SOLAR TELESCOPES

Introduction

Solar telescopes are based on the same construction principles as the night-time instruments, but solar observations require specialized telescopes and instruments, since they must withstand the heat input from the Sun while maintaining their high resolution in the spatial, spectral and temporal dimensions. The solar irradiation heats up the ground, causing a layer of turbulent air which in turn degrades the image quality. Solar telescopes are therefore normally installed in towers, above this turbulent layer.

Most of the existing solar telescopes are synoptic instruments with apertures ranging form a few centimeters to, say, half a meter. Several of these telescopes are organized as networks for helioseismology measurements. Others monitor solar activity and provide images of the solar disk at different wavelength bands, or magnetograms. These telescopes often provide important background information for high-resolution studies, although their importance has somewhat decreased, since the SOHO satellite delivers daily full-disk images without interruptions. New full disk telescopes offer synoptic data at a high cadence, for the investigation of short-lived phenomena.

Telescopes with apertures larger than, say, 0.5 meters have a field of view of only a small fraction of the solar disk at an image scale that allows for diffraction-limited imaging in the focal plane. In the past, most telescopes of the 0.5 to 1 meter class had evacuated light paths in order to suppress inhomogeneities of the air's index of refraction caused inside the telescope by thermal input from the Sun. For solar telescopes of the next generation with apertures of 1.5 to 4 meters, open structures are envisaged, with complex cooling systems for the primary optics that avoid the heating due to absorbed solar radiation. Optical elements are made of material with very low thermal expansion and, if possible, with high thermal conductivity. The latter property simplifies the cooling process and significantly shortens the time needed to reach thermal equilibrium.

Many of the phenomena that can be observed in the solar atmosphere have a lifetime of only a few minutes, and important changes may occur within a few seconds. High-resolution solar telescopes therefore have to provide light levels high enough to achieve a sufficiently high signal-to noise level. This is most important for the measurement of the (weak) magnetic field in the solar photosphere. Important small-scale objects have sizes of 100 km or less, and it requires telescopes with an aperture of at least one meter to resolve them. Next-generation telescopes with apertures of about four meters will be able to achieve high light level, short integration time, and good spatial resolution. It should be noted that for diffraction-limited observations, the light level per resolution element is the same for any telescope. For an increased light level one therefore has to sacrifice spatial or temporal resolution.

In this article we mainly discuss properties of high-resolution telescopes and the corresponding instrumentation. We do not attempt to provide a full list of existing telescopes, but mention only very few ones that represent important construction principles, and that are scientifically very successful, thanks to their adaptive optics systems.

Best sites

High-quality solar observations require sites with low levels of local and high-altitude turbulence. The atmosphere should also contain little water vapor and dust particles, in order to minimize the amount of scattered light. Sites on high mountains located on rather small islands have proven to be the best solar sites. Low levels of local turbulence can also be obtained at lake sites, where the nearby water keeps the ambient air temperature fluctuations low and inhibits the build-up of local turbulence. The comprehensive ATST solar site site survey, arguably the most testing so far, identifies three excellent site for solar observations: Mees Solar Observatory on Hawaii, Observatorio del Roque de los Muchachos on La Palma and Big Bear Solar Observatory in California. There is evidence that Antarctic sites such as Concordia Station at Dome C might have also have excellent day-time seeing. In the future, the quality of solar telescope sites may be more precisely characterized by the number and altitude of turbulence layers in the atmosphere above the telescope. Multi-conjugated adaptive optics systems (see below) will be able to correct the image degradation caused by such well-defined layers.

Existing telescopes

A large number of solar telescopes with apertures between 150 cm and about 10 cm is presently operational around the globe (see e.g. Landoldt-Börnstein for a list of solar telescopes). Many of the small-aperture telescopes are either used for routine observations of the full disk (images of the chromosphere, magnetograms of the photosphere), or are organized in networks for helioseismic measurements. Three of the large-aperture telescopes are presently equipped with adaptive optics, and are therefore suited for observations with highest possible spatial resolution, for imaging and spectroscopy. The Dunn Solar Telescope (DST, Sunspot, NM, 1969), the German Vacuum Tower

Telescope (VTT, Tenerife, 1987), and the Swedish 1-meter Solar Telescope (SST, La Palma, 2002) have a number of common features, but also important differences. All three telescopes (i) are tower constructions with the telescope entrance high above ground, above the local layer of turbulence, (ii) have a long focal length of the primary mirror or lens, to avoid a hot focal plane, (iii) use evacuated tubes for the light path, and (iv) are domeless or with retractable dome. The DST and the SST have a altitude-azimuth feed system ("Turret") that allow to have the full light path in vacuum, whereas the VTT uses a Coelostat system. The SST is a refractor, with a 1-m lens that acts also as entrance window.

Next generation solar telescopes

At present, three solar telescopes of the 1.5 to 2 meter class are in preparation or under construction, and two of them should become operational within the next one or two years. These telescopes mark an important design change, since they do no longer rely on evacuated or helium-filled telescope tubes to avoid turbulent air in the light path. They represent an intermediate step between the presently available telescopes and the next-generation 4 meter telescopes. The next generation of solar telescopes with apertures in the range of 4 meters have been enabled by two technical breakthroughs: adaptive optics for solar telescopes, and the feasibility of air-cooled, open telescopes. The Dutch Open Telescope (DOT) on La Palma has been a pathfinder for the new generation of open telescopes.

The German *GREGOR telescope* has an aperture of 1.50 m and is located at the Observatorio del Teide on Tenerife. It is an open telescope in a three-mirror Gregory configuration with a focal length of 50 m. The primary mirror is made of CESIC, a silicon-carbide material with high thermal conduction, and it is air-cooled from the backside. At Big Bear Solar Observatory, the *New Solar Telescope* is under construction. It is an open off-axis Gregory system with an aperture of 160 cm and an effective focal length of 88 m. Both telescopes will be equipped with high-order adaptive optics and become operational before 2010. In India, a project to build a 2-meter telescope in the Himalaya, at an altitude of 5000 m, has been initiated.

In the US, the *Advanced Technology Solar Telescope* (ATST) project of the National Solar Observatory is ready to enter in the constructions phase. The construction phase is expected to start in 2009, and First Light may occur in 2014. The ATST is a 4-meter, off-axis telescope, and it will be constructed on the Haleakala mountain (3000 m) on Hawaii. The telescope design is optimized for high sensitivity, polarimetric accuracy and low scattered light. Due to its open design, the telescope covers a wavelength range from 0.3 µm to 35 µm. The COronal SolarMagnetism Observatory (COSMO), a coronagraph with an aperture of 1.5 meters has been proposed by the High Altitude Observatory in Boulder, and the Universities of Hawaii and Michigan. Phase-A studies for this project are currently underway. In 2007, the European Association for Solar Telescope (EAST) has initiated the *European Solar Telescope* (EST) project. EST is a telescope of the 4-meter class, to be built in the Canary Islands toward the end of the second decade. During a design study, carried out between 2008 and 2010, the opto-mechanical design of EST will be worked out, and a local site characterization will be made. EST will measure the solar magnetic field with highest spatial and spectral resolution in the visible and near infrared wavelength region.

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