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LARGEST OPTICAL TELESCOPES

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Abstract. A review of the largest astronomical optical telescopes which are presently operational or under construction is presented. Their scientific capabilities are described briefly, particularly with respect to astrophysical spectroscopy and interferometry.

1. INTRODUCTION

The telescope, invented at the beginning of 17th century, was one of the most important inventions of the Scientific Revolution when Galileo and Isaac Newton used it to provide evidence for new theories about the heavenly bodies and the nature of the Universe itself. Since then the telescopes were significantly improved, both in their design and light gathering power. The latter capacity is a function of the diameter of their main lens (refracting telescopes) or mirror (reflecting telescopes) called the objective. The Technological Revolution allowed the construction of large objectives and corresponding large telescopes. Comparison of sizes of objectives of large optical telescopes constructed since the beginning of 20th century is shown in Figure 1. Dotted lines show objectives with effective light-gathering power, i.e. the diameter of the equivalent circular aperture of the telescope's total light collecting area. The telescopes shown in this comparison are listed below:

1) Great Paris Exhibition Telescope, 1.24 m, year built 1900 (largest refractor ever built; had practically no scientific usage). **2)** Yerkes Observatory's 1.02 m refractor, 1893 (largest refractor consistently used for scientific observations). **3)** Hooker Telescope, 2.5 m, 1917; world's largest telescope from 1917 to 1949. **4)** Hale Telescope, 5.1 m, 1949; world's largest telescope from 1949 to 1975. **5)** Multiple Mirror Telescope, 4.72 m effective, 1979-1998. **6)** Multiple Mirror Telescope, 6.5 m, from 1998. **7)** BTA-6, 6 m, 1975; world's largest telescope from 1975 to 1990. **8)** Large Zenith Telescope, 6 m, 2003; largest liquid-mirror telescope ever built; decommissioned in 2019. **9)** Gaia, 1.45 m $\times$ 0.5 m (area equivalent to a 0.96 m round mirror), 2013. **10)** Kepler, 1.4 m, 2009. **11)** James Webb Space Telescope, 6.5 m effective, 2022 (largest space optical telescope to date). **12)** Hubble Space Telescope, 2.4 m, 1990. **13)** LAMOST (Large Sky Area Multi-Object Fiber Spectroscopic Telescope), 4.9 m effective, 2009. **14)** Gran Telescopio Canarias, 10.4 m, 2007 (world's largest single-aperture optical telescope). **15)** Hobby–Eberly Telescope, 10 m effective, 1996. **16)** Southern African Large Telescope, 9.2 m effective, 2005 (largest optical telescope in the southern hemisphere). **17)** Large Binocular Telescope, 11.8 m effective (two 8.4-m telescopes on a common mount), 2005 and 2006; each individual telescope has the largest monolithic (non-segmented) mirror in an optical telescope, while the combined effective light collecting area was the largest for any optical telescope in non-interferometric mode,

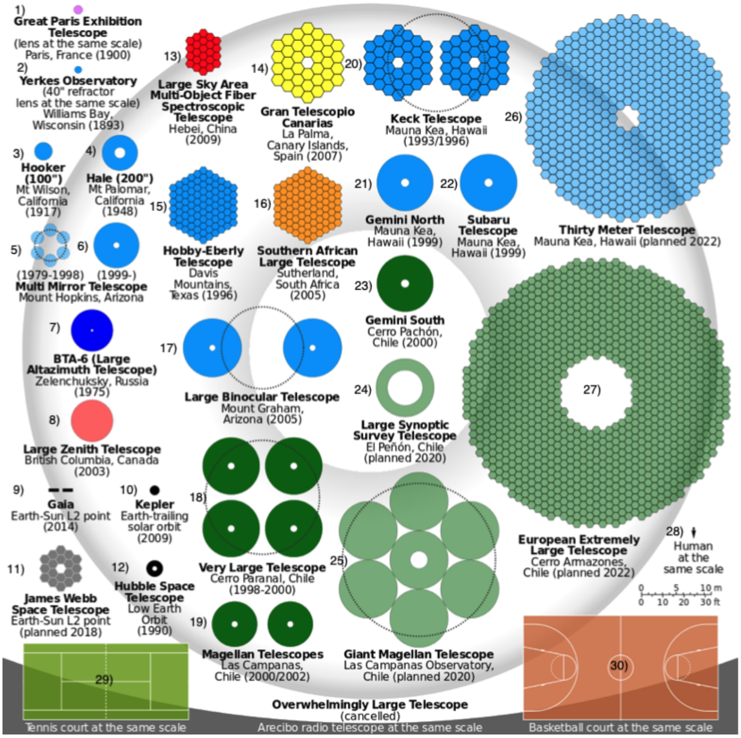

Figure 1: Comparison of nominal sizes of apertures of some notable optical telescopes. Image Source: `https://en.m.wikipedia.org/wiki/File:Comparison optical telescope primary mirrors.svg`.

