# Precision Engineering behind European Astronomy Programmes

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**Abstract** –The fields of astronomy science have presented significant precision engineering challenges. Numerous solutions for these fields of science have achieved unprecedented levels of accuracy, sensitivity and sheer scale. Notwithstanding of their importance to science understanding, many of these precision engineering developments have become key enabling technologies for wealth generation and other human well-being issues. This paper provides a brief historical overview of astronomy instruments. Later, details of critical precision engineering developments that supported the establishment of leading European astronomical instruments are illustrated. Finally, significant precision engineering demands to enable future sciences programmes are introduced.

***Key Words*: Telescopes, precision, machines**

In this short paper, we provide a brief historical overview of European astronomical developments. The paper subsequently provides details of significant precision engineering demands to enable recent European telescope programmes. Thereafter critical precision manufacturing developments that will progress future European astronomical projects are presented. The paper has been adapted from a comprehensive CIRP Keynote on Precision Engineering for Astronomy and Gravity Science [1].

## 1. Introduction

It has long been the dream of humankind to understand its place within the universe. This aspiration has led to detailed measurements which accurately described to movement and interactions of celestial bodies. From the advent of astronomical instruments it has been clear that these should have high effective resolving power, which is essentially a function of both; scale (eg. diameter of telescope) and quality (eg. accuracy of mirror surfaces). From experience these simultaneous demands are known to be difficult to reconcile. This dual requirement is at the centre of “Precision Engineering” and fundamentally coupled to being able to measure with high accuracy and with minimal levels of uncertainty. The maxim ascribed to Galileo tells us to “measure what is measurable, make measurable what is not”. Scientific progress made in the field of astronomy research has been achieved through significant precision engineering developments. Numerous engineering solutions have demanded unprecedented levels of accuracy, sensitivity and sheer scale. Notwithstanding of their importance to science understanding many of these precision engineering developments have become key enabling technologies for wealth generation and other human well-being issues.

## 2. Astronomical instrument development

From the beginning of astronomy as a science, discoveries have been made following the introduction of new manufacturing technology. Considering Galileo’s telescope, built over 400 years ago in 1609, the key manufacturing technology was the newly developed ability to fabricate glass lenses precisely, together with some critical innovations from Holland such as “stopping down the aperture” for enhanced seeing performance. Using his telescope Galileo discovered moons around Jupiter and consequently reinforced support for the Copernician model. James Gregory and Isaac Newton’s reflecting telescope concepts were enabled in the 1660’s through the combined techniques of grinding and polishing metal mirrors in speculum. These precision machining techniques enabled William Herschel to build his telescope which discovered Uranus and numerous nebulae. Léon Foucault invented the metallised-glass reflecting telescope, producing a 80 cm telescope in Marseille in 1864. By employing a “knife edge” measurement test during the mirror manufacturing (in-process metrology) a more controlled machining process was attained. The silvered glass reflecting telescope became the preferred technology for large ground-based telescopes, particularly after the limits of refractors were reached. Following a suggestion of Newton nearly 200 years earlier, Charles Piazzi Smyth in 1880 carried out observations from the top of Mount Teide, Tenerife. Smyth’s observations demonstrated the benefits of observation made through a reduced atmospheric layer. From that time onwards major ground based telescopes were positioned on mountain tops; the first notable example was the Lick Observatory.

During the first half of the 20th century the major development of telescopes was that of size scale-up. Large reflecting telescopes by George Ritchey and George Ellery Hale led to reflectors of up to 200 inches (5 metres) in size. The 200 inch Hale telescope was based on low expansion Pyrex mirrors, ship building structural engineering and passive flexure compensators. In 1929, using observations from the first of these large Californian telescopes, Edwin Hubble confirmed the expansion of the Universe. For the majority of the latter half of the 20th century telescope performance was most significantly advanced through implementation of electronic array detectors replacing photographic plates in visible and IR. Through the greater sensitivity and linearity of charge coupled devices (CCDs) and IR arrays, it was possible to improve the performance of existing 2 - 4 m scale telescopes. Better detectors achieved an order of magnitude improvement of sensitivity during this time. Computer control of a telescope was pioneered on the Anglo-Australian Observatory in 1975. The implementation of computer control paved the way to actively controlled telescopes and ultimately the 8-10 m telescope era of today.

