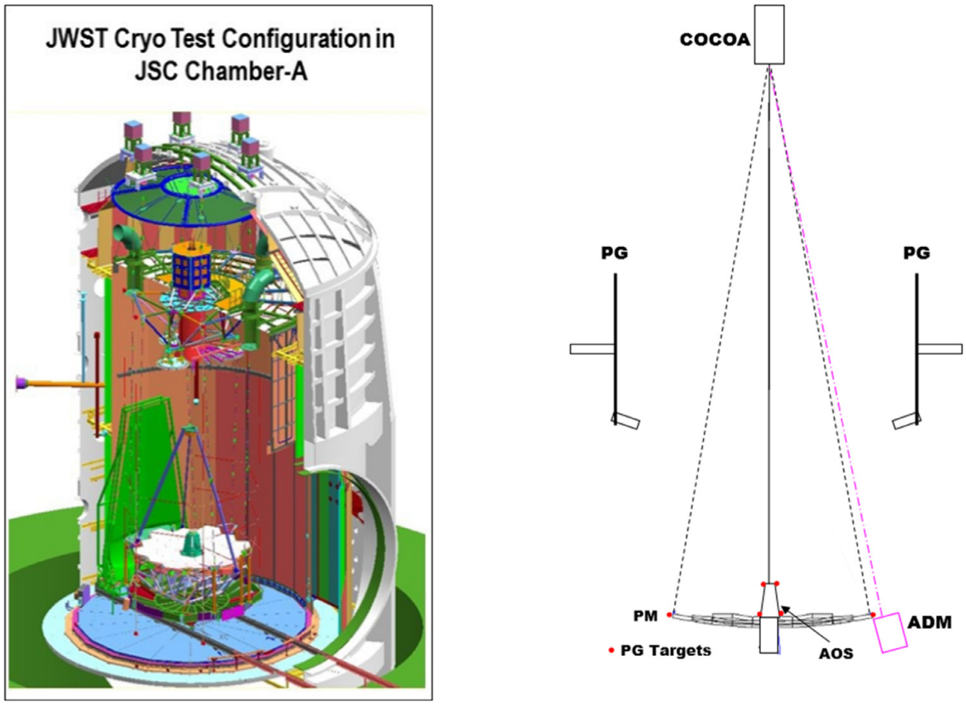

Fig. 11. JWST cryogenic test configuration shown in the cryo chamber (left) and the optical configuration (right). The Photogrammetry (PG) system is used as a global coarse alignment for the outer Primary Mirror (PM) segments and Aft Optical Subsystem (AOS), while the Center-of-Curvature Optical Assembly (COCOA) with help from the Absolute Distance Meter (ADM) assembly is used as a final phase measurement [34]. Image credit: J. Hadaway.

tive interferometer with HeNe source, CGH, and two spherical reflectors are required for such a test. Over the approximately 8.4 m clear aperture of the segment, 20 nm RMS residual error is achieved with the null test [33]. By using a CGH, which is fabricated leveraging the precision of the lithography industry, extremely accurate null tests can be implemented.

For cryogenic testing of the primary mirror in the Pathfinder James Webb Space Telescope (JWST), a center of curvature optical test consisting of an instantaneous multi-wavelength interferometer, reflective null, and calibration system are used to measure the wavefront error down to 10 nm RMS while starting from a coarse adjustment on the order of mm [34]. A diagram of this experimental setup is shown in Fig. 11. The instantaneous metrology is critical over the long path length required to be at the center of curvature because it freezes the random variations due to vibrations in the segments and the entire system, such that with many measurements they are averaged out.

High accuracy null tests are not limited to spherical or other traditional surfaces. Techniques have been developed that allow a range of freeform optical surfaces to be tested within a null condition, without significant time and effort in creating the test. One example is a reconfigurable optical null based on counter-rotating Zernike plates. With this method, many off-axis aspheric surfaces can be tested in a null configuration [35]. This testing capability could enable the use of more freeform surfaces in the smaller aperture optics used in astronomical telescopes.

However, for the highest accuracy in testing a freeform surface, custom CGHs are still the preferred method. Aligning such a component becomes a significant challenge, so building alignment features into the CGH in a smart way is critical. One exciting method uses auxiliary holograms to illuminate alignment elements outside the clear aperture that can be used for precise alignment, and therefore achieve high accuracy freeform null testing [36]. The external reference patterns are printed at the same time as the main corrector null, so they are aligned to the precision of the lithography tooling.

2.6. Instantaneous testing

Most null tests are completed at the base sphere's center of curvature in order to minimize the dynamic range. However, due to the long path length of the optical test employed at the center of curvature, air turbulence, vibrations in the mechanical structure, and temperature gradients can create too much error for traditional time domain (i.e. temporal) phase shifting interferometric tests. To overcome these challenges, instantaneous metrology tools have been developed, which capture all measurement data in a single moment of time.

The need for an instantaneous measurement spans multiple areas of the metrology for astronomical optics. An instantaneous test eliminates turbulence and air fluctuation effects from the measurement, but it can also be used to make dynamic measurements for adaptive optics, or actively controlled mirror surfaces. To create an instantaneous test, the required information for the test must be multiplexed in a single step of acquisition.