from 2006 to 2018. **18)** Very Large Telescope, 16.4 m effective (four 8.2 m individual telescopes), 1998, 1999, 2000, and 2000; total effective light collecting area is the world's largest for any present-day optical telescope in interferometric mode, and in non-interferometric mode since 2018, when the instrumentation required to obtain a combined incoherent focus was built. **19)** Magellan Telescopes, two 6.5-m individual telescopes, 2000 and 2002. **20)** Keck Telescopes, 14.1 m effective (two 10 m individual telescopes), 1993 and 1996. The two telescopes were combined only for interferometric observations rather than to simply achieve larger light collecting area. The interferometric mode has been discontinued in 2012. **21)** Gemini North Telescope, Mauna Kea, Hawaii, 8.1 m, 1999. **22)** Subaru Telescope, 8.2 m, 1999; largest monolithic mirror in an optical telescope from 1999 to 2005. **23)** Gemini South Telescope, Cerro Pachón, Chile, 8.1 m, 2000. **24)** Vera C. Rubin Observatory (formerly Large Synoptic Survey Telescope), 6.68 m effective (8.4 m mirror, but with a big hole in the middle), planned 2025. **25)** Giant Magellan Telescope, 21.7 m effective, planned 2029. **26)** Thirty Meter Telescope, 30 m effective, pending. **27)** Extremely Large Telescope, 37.4 m effective, planned 2028. **28)** Human height, 1.77 m on average. **29)** Tennis court, 23.77 × 10.97 m. **30)** Basketball court, 28.7 × 15.2 m. **Note)** The project of the Overwhelmingly Large Telescope, 100 m, (gray arrea in the figure), has been definitely cancelled.

2. CURRENT GROUND BASED TELESCOPES

The frontline ground based astronomy is based on new giant telescopes giving the best image possible. But having a giant telescope is not enough to reach this purpose, a big telescope on bad site does not allow to obtain high quality data. The quality of astronomical sites is the first step to be considered in order to have the best performances from the telescopes. The idea is to predict the reachable optical quality of large telescopes analysing the image obtained using small telescopes. An example of such site testing is shown in Figure 2 (Left). Atmospheric parameters as number of clear and dark nights, atmospheric transparency, infrared properties (height, temperature, precipitable water vapour, etc), seeing, atmospheric turbulence profile, mean coherence length and time, outer scale length, etc. This parameters can seriously limit the inherent properties of large telescopes.

It is not obvious to say which is the largest optical telescope on Earth. Since 2007 the Gran Telescopio Canarias, 10.4 m (Figure 2 (Right)) is the world's largest single-aperture optical telescope. However, for the Large Binocular Telescope, composed of two 8.4 m telescopes on a common mount, 11.8 m effective, the combined effective light collecting area was the largest for any optical telescope in non-interferometric mode, from 2006 to 2018, while each individual telescope has the largest monolithic (i.e. non-segmented) mirror in an optical telescope. For the Keck Telescopes (Figure 3 (Left)), 14.1 m effective (two 10 m individual telescopes), since 1996 the two telescopes were combined only for interferometric observations in a combined coherent focus, rather than to achieve larger light collecting area in a combined incoherent focus. For the Very Large Telescope, located at Cerro Paranal, Chile (Figure 3 (Right)), 16.4 m effective (four 8.2 m individual telescopes), the total effective light collecting area is the world's largest for any present-day optical telescope in interferometric mode since 2001, and in non-interferometric mode since 2018 when the instrumentation required to obtain a combined incoherent focus was built.