The Russian 6 m BTA telescope was one of the first to rely solely on computer control.

In 1923, Hermann Oberth proposed the benefits of space based astronomy. Lyman Spitzer in 1946 presented a seminal paper that defined the wider attributes and capabilities of space based telescopes. The launch of Sputnik in 1957 "changed everything". It led to the birth of NASA, the race to the moon and the consequent availability of space technology that led to the great NASA Observatories such as the Chandra X-ray telescope and the 2.4 m Hubble optical/near IR telescope. These NASA space telescopes, together with ESA's ISO and XMM-Newton telescopes, have produced a broad range of discoveries and provided beautiful images that have captured wide public interest.

By the late 1980s it was generally recognised that the scope for improved sensitivity of ground based telescopes was again only to be afforded through an increase in size. This situation was brought about through spectacular improvement of detector sensitivity during the 1970s and 1980s together with improved positioning and motion control. The late 1980s saw astronomy entering the era of the 8 – 10 m telescopes. Numerous enabling technologies that led to the very large telescope era (VLT, 8-10 m scale telescopes) will be covered in more detail later in this paper. Those considered having historical significance include: Segmented primary mirror technology, applied to the US Keck and European Grantecan telescopes, as proposed by Jerry Nelson [2]; and 8 m scale monolithic honey comb spun cast mirror moulding technique developed by Roger Angel [3] and applied to the Magellan Telescope and the Large Binocular telescope. In parallel, an 8 m mirror capability was also established in France during the 1980s. It is based around a meniscus mirror fabrication capability and use of active optics technology. This technology, developed by REOSC, was first employed by ESO on the 3.6 m New Technology Telescope and subsequently the four 8 m Very Large Telescopes [4]. Similar technology was subsequently employed for the Japanese Subaru telescope [5]. During the late 1990s and the first decade of the 21st century the 8-10 m scale ground based telescope technology matured. Adaptive Optics, discussed later on, significantly advanced the "seeing" performance of Keck, Gemini and the VLTs producing revolutionary high resolution images of gas giant planetary systems (much like Jupiter) and provided evidence of a massive black hole near the centre of our galaxy.

However, as was seen during the first half of the 20th century the main demand of 21st century astronomers is increase in telescope size for ground and space based systems. The detection of so called earth-like planets, presently a prime objective, is a central justification for the proposed US/Japanese Thirty Metre Telescope and the European -ELT 42m telescope projects [6-7].

The so-called Extremely Large Telescopes (ELTs) are presently in the design and preliminary manufacturing assessment stages. These telescopes are targeted for "first light" by 2017 – 2020, at which time the pioneering NASA led segmented mirror-based James Webb Space Telescope (JWST) having a 6.5 m diameter will be operational.

Used in combination the proposed ground based ELT's and the JWST will yield a new era of astronomical observation.

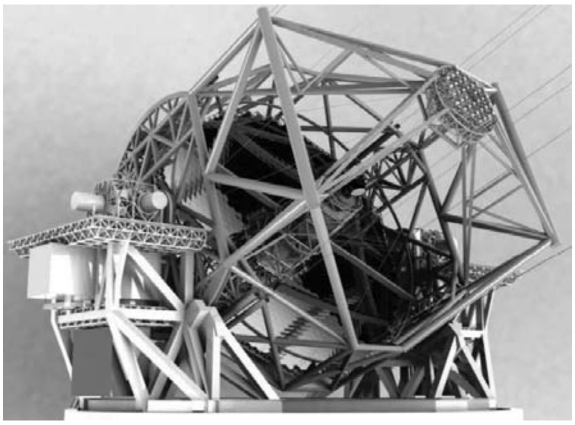

Fig. 1: European Extremely Large Telescope (42 m segmented primary mirror)

## 2. Precision manufacturing technologies

Ultra precision manufacturing technology for producing advanced optical surfaces has been, and continues to be, a fundamental "technology enabler" for telescope development. In this section we present European developments considered to have made a significant contribution.

