Perspectives for the OTT

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Summary

The *Open Tower Telescope* designed and built by R.H. Hammerschlag at Utrecht finally nears completion in "minimum configuration", encompassing the basic telescope and prime-focus image registration. This note outlines various possibilities for future extensions at the forefront of solar physics.

Contents

1 Introduction

1.1 The OTT project

The history of the OTT project is long and is not detailed here. The basic concept of an unenclosed open telescope on top of an open steel tower remains unique. Its aim is to minimize deterioration of image quality due to local seeing, by doing away with a telescope dome or vacuum enclosure. This concept is of general interest to astronomical telescope design, but it has never yet been proven.

The OTT is now being completed for assessment on La Palma with funding from the *Stichting Technische Wetenschappen*. In this note I assume that the telescope will pass this test. I concentrate here on future exploitation of the OTT to the full capabilities of its design goals.

Originally, the OTT was intended to test future sites for LEST, the large international solar telescope[1]. In the meantime, the LEST Foundation has selected a site foregoing the comparative testing of the candidate sites (including Mauna Kea) with 40-cm telescopes that was originally scheduled. LEST will go to La Palma — if it ever gets built. My motivation for completing and using the OTT squarely rests on its promise for doing excellent solar physics.

It is obvious that full-time usage of the OTT at the forefront of solar physics will exceed the scientific manpower at the Sterrekundig Instituut Utrecht considerably. Teaming up with colleagues abroad is an absolute necessity for exploiting the full science capability of the OTT if it performs as expected. It is equally obvious that no colleague abroad is going to invest money or time in the OTT before its concept is proven. Nevertheless, likely partnerships have been discussed already. This note is an inventory of the future paths that I, as future science manager of the OTT, regard as attractive ways to go.

1.2 Comparison with other projects

The OTT has been slow in coming. One reason is that it has always been and still is a small–sized project, trading speed for money by limiting manpower and industrial contracting severely. Its total cost is 1–2 orders of magnitude less than for all other solar telescope projects of the last two decades.

Nevertheless, the OTT aims to be scientifically competitive with the best solar telescopes worldwide, within the limits of its secondary instrumentation. Also, the realization of the OTT is not significantly slower than for the other projects, excepting the Swedish Vacuum Solar Telescope (SVST) which replaced an existing solar telescope in an existing tower.

[1]LEST stood for *Large European Solar Telescope* in the first decade of its planning, for *Large Earth-Based Solar Telescope* in the second.

Let me briefly review the other solar telescope projects. First the Canary Island telescopes:

– Swedish Vacuum Solar Telescope (SVST, 48 cm, La Palma).
  A vacuum refractor of exceptional quality, on a par with the Pic du Midi *Tourelle.* The doublet objective acts also as vacuum window. The two-mirror alt-azimuth turret is a smaller copy of the Sacramento Peak Vacuum Tower Telescope (SPVTT) turret.

  The SVST is used most of the time by the Lockheed Palo Alto Research Laboratories (LPARL; Title, Tarbell, Shine, Topka and others), in yearly campaigns in which Utrecht (Rutten, Zwaan, Strous, Balke) as well as Utrecht offspring (at CfA and LPARL; van Ballegooijen, Uitenbroek, Martens) participate. The LPARL postfocus equipment includes an active-mirror pore tracker, Ca II K filter and the tunable SOUP filtergraph which earlier flew in the *Challenger* Spacelab-2 payload. The LPARL funding for this work came so far from the OSL project; other sponsoring is now sought.

– German Gregory Coudé Telescope (GGCT, 45 cm, Tenerife).
  Operated by Göttingen; formerly installed at Locarno. Vacuum Gregorian, used mostly for spectroscopy including magnetometry.

– German Vacuum Tower Telescope (GVTT, 70 cm, Tenerife).
  Newly completed counterpart to the SPVTT of classical design (heliostat in air, vacuum off-axis reflector). The initial problems with heliostat wind shake seem largely cured; the emphasis is on high-quality spectrometry.

– French solar telescope (THEMIS, 90 cm, Tenerife).
  To be installed in 1995. Ritchey-Chrétien vacuum reflector with subtractive double-pass spectrometer. The emphasis is on precision polarimetry. The design is very complex and the initial shake-out will probably take a few years. When it performs properly, it will be the world's premier telescope for magnetometry until LEST functions.