2. 1. GRAN TELESCOPIO CANARIAS (GTC), (GTC 2023)

- Canary Islands, Spain, altitude 2 400 meters, first light 2006.
- 10.4-meter segmented, 36 hexagonal segments.
- High Resolution Spectroscopy: main spectrographs are MEGARA (wavelength range ($\Delta\lambda$) 0.4-1 μm), MIRADAS (1-2.5 μm), spectral resolution (R) up to 20 000, HORuS (0.4-0.7 μm), R up to 25 000. To be installed: GTCAO+FRIDA (1-2.5 μm), R up to 30 000, CHORUS (0.31-0.78 μm), R up to 110 000.
- Long Baseline Interferometry: None

2. 2. LARGE BINOCULAR TELESCOPE (LBT), (LBT 2023)

- Mount Graham, Arizona, USA, altitude 3 300 meters, first light 2004.
- 2 x 8.4-meter, monolithic equivalent to 11.8-meter effective. The largest single-mount telescope in the world.
- High Resolution Spectroscopy: PEPSI: the Potsdam Echelle Polarimetric and Spectroscopic Instrument for the LBT allows a spectral resolution of up to 250 000 while covering the entire optical wavelength range without gaps.
- Long Baseline Interferometry: Using both 8.4 m wide mirrors, with centres 14.4 m apart.

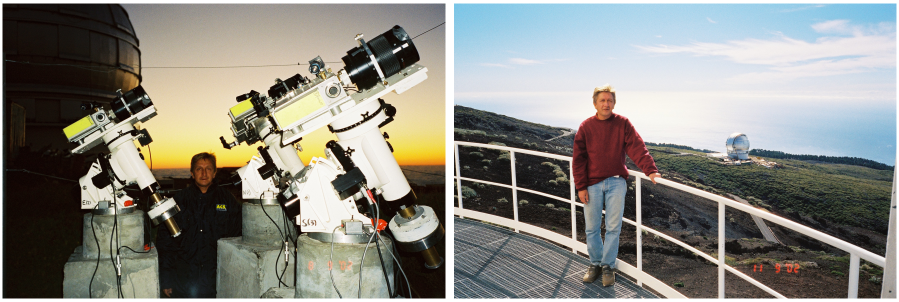

Figure 2: *Left*: Extremely Large Telescope site testing at Roque de los Muchachos observatory, La Palma, Spain. The dome of Gran Telescopio Canarias is in the background. *Right*: The Gran Telescopio Canarias located at the mountain slope.

2. 3. KECK OBSERVATORY (KO), (KO 2023)

- Mauna Kea, Hawaii, USA altitude 4 200 meters, first light 1993 (Keck I), 1996 (Keck II).
- 2 x 10-meter segmented, 36 hexagonal segments = 14.1 meter effective.
- High Resolution Spectroscopy: Keck I (spectrograph HIRES, R up to 85 000, $\Delta\lambda$ 0.3-1 μm), Keck II (KCWI, R up to 20 000, $\Delta\lambda$ 0.35 to 0.56 μm).
- Long Baseline Interferometry: resolving power equal to the distance spanned by the two Keck Telescopes, which is 85 meters. As of mid-2012 the Keck Interferometer has been discontinued for lack of funding.

2. 4. VERY LARGE TELESCOPE (VLT), (VLT 2023)

- Cerro Paranal, Chile, altitude 2 600 meters, four Unit Telescopes (UTs) 1998, 1999, 2000, and 2000, and Auxilary Telescopes (ATs). First interferometric light 2001.
- 4 x 8.2-meter UTs, monolithic + 4 x 1.8-meter ATs, monolithic equivalent to 16.4-meter effective (four 8.2-meter UTs only).
- High Resolution Spectroscopy: UVES (UltraViolet and Visible Echelle Spectrograph) is the high dispersion spectrograph of the VLT, observing from 0.3 μm to 1.1 μm, with a maximum spectral resolution of 110 000. CRIRES (CRyogenic highresolution InfraRed Echelle Spectrograph) provides a spectral resolving power of up to 100 000 in the spectral range from 1 to 5 μm. ESPRESSO (Echelle Spectrograph for Rocky Exoplanets and Stable Spectroscopic Observations) is installed at the incoherent combined Coudé facility of the VLT, observing in the wavelength range from 0.4 μm to 0.8 μm. It is an ultra-stable fibre-fed échelle high-resolution spectrograph (R 140 000, 190 000, or 70,000) which collects the light from either a single UT or the four UTs simultaneously.
- Long Baseline Interferometry: UTs: maximum 130 m baseline. ATs: maximum 200 m. The four 8.2 m Unit Telescopes and the four 1.8 m Auxiliary Telescopes are the light collecting elements of the Very Large Telescope Interferometer (VLTI). The UTs are set on fixed locations while the ATs can be relocated

