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Challenges in precision and vibration control for physics experiments

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Abstract

The present paper examines some of the ongoing development projects for new facilities for astronomy, high-energy particle physics and gravitational wave detection, from the viewpoint of precision and vibration control requirements.

Keywords

Telescope, particle physics, gravitational waves, precision, vibration control

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Physicists, unlike engineers, are notorious for knowing no limits, except, maybe, funding. This optimistic and ambitious attitude has led to a number of successful projects and engineering wonders,[1] like the HST (Hubble Space Telescope; NASA, 1990), the Keck telescope (first segmented telescope, 1993) and the LHC (Large Hadron Collider; CERN, 2009), to name only a few. The present paper examines some of the ongoing development projects for new facilities with even more impressive capabilities, from the viewpoint of precision and vibration control requirements.

Earth-based astronomy

There has been a change of paradigm in telescope technology with the advent of segmented mirrors (Keck, 1993), which, seemingly, makes very large telescopes scalable to infinity, especially with the success of Adaptive Optics which removes the blur due to atmospheric turbulence: 'the only clearly identified show stopper seems to be the funding'(!).[2] Several projects are due to see first light during this decade: the TMT (Thirty Meter Telescope; primary mirror M1 of 30 m) and the E-ELT (European Extremely Large Telescope; M1 diameter initially foreseen of 42 m, and recently reduced to 39 m) (Figure 1). Note that the wavefront error allowed for good image quality is only related to the wavelength observed ($\lambda/14$), making the ratio ε = precision/size significantly smaller than in any existing project. The size of these structures makes them increasingly sensitive to external disturbances such as the change of the gravity vector due to the Earth's rotation and wind; this requires control systems with larger bandwidth, conflicting with decreasing natural frequencies and very light damping. A scale effect analysis[3] shows that the behaviour of these complex opto-mechatronics systems is threatened by control–structure interaction, which so far has been insignificant, or at least manageable.[4]

The use of the VLT (Very Large Telescope) as an interferometer has long been prevented by the excessive vibration level of the system.

Space telescopes

Space telescopes are necessary to observe wavelengths which are not accessible from Earth (they have become less necessary in the visible, because of the advent of Adaptive Optics). The JWST (James Webb Space Telescope) will be the first telescope to be *deployed* in space (possibly in 2018); it will operate in the visible and near infrared at the Lagrange point L2. Its primary mirror will have a diameter of 6.5 m and will consist of 18 actively controlled segments (Figure 1). Even with this moderate size, the project turned out to be extremely expensive, the current budget of US$9 billion being five times the initial one, so that it has been described as 'the telescope that ate astronomy'.

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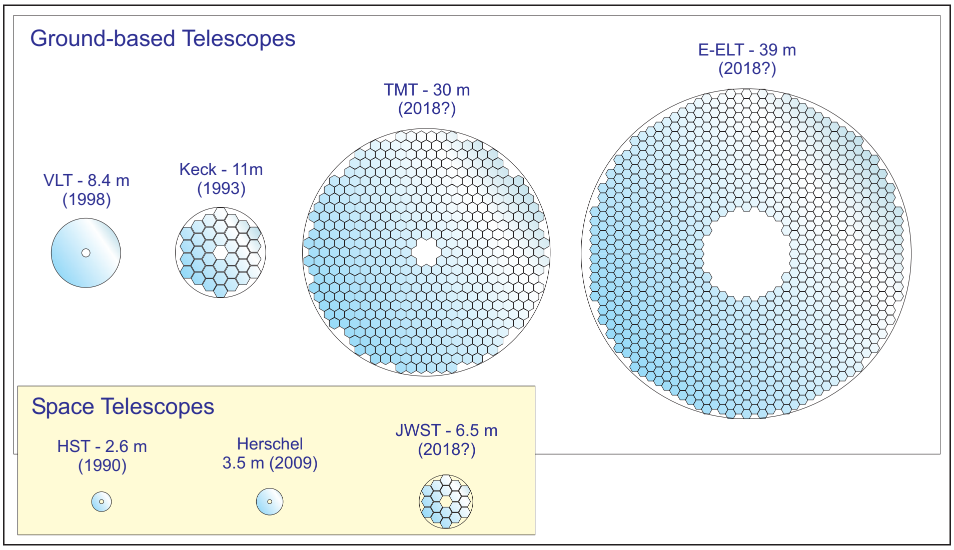

Figure 1. Primary mirror (M1) of the largest Earth-based and space telescopes (date of first light).
VLT: Very Large Telescope; TMT: Thirty Meter Telescope; E-ELT: European extremely large telescope; HST: Hubble Space Telescope; JWST: James Webb Space Telescope.