### 2.1. Mirror (lens) fabrication

The ESO VLT and Gemini telescopes employed Zerodur based meniscus substrates made by Schott. They were subsequently ground, polished and measured in-situ. An 8 m scale capacity mirror processing facility has been established in France by REOSC [8].

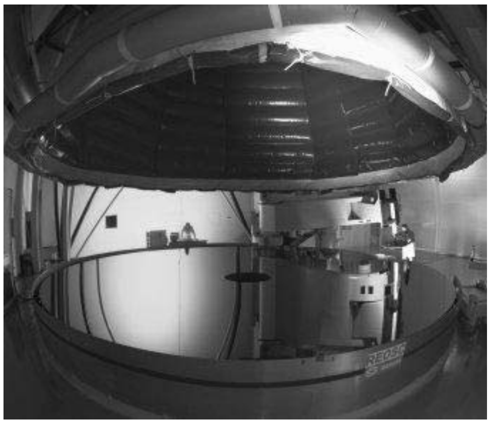

Fig. 2: VLT Mirror (8 m) undergoing optical measurement using in-situ measuring tower [9]

REOSC processes 175 mm thick so-called "meniscus" mirror blanks. The meniscus blanks are held on active supports during polishing as employed within the telescope itself. At REOSC a large 20 m high optical test tower is provided above the grinding/polishing system itself. The form accuracy achieved by Sagem-REOSC in producing the 4 VLT primary mirrors was 17.6 - 33 nm RMS [10]. The form accuracy achieved on the 8 m scale mirrors by Sagem-REOSC corresponds to an optical resolution (relating to image sharpness) of 0.03 arcsecond in the visible spectrum. It provides a theoretical capability of distinguishing two objects separated by only 150 mm at a distance of 1000 km.

Brinksmeier et al., has presented a detailed review of the development of Ultra Precision Grinding [11] which includes details relevant to astronomy surfaces.

2.2 Segmented mirror manufacturing

The idea was originally conceived by the Italian Horn d'Arturo in the 1950's. This segment mirror technology is pivotal as beyond 10 m scale monolithic, mirrors were becoming unrealistic; even considering their transportation. More complex shape primary mirrors (i.e. deep aspheric) would enable more sophisticated and elegant telescope designs. By making the primary telescope mirror from a number of smaller interlocking mirror segments, a scalable means for producing any size of telescope would be enabled [12]. Clearly, producing the off-axis aspheric shaped segments would be critical manufacturing issue. Significantly these complex shape mirror segments would need to demonstrate very limited so-called edge "roll-off". Any shape error at the edges of the segments would reduce the optical performance of the telescope and generate highly problematic stray light features.

Nelson applied it successfully to the two 10.2 m primary mirrors Keck telescopes. It was therefore important to develop a manufacturing process chain able to realise the 36 mirror segments of ~ 2 m scale. The developed fabrication route included a grinding process followed by a novel full-aperture polishing technique called "stressed" mirror polishing [13]. In addition a 2.5 m off-axis grinding machine was built at CUPE (Fig. 3) for Eastman Kodak's segment mirror programme [14].

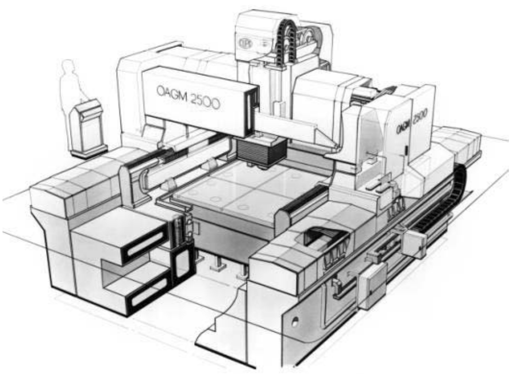


Fig. 3: Schematic layout of the laser interferometer controlled CUPE/CPE Ltd OAGM made for Kodak

The final figuring process, an ion beam figuring (IBF) technology causes ionised argon atoms to bombard the mirror surface causing atom to be "knocked out".