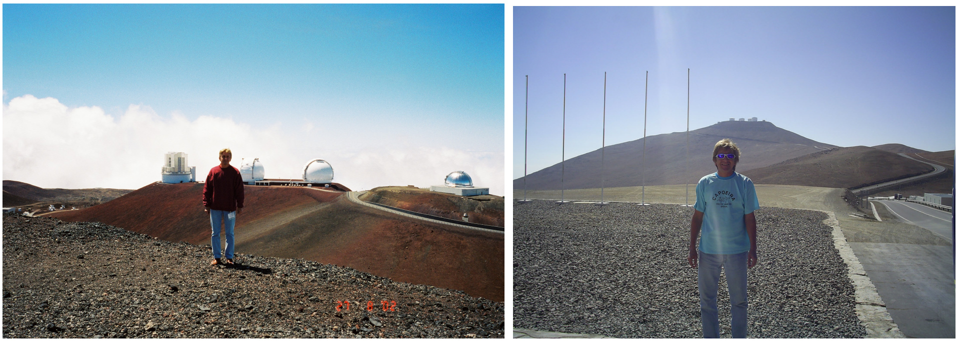

Figure 3: *Left*: Two Keck Telescopes at Mauna Kea Observatory, Hawaii, USA, are at the central position. Left and right are Subaru and NASA Infrared telescopes. *Right*: Cerro Paranal, Chile with VLT Observatory on the top.

on more than 10 different stations. VLTI instruments can recombine the light from four telescopes simultaneously. After the light beams have passed through a complex system of mirrors and the light paths have been equalized by the delay line system, the light recombination is performed in the near-infrared K band by the PIONIER (1.5-2.4 μm) and GRAVITY (2.0-2.4 μm) instruments, and in the mid-infrared L, M and N bands by MATISSE (3.2-13.0 μm).

3. JAMES WEBB SPACE TELESCOPE (JWST), (JWST 2023)

The Webb Space Telescope is the largest, most powerful and most complex telescope ever launched. It is located in the L2 Lagrange point, 1.5 million kilometers away from the Earth. Its larger size and richer infrared views allow it to go beyond Hubble Space Telescope (HST) observations witnessing the star forming regions, as well as the galaxies forming out of the early Universe.

- The second Lagrange point (L2), 1.5 million kilometers away from the Earth.
- Launched 25.12.2021, science operations started in July 2022.
- 6.5-meter segmented, 18 hexagonal segments.
- High resolution spectroscopy: Near-InfraRed Spectrograph (NIRSpec) and Near-Infrared Camera (NIRCam) are used to study astronomical objects in the wavelength range from 0.6 μm to 5.3 μm (red to near-infrared) focusing on very distant galaxies. Near-Infrared Imager and Slitless Spectrograph/Fine Guidance Sensor (NIRISS/FGS) wavelenght range is from 0.8 μm to 5 μm, while the Mid-Infrared Instrument (MIRI) wavelenght range is from 5 μm to 28 μm.

4. PLANNED GROUND BASED TELESCOPES

Now, astronomers stand on the threshold of a new telescope revolution. During the next several years, researchers expect three instruments that are great leap forward in size of their contemporary competitors to start observing the skies. The European Southern Observatory's Extremely Large Telescope (ELT) is implemented by intergovernmental organisation with 16 Member and 2 Partners States. The Giant Magellan Telescope is made possible by an international consortium of research institutions representing six countries from Australia, Brazil, Chile, Israel, South Korea, and the United States. The project of the Thirty Meter Telescope (TMT) is an international collaboration between Japan, the United States, Canada, China, and India. It is actually pending for various reasons, mainly because of lack of funding. Together, the TMT and GMT projects are seeking 3 billion USA dollars from the USA National Science Foundation, in addition to other sources of funding.

4. 1. EXTREMELY LARGE TELESCOPE (ELT), (ELT 2023)

- Cerro Armazones, Chile, altitude 3 060 meters, first light 2028?
- 39.3-meter segmented, with a 11-meter central obstruction (37.4-meter effective). 798 hexagonal segments + maintainance set, for a total of 931 segments.

4. 2. GIANT MAGELLAN TELESCOPE (GMT), (GMT 2023)

- Cerro Las Campanas, Chile, altitude 2 300 meters, first light 2029?
- 25.4-meter, uses seven 8.4-meter diameter circular non-segmented mirrors to form a light collecting area of 368 m^2 equivalent to 21.7-meter effective. On September 2023 the Giant Magellan Telescope started the four-year process to fabricate and polish its seventh and final primary mirror.