– International solar telescope (LEST, 250 cm, La Palma).
  Next-generation facility to be built by an international consortium including the US (still). Helium-filled actively-controlled modified Gregorian, prepared for adaptive wavefront correction. The designs are largely complete and ground work at La Palma has started, but the funding remains insecure.

The current projects for solar imagers in space are:

– MDI (NASA, 12 cm, onboard ESA's SOHO solar orbiter).
  Michelson-Doppler Imager, launch in 1995. It will deliver seeing-free Dopplergrams and some magnetograms at either $4''$ or $1.4''$ resolution. Most observing will be full-disk helioseismology at the lower resolution, but there will be campaigns at the higher one.

– OSL (NASA, 100 cm, Earth orbiter).
  The successor to the SOT and HRSO proposals, and likewise doomed due to NASA's present malaise; effectively killed last year. If flown, this would have been the Space Telescope of solar physics. No chance of revival, unless Congress kills Space Station Freedom soon.

– SIMURIS (ESA, 200 cm interferometer, attached Space Station payload).
  Proposal for a a co-phased linear interferometrical array using rotational tomography. Its realization depends on the future of the Space Station and on inter-ESA politics.

– SHARP (NASA, 20 cm, free flyer).
  Proposal in the Small Explorer program. This would be a small mission, severely limited in telemetry bandwidth and facing heavy competion, since over 200 SMEX proposals are anticipated for only a few mission slots.

Zwaan has been involved extensively in SOT/HRSO/OSL; I participate in the other three space projects.

The science capabilities of the OTT lie closest to the SVST. None of the present ground-based reflecting telescopes reaches the diffraction limit, due to alignment problems and the degradation inherent in the use of a vacuum window. Compared to these, the strength of the OTT will be its spatial resolution, especially if the concept of the open telescope pays off in reducing the degradation by locally-caused seeing. Indeed, most of the day-time seeing at the SVST originates close to the telescope, apart from "Caldeira seeing" around noon. More about this below.

The SVST suffers from turret shake and guiding errors which are compensated by the LPARL active-mirror pore tracker. The latter limits the observations to fields nearby a suitable pore, and causes the field to revolve around that pore during the day. The OTT has exceedingly high mechanical stability and should permit absolute long-duration guiding, without requiring a solar reference feature and with very high precision. It will be the first telescope suited to "heliometry", *i.e.,* tracking of solar surface features with sub-arcsecond precision.

The OTT will also be the first telescope on the Canaries which is inherently suited to solar polarimetry. In the existing ones, reflections at large angles (heliostat, turret) and vacuum windows cause large instrumental polarization and depolarization.

In contrast to the other telescopes, the OTT does not provide a solar image to a laboratory room inside a building. It cannot be used for ad-hoc setups on an optical table in an optics lab, or with large image-analysis instruments requiring laboratory conditions. Thus, the OTT is not suited to experimentation with new instrumentation or to feed large spectrometers; it will never be a general multi-purpose facility such as the SPVTT, GVTT or LEST. Its science capabilities are limited to programs employing robust post-focus equipment that is installed more or less permanently, either at the top of the telescope or in the larger space behind the primary, and which is controlled from ground level using fairly rigid, standardized modes of operation. All instrumentation described below is of this type.

2 Imaging

2.1 Background

The frontier of modern solar physics lies in high-resolution imaging, especially in narrow spectral bands within specific spectral lines. Its emphasis is on understanding time-dependent small-scale processes. The solar atmosphere is a very rich laboratory displaying an amazing variety of physics experiments in radiative transfer, hydrodynamics, magnetohydrodynamics and plasma physics, most of which occur on the sub-arcsecond scales set by pressure scale heights and photon mean free pathlengths. These are of order $0.1''$ and require resolution at or below the seeing limit. Observational solar physics is therefore much more seeing limited than most other astronomical observing.

Solar processes and structures are also highly time-dependent, are constrained by velocity fields and by magnetic fields, and extend with much variation from the subsurface layers to the outer heliosphere. They require high-resolution imaging in a number of spectral diagnostics, including filtergrams in lines from various heights (photosphere, temperature-minimum region, chromosphere, corona), Dopplergrams and magnetograms, also at different heights. These should be taken co-spatially and synchronously, in rapid cadence. The sequences should be long to follow the evolution of surface patterns and flows.

