Cornelis Zwaan, open principle, and the future of high-resolution solar telescopes

Robert H. Hammerschlag*[a], Felix C.M. Bettonvil[a], Aswin P.L. Jägers[a,b], Guus Sliepen[a,b]
[a]Astronomical Institute, Utrecht University, Princetonplein 5, 3584CC Utrecht, the Netherlands
[b]Technology Foundation STW, Utrecht, the Netherlands

ABSTRACT

It was in the years around 1970 that during site-test campaigns for JOSO masts were erected up till 30 m height with sensors at several heights for the measurement of temperature fluctuations. Cornelis (Kees) Zwaan discovered that the fluctuations decrease drastically at heights from about 15 m and upward when there is some wind. The conclusion from this experience was the open telescope principle: the telescope should be completely free in the air 15 m or more above the ground. The Dutch Open Telescope (DOT) was the pioneering demonstrator of the open-telescope technology. Now that larger high-resolution telescopes come in view, it is time to analyze again the principle: (*i*) the essentials for proper working of the open principle; (*ii*) the differences with nighttime observations particularly concerning the seeing; (*iii*) the design consequences for the new generation of high-resolution solar telescopes.

Keywords: solar telescopes, open-telescope principle, wind flushing, stiff constructions, high spatial resolution, day- and nighttime seeing, ground effects, open towers

1. INTRODUCTION

Kees Zwaan was one of the key persons of the Joint Organization for Solar Observations (JOSO). One of the organization's original goals was to determine one or more excellent places for the erection of solar telescopes. High spatial resolution was at that time and still is one of the most important observational requirements.

Over the past years modern image processing combined with wavefront-correction and image-reconstruction techniques like Adaptive Optics (AO), Speckle Reconstruction, Phase Diversity and Multi-Object Multi-Frame Blind Deconvolution (MOMFBD) improved drastically the spatial-resolution capabilities of ground-based telescopes. However, all these reconstruction techniques are limited in the gain of image improvement by signal-to-noise aspects. Therefore the quality of the raw images determines the attainable final image resolution.

The raw-image quality is limited by fast-optical-refraction-index fluctuations in the light path through the earth's atmosphere. This is called the 'seeing quality'. The disturbances themselves are indicated as 'seeing'. The refraction-index fluctuations are caused by density fluctuations in the air, which in turn can be caused by fluctuations in temperature and pressure. Fast-pressure fluctuations are only caused by wind fluctuations. Moreover, calculations show that these pressure fluctuations are too small to explain the seeing for wind velocities during observations, ranging up to 20 m/s. Consequently, the temperature fluctuations are the primary source for the seeing.

Nevertheless, indirectly the wind has a strong influence on the seeing, because the dispersion of temperature fluctuations from heated sources is largely determined by the wind influence on the airflows. In section 2 we discuss the interaction between the wind and the ground surface, leading to the open tower design. In section 3 we consider the interaction between the wind and the telescope structure itself, leading to the open wind-flushing principle. Section 4, at last, summarizes our conclusions for the construction of future high-resolution solar telescopes.

---

[*] R.H.Hammerschlag@uu.nl; phone and fax +31 30 2535220; http://dot.astro.uu.nl

Ground-based and Airborne Telescopes II, edited by Larry M. Stepp, Roberto Gilmozzi,
Proc. of SPIE Vol. 7012, 70120M, (2008) · 0277-786X/08/$18 · doi: 10.1117/12.789944

2. GROUND INFLUENCE ON SEEING: DIFFERENCE BETWEEN DAY- AND NIGHTTIME

The ground is heated by the sun during daytime solar observations. As a consequence, warm air bubbles rise upward, hundreds of meters high if wind is completely absent. Under such conditions no solar telescope will produce sharp images, no matter its construction.