The fabrication of Grantecan mirror segments at Sagem-REOSC was achieved using sub-aperture polishing with industrial robots and final ion beam figuring [15]. Importantly, the ability to polish/ion beam figure the edges of the segments without inducing edge roll-off was developed, ensuring low levels of consequent stray light in the telescope.

A notable difference to Keck project, in the production of the Grantecan segments, was that they were polished as hexagonal segments prior to IBF. The achieved form accuracy of the Grantecan segments was 12 – 30 nm RMS.

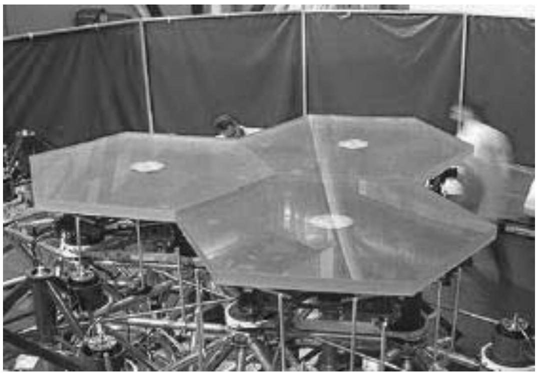

Fig. 4: Grantecan mirror segments being readied for optical testing using the REOSC test tower [16]

2.3 Space mirror manufacturing

The Hubble Space Telescope is perhaps the most iconic and famous telescope. It has undoubtedly been a major scientific success, operating in the UV to the near infrared, ~200 – 2400 nm. Unfortunately a measurement error made during the final polishing of the primary mirror led to a highly complex servicing mission. The flight mirror was polished by Perkin Elmer in 1979 using pre-CNC lapping and polishing technologies. Interestingly, a second (spare) Hubble mirror was produced by Kodak. Whilst it took Kodak 16 months to produce it is claimed the actual polishing time itself was limited to 74 hours [17]. It was also made using traditional pre-CNC controlled grinding and polishing machines.

In regard to developing advanced manufacturing technology, it is perhaps the X-ray space mirrors have led to the widest range of advancements. X-ray telescopes are themselves a relatively new development, the first being launched in 1977. A highly detailed account of their development has recently been provided by Aschebach [18]. X-ray space telescopes are most significantly based on the application of Wolter type mirror designs employing grazing incidence optics [19]. The primary mirror optics are tube-like in shape typically having internal mirror surfaces of parabolic and hyperbolic shape. A number of the Wolter type mirrors are nested: The greater the number of nested mirrors, the greater the X-ray light collecting capacity. Consequently the manufacture of thinner section mirrors has been a significant X-ray telescope technology driver. This has led to a notable ultra precision manufacturing demand. As might be expected, these shorter wavelength mirrors demand ultra smooth surfaces typically 0.3-0.8 nm RMS, having form accuracy demands below the 30 nm RMS region.

Pioneering X-ray telescopes, such as Exosat launched in 1983, used mirrors produced by a replication process. This replication process used solid glass mandrels that were ground and polished to the inverse shape and to the form accuracy of the demanded mirror. Mandrels were subsequently gold coated. Carrier mirror shells machined to an accuracy of 0.5 mm were produced. The gold coated glass mandrels were placed inside the carriers and epoxy injected between them. After curing, mandrels were removed, leaving behind the gold mirror surface on the carrier. The EXOSAT mirror carriers were made from beryllium. The ultra precision mandrels were said to be reusable up to 6 times.

Subsequent to EXOSAT, the Rosat X-ray telescope launched in 1998, employed an eight mirror X-ray system. Four nested parabolic mirrors and four nested hyperbolic mirrors (Fig. 5).