Direct imaging of the photosphere and low chromosphere (*e.g.,* in Ca II K which provides a valuable proxy to magnetograms) is therefore worthwhile if the spatial resolution is sufficient to identify small features such as granular structure, photospheric filigree (clusters of magnetic fluxtubes) and chromospheric grains, and the sequence durations are sufficiently long to register the horizontal flows marked by such tracers.

Suitable research topics for such imaging are the hydrodynamic structuring of the lower photosphere (granulation, mesogranulation, supergranulation; giant cells if they exist) and the magnetohydrodynamic structuring of the photosphere and chromosphere (field emergence and disapperance, network topology and evolution; umbra and penumbra dynamics; active region patterning; nests of activity).

Solar imaging of this type is an old activity in principle, but a new one in practice. There was much solar imagery on ciné film and spectroheliograph plates in the sixties, but it was dropped in favour of quantitative spectrometry using photomultipliers and diode arrays in the seventies and eighties. The CCD detector revolution has now turned the scales back to two-dimensional registration. Even more important is the advent of efficient digital image-processing techniques permitted by the new generation of graphics-oriented workstations. Only now can a small university group like ours handle time-dependent two-dimensional data sets of multi-Gigabyte size. We are in the midst of a computer revolution in which the data reduction, analysis and presentation techniques are evolving rapidly, with drastical changes in the way observational solar physics is done. Prime examples are the sophisticated solar image analysis techniques developed at LPARL[2]. In these, image sequences are reregistrated, rubber-sheet corrected, 3-D Fourier filtered and analysed with pattern-recognition software, cork sprinklers, local-area autocorrelation and other software gadgets that bring a host of new diagnostic means to solar physics. One important trick is to use human vision in the analysis process by using image blinking and fast video display techniques on all kinds of computer-generated diagnostics.

The OTT, with its emphasis on high-quality imaging, fits very well in this development. I, for one, do not regret that the OTT wasn't completed before the CCD's, workstations, IDL and video presentation techiques came around. We now have the tools to apply the OTT to frontier solar physics.

2.2 Implementation

The OTT in minimum configuration (prime-focus CCD image registration[3]) is suited to wide-band imaging for heliometry at large signal-to-noise, intermediate-band imaging for photospheric fine structure (for example in the Fraunhofer G–band which depicts the granulation and filigree particularly well), and narrow-band imaging for chromospheric pattern tracing.

The simplest mode of operation is simply to digitize and store CCD images in fixed cadence, much as we do it now with the LPARL set-up at the SVST. A step up is to apply real-time CCD frame selection using a hard-ware seeing monitor. The latter may consist of a linear or small-area CCD, sampling the granular RMS contrast with large frequency and triggering the imager when the seeing gets good. Such an extension takes only fairly simple electronics and yields sizable improvement of the resulting data sequences.

The next stage comes when the OTT is equipped with secondary optics to provide the secondary image behind the main mirror, where there is more space to accommodate beam splitters and larger birefringent filters such as the LPARL Ca II K filter. Synchronized co-spatial and simultaneous multiple-beam imaging is then feasible. It will enable pattern correlation between the photosphere and chromosphere, for example to tie the so-called Ca II K_{2V} internetwork grains (probably locations of shocks in the chromosphere, according to a recent numerical simulation by Carlsson and Stein 1992) to piston excitation sites in the underlying granulation.

A particularly attractive option is to implement multiple-beam speckle interferometry. In this technique, a broad-band speckle imager uses the solar granulation to

[2]Including R.A. Shine, one of the architects of IDL which is another example of modern image processing.

[3]Actually in the secondary focus, just behind the water-cooled diaphragm.

measure the optical transfer function of the atmosphere per isoplanatic patch, while the synchronous specklegrams of a narrow-band imager are subsequently deconvolved with the broad-band results (Keller and von der Lühe 1992). This requires fast speckle camera's, fast digitization and storage hardware, and effort on specklegram processing algorithms. It promises substantial improvement of the image quality, restoring images taken from only moderate to good seeing quality and approaching the telescope diffraction limit at good seeing. It does so independent of the spectral bandwidth, for the broad- and narrow-band channels alike.