Fortunately, a small breeze already mixes the air and at a sufficient height above the ground the air temperature can become adequately homogeneous that sharp solar images become possible. It was Kees Zwaan, who recognized this effect when analyzing data of many temperature fluctuation measurements obtained with a set of sensors at different heights along 30-m high masts at several candidate sites for a future solar telescope. The measurements indicated that typically in the region within a height of 10 to 15 m above the ground the homogeneity of the air temperature improves drastically if there is a wind breeze of 5 to 10 m/s.

Kees Zwaan discussed these results with one of the authors (Hammerschlag), who had an instrumentation research position at the astronomical institute of the University Utrecht and was partly involved in the development of the site testing instrumentation for the JOSO campaigns. As a result, the idea rapidly crystallized that a high-resolution solar telescope should stand 'free' in the air at a height of 15 m or more above the ground.

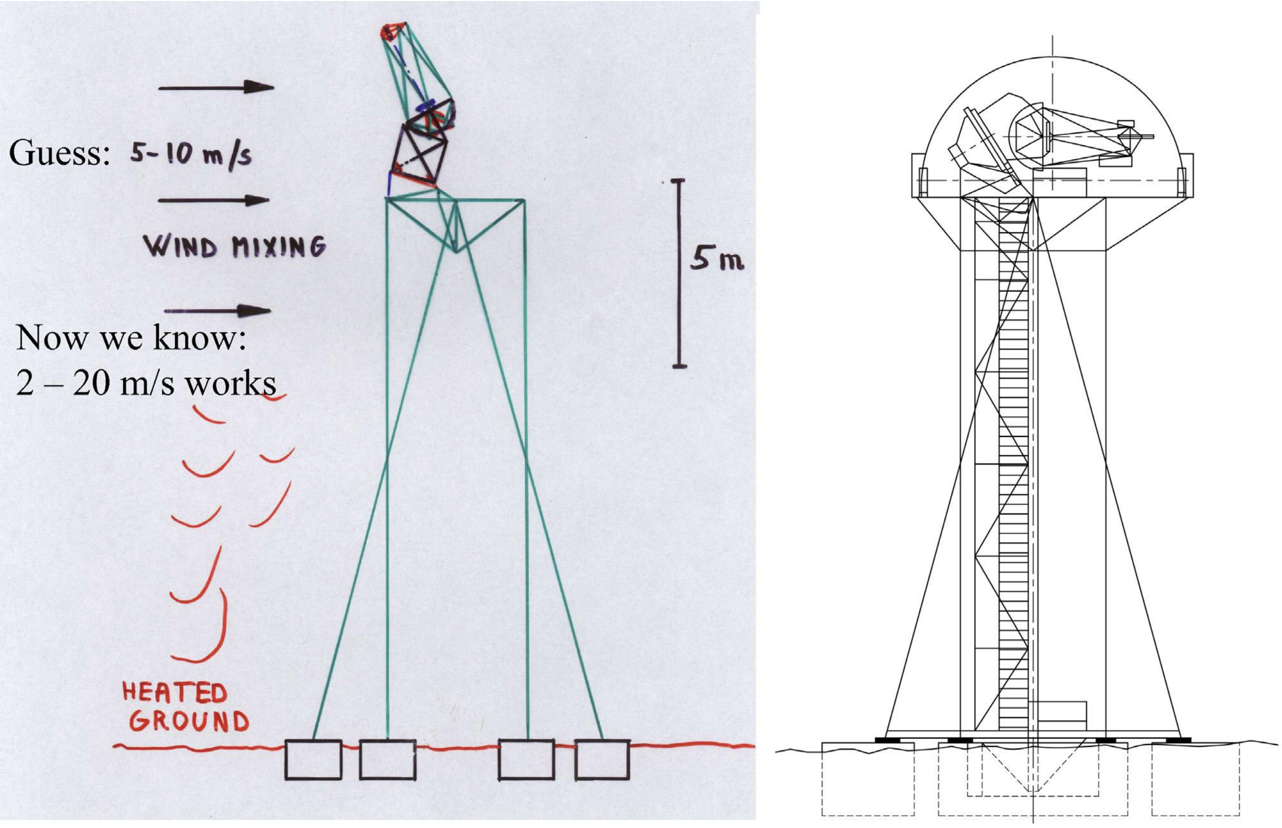

Fig. 1. *a* (*left*): Conceptual scheme of the open tower for solar observations. *b* (*right*): Design scheme with open-foldable dome and telescope in parked position. From the bottom upward: foundation consisting of four 2-m deep blocks of 25 cubic meters concrete each; a 15-m high tower with two vertical leg triangles seen face-on, the other two edge-on; disconnected open-frame stairs and elevator; telescope in parked position; closed canopy. At about 13 tons the tower weighs less than the telescope on top of it (about 17 tons), but nevertheless provides very high pointing stability in strong wind buffeting through its special leg arrangement. Each of the two parallel triangle pairs inhibits tipping of the platform but permits only plane lateral motion. That is permitted since the sun is an object at infinity. The triangle pairs also provide extreme stiffness against platform rotations around a vertical axis.

Any closed building between the telescope and the ground would disturb this favourable situation for two reasons: (*i*) the necessary breeze to mix the air would move the warm air from the ground upward against the wall of the building towards the telescope; (*ii*) the wall of the building itself would have a temperature deviating from that of the air coming with the breeze to the telescope. Already deviations of 0.1° C in the air in bubbles of 10 to 20 cm will disturb the image. It is practically impossible to keep building walls within 0.1° C of the air temperature.