4. 3. THIRTY METER TELESCOPE (TMT), (TMT 2023)

- Mauna Kea, Hawaii, USA altitude 4 200 meters, first light ?
- 30-meter segmented, 492 hexagonal segments.

5. DISCUSSION AND CONCLUSION

The observational astronomy evolved breathtakingly in the past 50 years, some notable operational and planned large optical telescopes are shown in Figure 4. This research is supported by the institutes from the whole world, and the international collaboration together with constructive competition is mandatory because of the extremely high investments of human and financial resources. The largest optical telescopes allow high spatial, temporal and spectral resolutions of astronomical objects which lead to new discoveries, from origins of life and habitable planets to the origin of our Universe.

Since early 1970s, when the idea of Serbian national 1.5 m class telescope arose, the potential of astronomical telescopes has grown dramatically, as shown in Figure 5. At that time it was a rule that astronomers are involved in long-term observations which produce results only after several decades. This kind of observations has a scientific value even today, but the significant difference is that now the scientists involved in such projects face strong international competition and funding of their work requires the results in much shorter term. The quantity and the quality of astronomical information, provided by large ground based and space telescopes, grows exponentially, and the results similar to long-term observations can be reached by

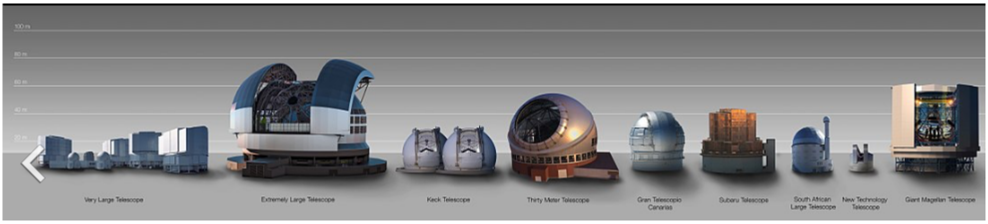

Figure 4: From left to right: 1. Very Large Telescope. 2. Extremely Large Telescope. 3. Keck Observatory Telescopes. 4. Thirty Meter Telescope. 5. Gran Telescopio Canarias. 6. Subaru Telescope. 7. Southern African Large Telescope. 8. New Technology Telescope. 9. Giant Magellan Telescope. Image Source: `https://en.m.wikipedia.org/wiki/File:Size comparisonbetween the E-ELT and other telescope domes.jpg`.

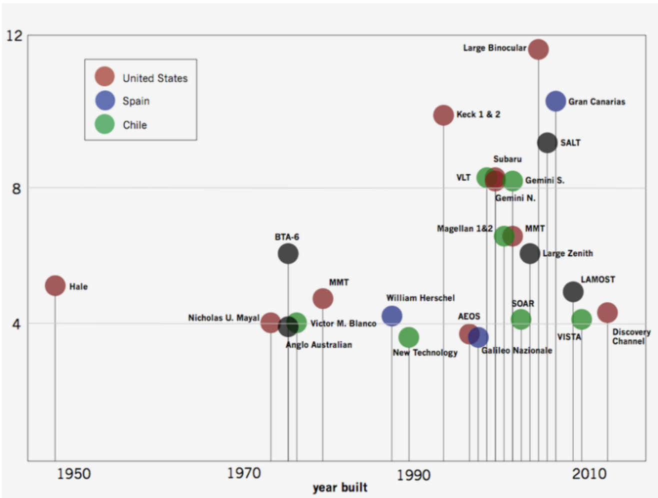

Figure 5: Effective diameter (in meters) in function of telescope's first light date. Note that for the VLT the effective diameter is 16.4 m since 2018, when the observations were made in incoherent focus of 4 UTs. Image Source: `https://en.m.wikipedia.org/wiki/File:Telescopes Size and Year Built.png`.

gathering data from different observatories through open access to their databases. Regarding the original short-term scientifically valid projects, the class of objects that can be studied with small telescopes is somewhat limited, and concerns only a small fraction of astronomical community. The follow-up programmes for selected astronomical objects require the real-time observations and multi wavelength (from UV to infrared) instruments. The national telescopes, such as the operational Serbian telescopes (ASV 2023), have a significant challenge to make their data known and accessible at the international level. For the entire community of Serbian astronomers the sustainable solution is to also collaborate closely with much larger observatories, such as European Southern Observatory, for example.

Acknowledgements

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https://en.m.wikipedia.org/wiki/File:Size comparison between the E-ELT and other telescope domes.jpg (Image Credit: ESO/ Wikipedia, CC BY-SA).

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