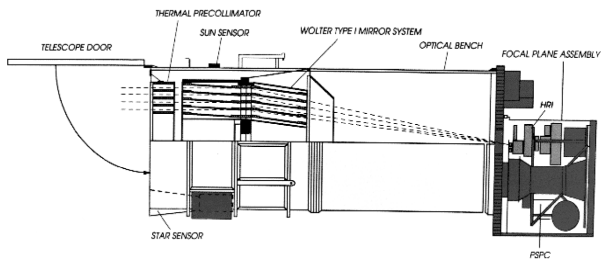


Fig. 5: Cross section of Rosat X ray space telescope showing 4 nested Wolter type mirrors [20]

The largest of the X-ray mirrors was 0.84 m. Co-aligned with the X-ray system was an extreme ultra violet optical system called the Wide Field Camera (not shown in Fig. 5) having a three nested mirror arrangement, the largest being 0.6 m. Rosat's X-ray wavelength mirrors were made of Zerodur and manufactured in Germany by Zeiss [21]. These Zerodur mirrors were ground on a vertical grinding machine employing air bearings. During grinding, the Rosat mirrors were supported in aluminium fixtures having many supporting pins. The numerous support pins ensured grinding forces did not induce significant distortion. Subsequent to grinding, polishing was carried out using a sub-aperture free abrasive polishing technique. Final polishing runs were undertaken with the mirror in a constrained free state, as suggested by Young [22]. The Rosat X-ray mirrors had a 3 Å RMS roughness. Critical geometrical errors of X-ray telescope mirrors have been discussed by Zombeck in 1981 [23].

The two most critical errors were stated as; circularity error about axial direction (akin to roundness/cylindricity) and profile error again in an axial direction. Rosat X-ray mirrors typically had circularity quality and axial direction profile accuracy at 0.5 µm and 0.2 µm respectively. Data to confirm this is presented by Aschenbach and measured using in-house constructed profilometers at Zeiss [24].

Rosat's EUV mirrors were electro-less nickel coated aluminium and manufactured by CUPE and Ferranti in the UK. The aluminium substrates were diamond turned by CUPE in 1981 using an in-house developed large diamond turning machine (Fig. 6) [24].

Fig.6: Rosat EUV mirror being measured on CUPE LDTM prior to NC error correct diamond turning

The so-called LDTM employed a post-process profilometer which allowed form errors to be measured in-situ. The profilometer was based on an air bearing supported contacting probe, referenced using a HeNe laser interferometer to optical straight-edges mounted within the machine envelope. Circularity and axial profile accuracies were better than 1 µm.

Post diamond turning, the EUV mirrors were processed by Ferranti Astron. Ferranti carried out a pre-polish prior to coating with electro-less nickel (~60 µm thickness). This was followed by a final super polishing employing alumina oxide abrasive and a conventional pitch polishing sub aperture technique. Achieved roughness was claimed at 0.3-0.5 nm RMS.

In 2009 the Herschel Space Telescope was launched. It is a far infrared region telescope operating in the 60 – 670 µm wave-length range and it complements the Hubble and the soon to be launched James Webb Space Telescope.

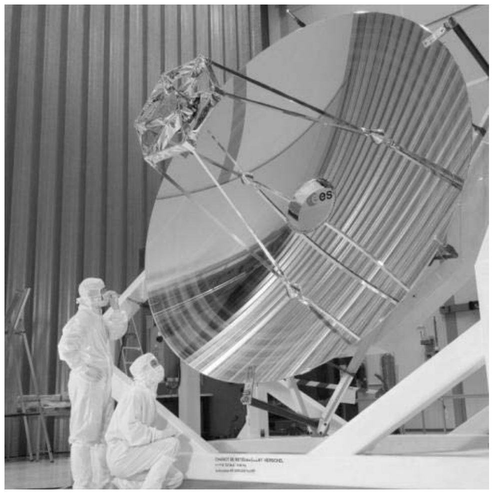

Fig. 7: Herschel Space telescope 3.5 m silicon carbide based primary mirror [25]