A solution would be an open tower, highly transparent to the wind, but of a sufficient stiffness to avoid shaking harmfully to the image. An early conceptual scheme is shown in fig. 1a. Our estimate was that this concept would work in a wind-velocity range of 5 to 10 m/s (i.e. 18 to 36 km/h, 11 to 22 miles/h).

Starting from this conceptual scheme, the Open Tower Telescope (OTT) has been developed with financial support of the Technology Foundation STW in the Netherlands. The design scheme is shown in fig. 1b. The tower has a height of 15 m, the minimum required for reaching the air with sufficient temperature homogeneity, expected from the measurements of the temperature fluctuations, as explained earlier. The special geometry of the tower holds the platform parallel to the ground, as explained in the caption of fig. 1b. In this way, a very lightweight tower construction is reached, which is still extremely stiff against all rotations of the platform[1 (section 2)]. Furthermore, the design details of the joints are important to keep the principal extreme stiffness of the geometries[2 (section 3), 3 (section 6)].

Fig. 2. Dutch Open Telescope (DOT) on La Palma. *Left:* tent dome open for solar observations. *Right:* tent dome closed during wintertime with ice in ladder/elevator framework. Practically no ice sticks on the tent cloth due to its smooth coating. The viewing direction in this photograph corresponds with the scheme of fig. 1b.

The OTT has been designed as a steel construction with all joints bolted, such that it could be erected without any welding onsite. It has been installed at the Observatorio del Roque de los Muchachos (ORM) of the Instituto de Astrofisica de Canarias (IAC)[22] on the Canary island La Palma, see fig. 2. From his large site-testing experience Kees Zwaan had decided that ORM would be the best seeing location. At the first-light ceremony in presence of the Dutch Crown Prince Willem Alexander and the president of the Canary Islands Manuel Antonio Hermosa Rojas, the OTT has been renamed to Dutch Open Telescope (DOT)[19], see fig. 3a. The DOT became the pioneering demonstrator of the open-telescope technology under scientific guidance of Rob Rutten[4,5]. It became an outstanding supplier of solar-atmosphere movies sampling the photosphere and chromosphere simultaneously at up to 0.2 arcsec resolution in the short-wavelength part of the visible spectrum. Fig. 3b shows the open telescope on top of the tower platform with two key persons, who contributed to its successful operation: Felix Bettonvil for the technical scientific management and Pit Sütterlin in control of all observing and speckle processing.