3 Magnetometry

3.1 Background

Most of the above imaging concerns studying magnetic field structuring, be it indirectly. Chromospheric and coronal fields can only be studied through proxies (Ca II H & K, Hα, He I 10830, soft X-ray intensities), but photospheric fields can be measured directly from Zeeman-sensitive lines in the visible and infrared. Magnetograms obviously offer the best diagnostic to any program in which the surface field distribution is required, adding at least the field polarity and better yet the field vector, measuring both longitudinal and transverse components.

The best is to obtain vector magnetograms at high spatial resolution, resolving at least the larger flux elements to obtain their intrinsic field strength rather than only the flux with an unknown area filling factor. Such high-resolution vector magnetography wil be exceedingly valuable to nearly any program in observational solar physics.

3.2 Implementation

Vector magnetography is a major goal of most modern solar physics installations. Examples are the Big Bear video magnetograph, the Stokes vector magnetograph recently installed by the High Altitude Observatory (Boulder) at the SPVTT, and the clever magnetograph designs for LEST proposed by Stenflo and colleagues at Zürich. Most existing magnetographs employ a grating spectrometer to isolate the Zeeman π and σ components of a magnetically sensitive line. The OTT cannot easily accommodate spectrometers, but fortunately, there is a variety of modern filtergraph techniques that permit magnetography within a small volume. They are also two-dimensional, producing images directly rather than from stepped-image scans.

The first possibility is to employ a Cacciani resonance-cell magnetometer (Cacciani *et al.* 1990). This is a small and stable instrument which is very well suited for vector field monitoring. An attractive option is to combine efforts with S. Tomczyk and B.W. Lites of the High Altitude Observatory (part of NCAR). Tomczyk developed a Cacciani seismometer in his PhD thesis and is now constructing a prototype Cacciani vector magnetograph at HAO. Initial contacts have been laid and are promising.

The second possibility for building compact magnetographs is to use multiple Fabry-Perot interferometers. There are two options, both attractive too. The first is to use two-stage solid etalons made of lithium-niobate, in cooperation with D.M. Rust (Johns Hopkins) who has suggested moving his Australian-built instrument now on the Sacramento Peak Hilltop telescope to the OTT. The second option is to design a three-stage Fabry-Perot magnetograph in cooperation with Italian colleagues (Naples and Florence), with the one they have developed for the SPVTT as example, and to have it built by Queensgate Ltd. The commercial Fabry-Perot's are now so good that a compact two- or three-stage system which does not require a universal birefringent filter for order selection appears well feasible.

4 Aperture

4.1 Background

The primary mirror of the OTT measures 45 cm in diameter but the mechanical structure may accommodate an 80 cm mirror without change. The solar physics motivation for such an upgrade will be strong if indeed the OTT manages to keep both internal and locally-induced seeing low, and when fast-frame image-selection and speckle restoration methods are used. Let me elaborate this point.

The background here is that most telescopes never reach their resolution limit at all, even if that is well below their theoretical diffraction limit as is usually the case. The exceptions are the Pic du Midi *Tourelle* and the SVST. These refractors not only have outstanding optical quality, primarily due to their optical simplicity, but they are also at very good sites while much precaution has been taken to avoid the excitation of local atmospheric disturbances. Nevertheless, even these telescopes perform at their limit only in "super-seeing", which is extremely rare at the Pic du Midi and not at all frequent on de Roque de los Muchachos. One regularly spends weeks of dedicated telescope time waiting for excellent seeing; super-seeing is more of a fluke once-in-a-career commodity.

The proper measure in this respect is the value of the Fried parameter r_0. It equals the diameter of a telescope for which the diffraction limit equals the average resolution permitted by the atmosphere at a given moment, and so quantifies the atmospheric quality in resolution terms. At Sacramento Peak, r_0 is between 3.5 cm and 20 cm during 90% of the clear-sky observing time (Brandt *et al.* 1987). The statistics at La Palma are *not* significantly better, except that there is more sunshine, that good seeing tends to come with longer duration, and that it may occur in the afternoon as well.

At the very best seeing, the SVST solar images are nearly diffraction limited, with r_0 about equal to the telescope diameter of 48 cm. This implies that the SVST diameter is very well suited to the best seeing it experiences. If the aperture were larger, the best images might actually be *less* sharp due to cross-talk between different seeing-cell sized parts of it.