As might be expected, the form accuracy requirement for its primary mirror is less demanding than for shorter wavelength telescope mirrors. Its 3.5 m mirror has form accuracy around 6 µm RMS with a 30 nm RMS roughness. Nonetheless the Herschel telescope represents a significant precision engineering achievement. It is structurally and optically fabricated from silicon carbide. Its primary mirror has been constructed by brazing together 12 large mirror segments produced by the French company Boostec [26]. The light-weighted mirror segments are moulded using an isostatic pressed sintered silicon carbide. The segments were accurately machined and subsequently joined using a silicon braze technology establishing the 3.5 m mirror substrate. Since the Herschel space telescope operates at cryogenic temperatures it is clearly critical the silicon braze technology is employed so that a "stress-free" bond across the substrate in achieved. The application of silicon carbide for the primary and secondary mirrors and the strut supports of the Herschel telescope ensure its total mass is less than 300 kg. The use of hard silicon carbide requires adaptation to conventional polishing. The polishing of the Herschel primary mirror was carried out by Opteon in Finland who developed and employed a novel diamond based polishing technology [27]. The polished mirror was subsequently coated with an adhesive nickel chrome layer, a reflective aluminium layer and finally a protective silicon based polymer.

The James Webb Space Telescope, scheduled to launch in 2014, will be the first operationally segmented mirror telescope to be deployed in space. Although the joint NASA/ESA telescope has its primary mirrors made in the US, astronomy mirror demands are not limited to large mirrors. Complex shape multi-mirror arrays are also demanded, especially within telescope instrument systems [29]. A significant example is image "slicers" (Fig. 8) and "re-imagers" as used within spectrometers.

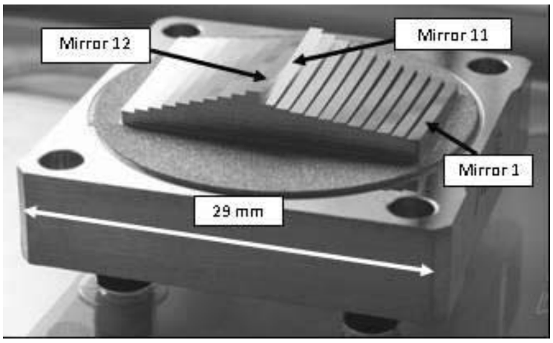


Fig. 8: Photograph of an image slicer made by Cranfield University Precision Engineering for the JWST MIRI instrument [30]

Development of multi axes diamond machining techniques for producing these mirror arrays has been undertaken [31]. Shore reported the diamond machining technique employed to produce such optics for the James Webb Space Telescopes MIRI instrument [30]. Morantz reported their measurement using a miniature Twyman-Green interferometer mounted onto a stability enhanced ultra precision CMM [32].

3. Future demands

3.1 Extremely Large Ground Based Telescopes (ELT's)

Extremely Large Telescopes are classed as telescopes possessing an aperture diameter greater than 20 m for observation in the UV, visible and near IR wavelengths. Monolithic mirrors are limited to around 10 m diameter for reasons of manufacturing, measurement and transportation difficulty. Larger effective apertures are possible through the aperture synthesis achieved by interferometry of combined smaller aperture telescopes, but there are significant advantages in an optically-filled aperture, not least light-gathering power. Consequently, segmented mirror technology, as applied to the Keck telescopes, has become the main basis for telescope scale up.

Funded ELT programmes scheduled for first light around or before 2020 include E-ELT at 42 m apertures, requiring 984 segments for its primary mirror. The mirror supply issue is non-trivial: all 20 of the world's operational very large (> 5 m diameter) telescope primary mirrors, manufactured over a period of more than 50 years, have a combined area of around 1,000 m2; just TMT and E-ELT between them will require in excess of twice that for their primaries, manufactured within a period of only 10 years. This represents a requirement for a rapid increase in worldwide supply capacity, currently underway, perhaps approaching an order of magnitude.

The stress-lap and stressed mirror polish techniques, employed for some existing large mirrors and segments, utilise modified spherical surface generation techniques with subsequent sub-aperture figure correction.

An alternative approach has emerged, which is geared towards higher volumes. This utilises CNC sub-aperture techniques at every stage of surface generation, with an essentially unlimited freeform capability [33]. Targeting a 20 hour cycle time for each stage of surface generation for a 1.5 m class mirror, it specifically addresses the requirement for worldwide supply ramp-up, where existing techniques take at least an order of magnitude longer.