Fig. 3. *a (left)*: DOT first-light ceremony with the Dutch Crown Prince Willem Alexander and the president of the Canary Islands Manuel Antonio Hermosa Rojas. *b (right)*: The open telescope seen from its backside on top of the platform with its super-stiff drives and mount. Next to the mount stand Felix Bettonvil (at left), responsible for the technical scientific management, and Pit Sütterlin (at right), responsible for observing and speckle processing.

During the very successful operations of the DOT it became clear that the first estimate of 5 to 10 m/s for the wind-velocity range for good seeing conditions and sharp images was much too modest. Excellent observations are obtained for wind velocities between 2 and 20 m/s (i.e. 7 to 72 km/h, 4 to 45 miles/h). Moreover, it became clear that the wind direction also is of eminent importance in combination with the shape of the local landscape. For the DOT-site the best direction range is between northeast and west, where the wind comes directly from the ocean over a continual rising slope. At the east and south sides the slopes are steep and heated by the sun from the early morning onward. Wind coming over these slopes is thermally disturbed and deteriorates the images. In addition, south and east give more chance for wind from the African continent.

Another factor required for high-quality images is a large-scale homogeneity of the air coming to the site. For instance, the clouds have to be sufficiently lower – at least a few hundred meters – than the telescope site, which in case of the DOT is at an altitude of 2350 m. Above these clouds the seeing conditions can be extremely good. Naturally, also the high air layers above the telescope have to be homogeneous in temperature. The so-called jet streams with high wind velocities have a negative influence due to shear effects between layers of different temperature. Fortunately, the Canary Islands are in a region with relatively few jet streams.