To test the flight hardware mechanics of the JWST, an instantaneous interferometer was implemented. This interferometer uses a pixel-wise phase-shifting method of multiplexing the data. Data collection rates from this instrument are 1 KHz for a 720 by 720 pixel area and 2.25 KHz for a 400 by 400 pixel area. With this high-speed interferometer, the characteristic structural responses to applied stimuli over varying locations were measured such that a transfer function for the structure could be defined [37]. Nanometer level characterization of the optomechanical systems was achieved. Without such an instantaneous capability, the test is not feasible due to the nature of applying impulses to the mechanical structure, which are a function of time.

A dynamic surface metrology is becoming more important with each new generation of astronomical telescopes. Instantaneous deflectometry provides a high dynamic range solution to this metrology need. One method of creating a snap-shot deflectometry measurement uses Fourier Transform Profilometry (FTP), which can extract the data from a single monochromatic fringe pattern [38]. Further developments in this area also include using color to create two fringe patterns, which results in lower errors in the measurement [39]. Another method using instantaneous phase shifting deflectometry instead of FTP also enables dynamic surface metrology. Instantaneous phase shifting deflectometry is a high accuracy method that can achieve agreement with interferometric data on the order of 25 nm RMS for a surface deviation of 2 μm [40], as shown in Fig. 12.

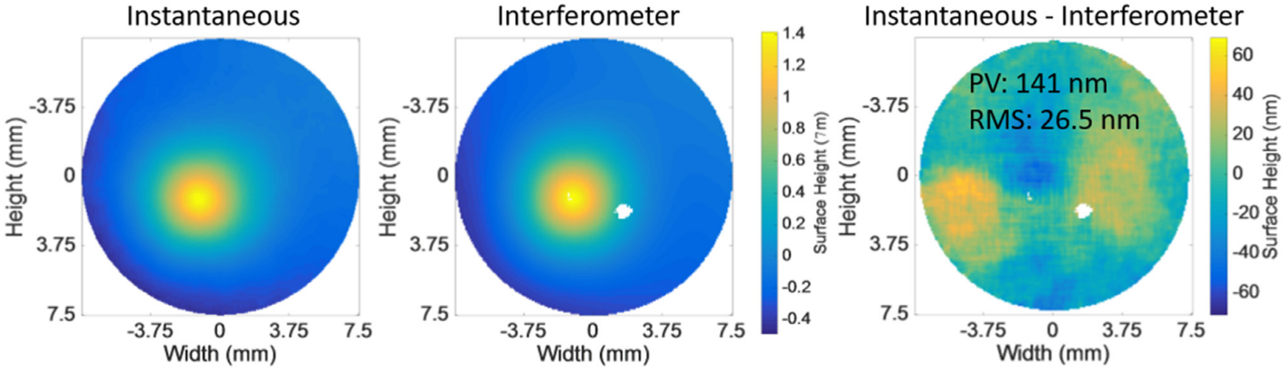

Fig. 12. Measurement results of an instantaneous deflectometry measurement (left) and a traditional interferometric measurement (center) of the same surface. The difference (right) between these two results is on the order of 25 nm RMS over the 15 mm diameter aperture for a 2 µm surface feature. Image credit: I. Trumper.

With the capability of an instantaneous measurement, we can now characterize the dynamics of an actively controlled surface, which are found on the primary with active support and/or adaptive secondary mirrors of most astronomical telescopes. The non-null benefits of the instantaneous deflectometry system can also be leveraged to test time-varying optical surfaces with a high dynamic range. The next generation of astronomical optics will depend on instantaneous metrology tools to measure the effects of time-varying changes, both desired and unforeseen.

3. Concluding remarks

Each metrology tool presented in this summary paper satisfies a niche testing requirement that when combined, forms a basis set for the types of astronomical optics that can be generated using state of the art techniques. To ensure efficient manufacturing of ever increasing apertures, metrology tools that guide fast generation are now employed. Even after a polished surface is created, the surface is not yet ideal, so accurate non-null tests provide a means of testing the in-process surfaces. To meet the demands of higher surface quality, new metrology tools developed for mid-to-high spatial frequencies have been developed. As a final performance verification, high accuracy null tests push the limits of optical testing to ensure that the desired surface has been fabricated. As more dynamic control of the optical surfaces is used, instantaneous metrology has been developed to provide a means of authenticating the system behavior. Developments in testing are not limited to complex primary mirror surfaces, but also applied to large steep secondary optics through sub-aperture stitching. These emerging technologies in the field of metrology for astronomical optics span the full range of optical surfaces currently planned. From the first stages of manufacturing, to the final steps of polishing, concave to convex, null to non-null, statics to dynamics, we are proud and impressed by the current metrology toolbox.

The next generation of astronomical optics have brought advances in the metrology tools used throughout the optics community. Developments across the entire range of methods allow for new and exciting optics to be used in the telescopes. Our goal in sharing these emerging technologies with the community is to inspire others to utilize the amazing capabilities and inspire further advancements in this field.

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