Fig. 9: Rapid production of large scale mirror segment using the – BoX® Cranfield ultra precision grinding/measuring machine

The approach is based on a high speed, high accuracy ultra-low damage freeform CNC grinding stage, followed by a relatively short CNC figure corrective polishing stage. These technologies have been demonstrated; grinding achieving cycle time and form accuracy targets below 1 μm RMS [34]. An additional CNC sub-aperture Reactive Atom Plasma figure correction technology is at an advanced stage of development [35]. Mass production of ~1 m scale mirrors has become a commercial demand defined by future astronomy programmes providing a clear potential benefit for optic fabrication.

3.2 International X- ray Observatory

The International X-ray Observatory (IXO), a large deployable Wolter type X-ray mirror structure with 20 m focal length, is a joint effort (NASA/ESA/JAXA) currently planned to be launched for 2021. The IXO demand represents a new ultra precision production engineering challenge and a major commercial contract.

It employs segmented mirror technology similar to that employed in JSWT and the proposed ELTs. IXO requires 6948 parabolic and 6948 hyperbolic mirror segments. The surface area demanded for the polished forming mandrels is 60 $m^2$ (721 mandrels). Total mirror segment area over 800 $m^2$. The form quality requirements for individual mirror segments equates to 100 nm RMS with tighter short wave-length demands.

Mirror manufacturing technologies for the IXO mirror shell segments include "slumped glass" and "silicon pore optic". These processes are being used commercially: glass slumping is used in liquid crystal flat panel display industry, "silicon pore" optics are standard semiconductor wafer technology processes [36]. The IXO demand is creating a higher accuracy capability from these manufacturing technologies.

For example, ESA silicon pore optics are 12" silicon wafers that are diced, wedged and ribbed. Rectangular silicon plates produced having thin ribs on one side and thin membranes between the ribs. The sandwich construction is bent into the required shape and stacked automatically to obtain a stiff pore structure. The stacks are then mounted into "tandem" structures which are combined to form the X-ray mirror [37].

## 4. Conclusions

This paper has introduced European precision engineering achievements borne of the demands of large scale astronomy. These have included: Ultra Stable and Lightweight Materials, Ultra Precision Surface Fabrication & Measurement (especially at large scale) and Ultra Precision Machine Tool Techniques.

The paper has also identified key precision manufacturing demands of future astronomy ESA/NASA programmes and the even greater demands that these future programmes place on Ultra Precision Technologies. The scale of future programmes, such as the Extra Large Telescopes, requires greater attention to production engineering capabilities in order for them to be realised in acceptable timescale and cost.

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## References

[1] P. Shore et al.: Precision engineering for astronomy and gravity science. CIRP Annals 59(2):694-716, 2010.

[2] J.E. Nelson et al.: The design of the Keck Observatory and telescope. Keck Observatory Report 90:5.1-5.44, 1985.

[3] J.R.P. Angel et al.: Progress toward making lightweight 8-m minors of short focal length. Proc. SPIE 1236:636-640, 1990.

[4] P. Dierickx et al.: VLT primary mirrors: mirror production and measured performance. Proc. SPIE 2871:385-392, 1997.

[5] N. Kaifu: Subaru Telescope. Proc. SPIE 3352:14-22, 1998.

[6] R. Gilmozzi, J. Spyromilio: The European Extremely Large Telescope (EELT). ESO Messenger 127:11-19, 2007.

[7] L.M. Stepp, S.E. Strom: The Thirty-Meter Telescope project design and development phase. Proc. SPIE 5382:67-75, 2004.

[8] R. Geyl, M. Cayrel: REOSC contribution to VLT and Gemini. Proc. SPIE 3739:40-46, 1999.

[9] VLT main mirror: http://www.eso.org/public/news/eso9952, 2011.

[10] M. Cayrel: Completion of VLT and Gemini primary mirrors at REOSC. Proc. SPIE 4003:14-23, 2000.