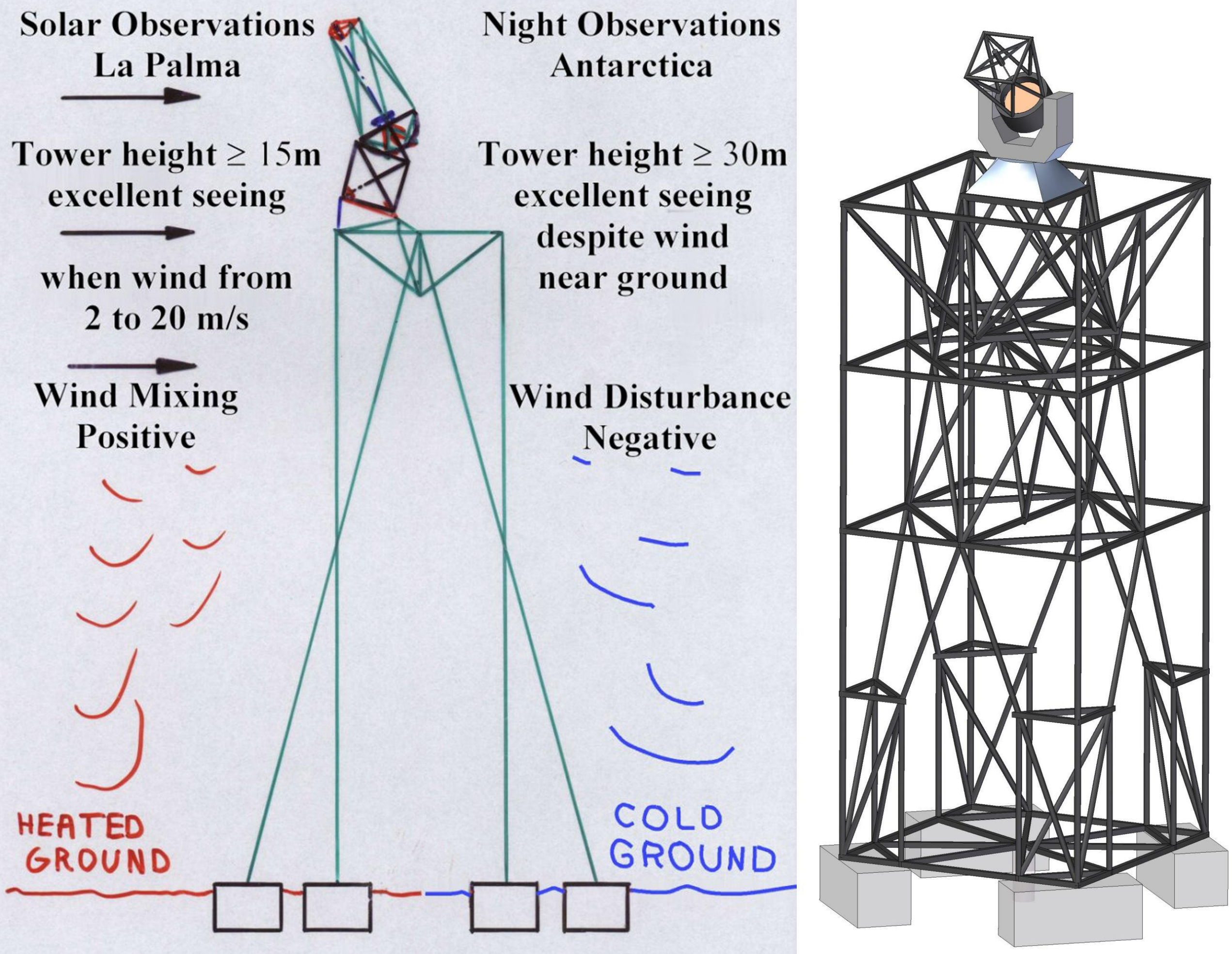

Fig. 4. *a (left)*: With respect to the ground influence, the presence of wind has a positive effect on the seeing for solar observations –the wind is our friend– see text at the left of the tower scheme. For nighttime observations, on the other hand, wind has a negative effect on the seeing –the wind is our enemy– see text on the right-hand side of the tower scheme. However, putting the telescope on an open wind-transparent tower improves strongly the seeing in both cases.
b (right): Open-tower design with 4 levels and a geometry, which holds the platform parallel to the ground. The in-between levels reduce the free length of the connecting tubes. This tower with a height of 30 m and a base of 12×12 m has been developed for nighttime applications on Antarctica. A similar tower design can be used for solar observations. A height of about 15 m per level is possible with single-tube members between the corner points. Hence, this 4-level concept is suitable for heights up to 60 m.

The stiffness and effectiveness of the parallel platform motion have been proven by the sharp images obtained during wind speeds up till 20 m/s. At higher wind speeds the weather always changed to a cloudy sky and precipitation. A certain deformation is always required to build up a counterforce against the wind force. In this respect the tower is as stiff as possible by its geometry of merely triangles and a careful design of the joints. The translations of the 15-m high platform relative to the ground are a few tenths of a mm for hard wind: cf. a calculated translation of 0.4 mm for a wind speed of 20 m/s. However, the tilt of the platform is only some μm corresponding to a few tenths arcsec because of the parallel motion and, likewise, the rotation around the vertical axis is small. Interferometric measurements between the foot points of the telescope mount on the platform during 10 m/s wind showed a tilt of 1.4 μm corresponding to 0.102 arcsec. Numerical simulations made at Harvey Mudd College confirmed these results[3 (section 6)].

It is important to realize that during nighttime the seeing is fundamentally different from that at daytime. A few hours after sunset the ground is sufficiently cooled by infrared radiation (10-μm wavelength region) to the open sky that warm air plumes no longer are rising up. To the contrary, the ground becomes colder than the air above it. As a consequence, good seeing conditions can develop without any wind, which is impossible during sunshine at daytime, as discussed before. The gradual increase of temperature from the ground upward permits a stable air mass around a closed building and an open tower is not required in this case.