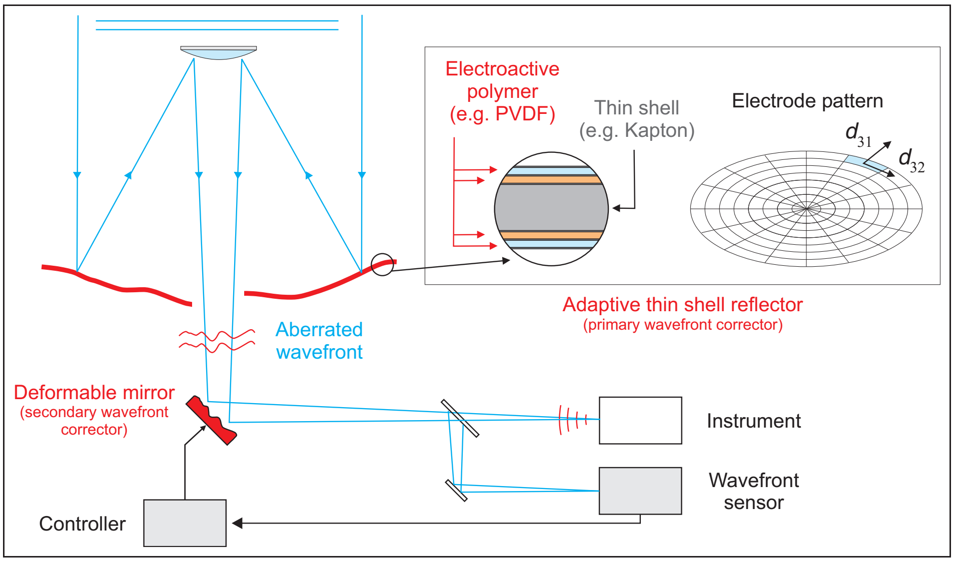

Figure 2. Conceptual design of a space telescope consisting of an adaptive thin shell reflector (which deploys under its own strain energy) and an Adaptive Optics deformable mirror used as secondary wavefront corrector.
PVDF: polyvinylidene fluoride.

On a longer time scale, there is a need for large space reflectors with a diameter of 10 m and more, but this can only be achieved by so-called gossamer telescope structures and membrane optics. The surface figure accuracy will require several active control layers, by means of active material integrated in the primary reflector, and a secondary wavefront corrector working in a manner similar to Adaptive Optics (Figure 2). Structures will be replaced by information.[5]

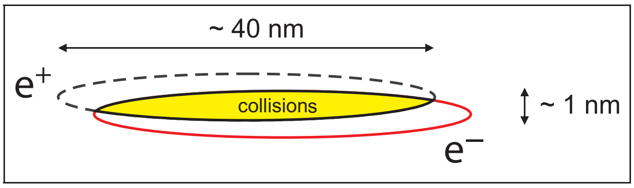

Figure 3. Typical cross-sections of the colliding beams in the future linear collider CLIC.

High-energy particle physics

Since the early days of particle physics, the energy and size of the colliders have been multiplied by five orders of magnitude. Capitalizing on the success of the LHC, which collides particles of proton size, the next generation of colliders is being developed at CERN and other research institutes. One of the options considered, called CLIC (Compact Linear Collider), consists of a

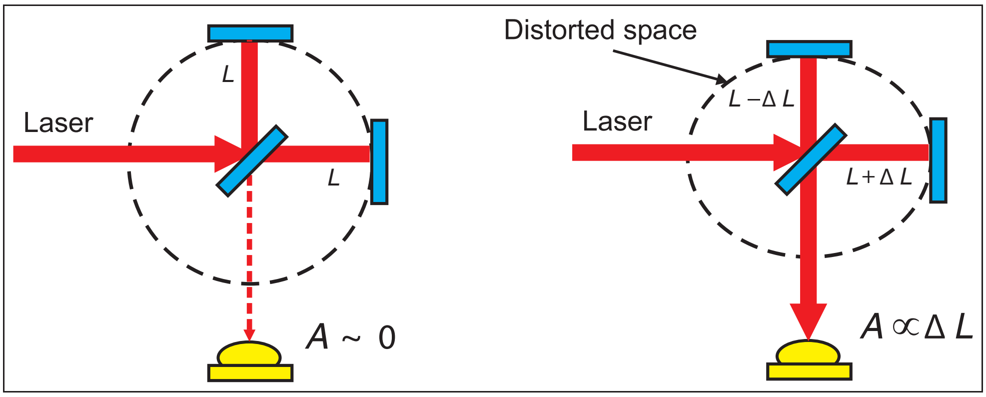

Figure 4. Michelson interferometer for gravitational wave detection (Virgo, LIGO).

straight line of 48 km colliding two beams of electron size particles; in order to achieve an adequate luminosity, the size of the beam in the final focus section is of the order of 1 nm, requiring a sub-nanometric precision in the beam positioning (Figure 3). The system is segmented into short modules which accelerate and steer the beam of particles; several control layers are foreseen to isolate the system from the environment, and align the various segments.

Gravitational wave detection

According to Einstein's general theory of relativity, astronomical events like the coalescence of black holes and supernovas generate gravitational waves which distort space. Over the years, various instruments have been developed to detect them, but so far none was successful, because they did not have (by far) the adequate sensitivity. It is currently estimated that the instrument should be able to detect deformations of the order of 10^{-21}, i.e. a relative displacement of $\Delta L = 10^{-18}$ m of two points located $L = 1$ km apart, which probably appears out of scope to most precision engineers (the ultimate limit in manufacturing, the atomic lattice distance, is of the order of 10^{-10} m). The most recent Earth-based projects, called Virgo and Laser Interferometer Gravitational wave Observatory (LIGO), use multi-kilometre interferometers (Figure 4). The sensitivity of the detector is essentially proportional to the distance travelled by the light in the instrument; the principal disturbance is the natural seismic noise which must be reduced by ten orders of magnitude at 10 Hz (assuming a decay rate of 40 dB per decade, this calls for an isolation corner frequency of 10^{-4} Hz).

The joint European Space Agency/NASA mission called LISA (Laser Interferometer Space Antenna) will attempt to detect gravitational waves by monitoring the position of three spacecrafts located at the apices of an equilateral triangle, at distance of 5 million km.

Conclusion

The future of experimental physics will demand larger and more precise experimental facilities. According to the roadmap, the increase in size of the instruments could even accelerate during the 21st century, at least if the funding is available. Larger size and more precision will inevitably lead to new challenges for the engineering community, in the field of systems and control, vibration alleviation, control–structure interaction and precision metrology. We should prepare for it.

On the other hand, there has been constant progress in extreme precision engineering, which has been translated in the continuous application of Moore's law from the 1970s until now. Many control systems initially developed for experimental physics have been transferred to medicine and other daily life applications.

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