[11] E. Brinksmeier et al.: Ultra Precision Grinding. CIRP Annals 59(2):652-671, 2010.

[12] R.N. Wilson: Reflecting Telescope Optics II: Manufacture, Testing, Alignment, Modern Techniques. Series: Astronomy and Astrophysics Library, XVIII, ISBN: 978-3-540-60356-6, 1999.

[13] J.E. Nelson et al.: Stressed mirror polishing. 2: Fabrication of an off-axis section of a paraboloid. Applied Optics 19(14):2341-2352, 1980.

[14] W.J. Wills-Moren, T. Wilson: The Design and Manufacture of a Large CNC Grinding Machine for Off-Axis Mirror Segments. CIRP Annals 38(1):529-532, 1989.

[15] R. Geyl et al.: Large optics ion figuring. Proc. SPIE 3739:161-166, 1999.

[16] E. Ruch: Presentation at Polissage Optique pour les Grands Instruments de la Physique et de l 'Astronomie, Bordeaux, 2009.

[17] ITT: http://www.ssd.itt.com/heritage/hubble.shtml, 2011.

[18] B. Aschenbach: X-ray telescopes. Prog. Phys. 48:579-629, 1985.

[19] H. Wolter: Mirror systems with glancing incidence as image-producing optics for X-rays. Ann. Phys. 445:94-114, 1952.

[20] ROSAT mission: http://www.mpe.mpg.de/xray/wave/rosat, 2011.

[21] D. Reinhardt: Features of manufacturing and qualification tests of a high-resolution Wolter I mirrors. Proc. SPIE 733:145-148, 1987.

[22] P.S. Young: Fabrication of the high-resolution mirror assembly for the HEAO-2 X-ray telescope. Proc. SPIE 184:131-138, 1979.

[23] M.V. Zombeck: Advanced X-ray Astrophysics Facility (AXAF). Opt. Eng. 20:297-309, 1981.

[24] K. Beckstette, E. Heynacher: Contour line measurements on ROSAT X-ray mirrors. Proc. SPIE 429:126-129, 1983.

[25] P.A. McKeown et al.: Experiences in the precision machining of grazing incidence X-ray mirror substrates. Proc. SPIE 571:42-50, 1986.

[25] Herschel: http://www.esa.int/esaMI/Herschel, 2011.

[26] J. Breysse et al.: All-SiC telescope technology: recent progress and achievements. Proc. ICSO: 659-671, 2004.

[27] T. Korhonen et al.: Polishing and testing of the 3.5 m SiC M1 mirror of the Herschel space observatory of ESA, Proc. SPIE 7210: 218-220, 2008.

[28] H.P. Stahl: JWST mirror technology development results. Proc. SPIE 6671:667102-667104, 2007.

[29] D. Lee et al.: Image Slicers – Design for Manufacturability. Proc. SPIE 5494:176-187, 2004.

[30] P. Shore et al.: Manufacturing and Measurement of the MIRI Spectrometer Optics for the James Webb Space Telescope. CIRP Annals 55(1):543-547, 2006.

[31] M. Dubbeldam et al.: Free Form Diamond Machining of Complex Monolithic Optics for Integral Field Systems. Proc. SPIE 5494:164-175, 2004.

[32] P. Morantz et al.: Metrology of Imaging Mirror Arrays for Space Telescope Spectrometer Optics. Proc. Lamdamap, Cranfield, 513-522, 2005.

[33] P. Shore: Ultra Precision Surfaces, Proc. ASPE:75-78, 2008.

[34] X. Tonnellier: Precision grinding for rapid manufacturing of large optics, PhD Thesis, Cranfield University, 2009.

[35] C. Fanara et al.: A New reactive Atoma Plasma Technology for Precision Machining. Adv Eng Materials 8(10):933-939, 2006.

[36] W. Zhang: Mirror Segment Fabrication and Metrology for the International X-ray Observatory. Astron. X–Ray Optics, 2009.

[37] M.J. Collon et al.: Stacking of Silicon Pore Optics for IXO. Proc. SPIE 7437:74371A-74371A-7, 2009.