However, wind during the night causes the cold air from the ground to move upward into the telescope beam. And the colder air is equally harmful to the seeing, because decisive are the temperature differences. In this situation, an open tower likewise can be helpful. Measurements at Antarctica showed that a height of 30 m is required to bring a telescope above the thermally disturbed layer due to the combination of a much lower ground temperature (up to a difference of some tens of degrees) and the presence of wind[3 (section 2)]. Fig. 4a illustrates the Antarctic situation (see text to the right of the tower sketch) in contrast to the daytime situation on La Palma (see text to the left of the tower sketch).

An open 30-m high tower is required to make profit of the super nighttime seeing on Antarctica. Fig. 4b shows the tower design developed for Antarctic observations[6]. Essential in this design is the introduction of in-between levels without disturbing the parallel motion of the platform. Numerical simulations performed at Harvey Mudd College confirm the proper working of this concept[3 (section 6)]. The in-between levels reduce the free length of the connecting members between corner points. For single-tube connections a practical maximum level height is 15 m. Consequently, this 4-level design is suitable for heights up till 60 m.

This tower concept, developed in more detail for Antarctic applications, is also very suitable for future large solar telescopes. The tower has been adapted for deployment on an unstable underground, like the Antarctic ice. This goal is reached by designing a framework structure, which is stiff and stable for all basepoints in all directions. Consequently, a small relative motion of the underground under the basepoints will not harm the tower structure, only a small displacement of the tower as a whole can occur. Moreover, the open, but still extremely stiff, steel construction is very lightweight compared to a concrete building. This reduces enormously the specific load on the ice. The design is as well very suited for deployment on loose lava stone, as is the case at the observatory sites on the Canary Islands. It simplifies the construction and reduces largely the costs for the foundation.

3. SEEING INSIDE AND CLOSE TO THE TELESCOPE STRUCTURE

During solar observations, also the telescope, its mount and dome are being heated by the solar light. Evacuated telescopes solve the problem for the optical beam inside the telescope. The R.B.Dunn Solar telescope in New Mexico with a 76-cm aperture was the first telescope of this type[7,8] and still operates successfully. The largest and sharpest vacuum telescope is the Swedish Solar Telescope (SST) on the Canary island La Palma with a 97-cm aperture[9,10]. Special design characteristic of the SST is an entrance vacuum window in lens shape and consequently a relatively simple optical setup with a limited number of optical surfaces. As each surface adds its fabrication deviation, a limited number of surfaces favours reaching high optical quality of the system as a whole, required for high-resolution observations. Other particular characteristics are a relatively slender tower and on top the so-called turret, which consists of the entrance window and two folding mirrors under 45°. This system directs the light downward. This turret is made as compact as possible around the optical beam and possesses large bearings with incorporated gears resulting in a very high stiffness and precision. Consequently, the compact turret minimizes the disturbance of the surrounding air and is at the same time very stable against wind shaking, see fig. 5.

The practical limit for vacuum telescopes is probably a little over a 1-m diameter, only slightly larger than the SST. The reason is the support problem, the same as earlier encountered for stellar lens telescopes. For the latter the practical aperture limit of about 1 m was reached a long time ago and, consequently, a move to mirror telescopes followed. An alternative for vacuum is a telescope filled with helium instead of air. The harmful effects of heat inside the telescope are greatly reduced, although not as much as in the case of vacuum. It avoids the large forces on vacuum windows, but still the support problem remains. For future very large solar telescopes, a solution is a mirror telescope, however not in a dome with a slit, but with the primary beam as open as possible, fully exposed to the natural airflow.

Fig. 5. The Swedish Solar Telescope (SST) at the Observatorio del Roque de los Muchachos (ORM) at an altitude of 2360 m. The area is free to the ocean between west (left) and northeast. Wind speeds of just a few m/s (e.g. 2 m/s) up till 20 m/s from over the ocean or from over a layer of clouds above the ocean permit excellent seeing conditions. The relatively slender tower of 17 m height (right) has on top the so-called turret, which consists of an entrance lens of 108 cm – clear aperture 97 cm – and two folding mirrors under 45° of 1.4 m diameter. This system directs the light downward through a steel tube in the tower to an optical lab in the basement of the building. The light path from the entrance lens to the optical lab is evacuated to eliminate image disturbance from air-temperature fluctuations inside the telescope. The entrance window is visible as a black ellipse on top. The turret is made as compact as possible around the optical beam. At the left side of the picture one can see the Dutch Open Telescope (DOT), likewise a high-resolution solar telescope, but with a contrasting principle: the primary light beam 'inside' the telescope is as open as possible for air flushing by natural wind. Both principles prove to be very successful on La Palma.