Much of the seeing deterioration occurs close to the telescope, especially at La Palma. Solar heating of the building and telescope enclosure plays a large role, evident from the fact that the SVST night-time seeing statistics are far better than the day-time ones. The nearby NOT telescope, of which the dome has been very carefully designed to minimize night-time disturbances, often reaches r_0 values of a meter or so (much more often than the WHT with its classic dome and integrated office building).

If the OTT with its new concept manages indeed to reduce local disturbances better than the present solar telescopes do, it may well turn out to have the best r_0 statistics worldwide, and in particular, reach r_0 values above 40 cm when the seeing gets good. In that case, increase of the aperture above 40 cm translates directly into corresponding increase of telescope resolution in the best images.

The second aspect is that the seeing changes fast (up to 50 Hz), with Kolmogorov-type behavior (Hecquet and Coupinot 1985); these properties can be exploited to build images that are much better than r_0. Short exposures freeze the wavefront disturbances; taking many frames collects the statistics needed for restoration. Fast-frame image selection alone improves image quality considerably; Beckers (1989) estimates over a factor three enhancement if exposures are made from the best 10 percentile of 10 ms frames rather than in a single long exposure. The recent, impressive speckle restoration results of Keller and von der Lühe (1992) demonstrate a total factor of five improvement over the typical seeing quality with the SVST. With these techniques, bad-seeing data are restored to good-seeing quality, and the telescope rather than the atmospheric r_0 sets the resolution limit when the seeing is good.

4.2 Implementation

As noted above, installing a mirror of up to 80 cm diameter is feasible with the present OTT mechanical structure. D.M. Rust has informally proposed to provide an existing mirror of that size and of excellent optical quality to such an upgrade.

5 Antarctica

5.1 Background

Antarctica offers special value to astrophysics in that the sun doesn't set there in the austral summer, the stars not in the winter. It is therefore suited for campaign-wise observing which aims at continuity across the day-night cycle. The summer weather patterns are such that periods of over a hundred hours of continuous sunshine are not rare. These conditions have been exploited over the past decade by helioseismologists (E. Fossat c.s. at first, J.W. Harvey c.s. in more recent years). In campaign duration, lack of accessibility and cost Antartica lies between using a normal observatory and operating a 24-hour telescope network around the earth, and of course far below space platforms.

More in general, the trend in solar astrophysics is no longer to study a single sharp picture but to study the evolution of structures, patterns and processes. The duration of the data sequences that one obtains is now an item of vital importance. This is illustrated by the new telescopes on the Canary Islands. They are not significantly better or better-equipped than the SPVTT in the US, but they experience longer periods of fair, good and even excellent seeing, sometimes all day long. The best high-resolution data sequences taken with the Sacramento Peak facility (from J.M. Beckers' famous HIRKHAD program) had typical durations of 20–30 min only. The best LPARL SOUP sequences with the SVST reach up to 3–4 hours; this increase of duration is the major gain of the last years. Extending sequence durations to 20–100 hours by going to Antarctica (rather than setting up an expensive network or going to space) is a definite option for which a strong scientific case can be made.

However, contrary to initial expectations and various reports, the seeing at the well-equipped Scott-Amundsen base at the South Pole is *not* good. This does not impede helioseismology with $2''$ pixels, but it spoils the site for any high-resolution programs except in the infrared.

Night-time astronomy is also getting interested in Antarctica. The US Academy of Sciences is formulating plans to install an infrared facility in a mountain-top observatory at the rim of the Antartic plateau, at a good-seeing site. The IAU has set up a working group to make that international. It might eventually be a good site for the OTT as well.

5.2 Implementation

My reason for adding Antarctica as an OTT perspective here is not that I want to move the OTT there now. It is clear that the OTT will be more productive at La Palma at far smaller cost; anyhow, the Antarctica Observatory doesn't yet exist even on paper.

Nevertheless, by the next decade LEST will (hopefully) be in full operation; it may be time then to put the OTT to something else. Its virtue will then be that is is easily disassembled and transported to another site. The mechanical structure, including the drives, can be employed at and near the poles without much change. Relocation to the Antarctic Observatory may eventually be a worthwhile venture. Obviously, such a move might suit national policies concerning Antarctica.

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