Mechanical and thermal ingredients for the successful construction of the DOT are: (*i*) primary beam completely open to natural wind flushing, (*ii*) effective water-cooling and air-suction near the diaphragm in prime focus, (*iii*) thermal equilibrium of the telescope structure parts with the surrounding air using passive methods, (*iv*) minimum heat production by telescope parts like drive motors, power supplies for cameras and other electronics, (*v*) stiff design of the telescope structure and drives to prevent wind shaking, (*vi*) no large objects at the telescope level during observations, reached with the completely open foldable tent construction based on strongly tensioned cloth. Additional ingredients are the use of relatively simple optics and large-volume image restoration.

We will discuss here in detail only the first ingredient concerning the completely open primary beam. Fig. 6 shows the DOT observing on the tower platform. The front side of the primary mirror is above the declination axis, which on its turn does not go through the right-ascension axis, but is situated higher upward at the rim of the right-ascension gear wheel. Consequently, the complete primary light path is freely accessible to the wind flushing.

The effect of warm air bubbles depends on the temperature difference and on the length of the light path through the deviating temperature. In the previous section it was already mentioned that deviations of 0.1° C in air bubbles of 10 to 20 cm will disturb the image, hence the light path through 0.1° C deviating air temperature has a length of 10 to 20 cm. However, wind flushing will keep the thickness of the air layer with deviating temperature very small. Consequently, temperature deviations of 1 or 2° C of the mirror surface or other parts nearby the primary beam are permitted as long as the air can move away completely freely without eddies and wind shadow areas, caused by nearby obstructions or walls. In this case even a very low wind velocity is enough for flushing. Experience with the DOT showed that velocities of 1.5 m/s and higher can produce sharp images. Further investigations of these effects are of importance to future large solar telescopes. Noticeable is that the huge mount of the DOT, designed for a much larger mirror than the present 45 cm, gives excellent results, which indicates that the wind flushing principle will work as well for much larger mirrors.

Fig. 6. Close-up of the DOT on the tower platform. The primary mirror and the optical beam to the primary focus are fully open to wind. The DOT was the first telescope showing that such an open-air path can permit diffraction-limited resolution. Note that the primary mirror is located well above the declination axis of the equatorial mount. It sticks out high above the platform into full wind flushing.

Another typical daytime effect is that under wind conditions the air temperature continually changes on a time scale of minutes. It is much more variable than during nighttime, an additional reason to make it practically impossible to keep all parts near and in the primary beam within 0.1° C of the surrounding air and to recognize the solution given by air flushing. The heated ground discussed in the previous section and the air temperature variations discussed here are the two main sources that cause the difference between day- and nighttime seeing, the latter with a cool ground and a stable temperature. Nevertheless, also for nighttime observations open designs may be attractive, as mentioned in section 2.

From the viewpoint of wind flushing, the sharpest vacuum telescope, the SST[9], is also an open telescope with respect to the direct neighbourhood of the telescope, see fig. 5. The turret has been made as compact as possible around the optical beam and has been designed very stiff[10]. Around the telescope is no dome. The 17-m high tower is slender and has a cross-section of only 5×5 m. Consequently, there are no large surfaces which can heat the air and the tower's upward air stream is limited.

Fig. 7. Kees Zwaan doing site testing with a commercial 20-cm Maksutow telescope protected against wind shaking by a semitransparent windshield on top of a sand dune on a lagoon island at the south coast of Portugal.

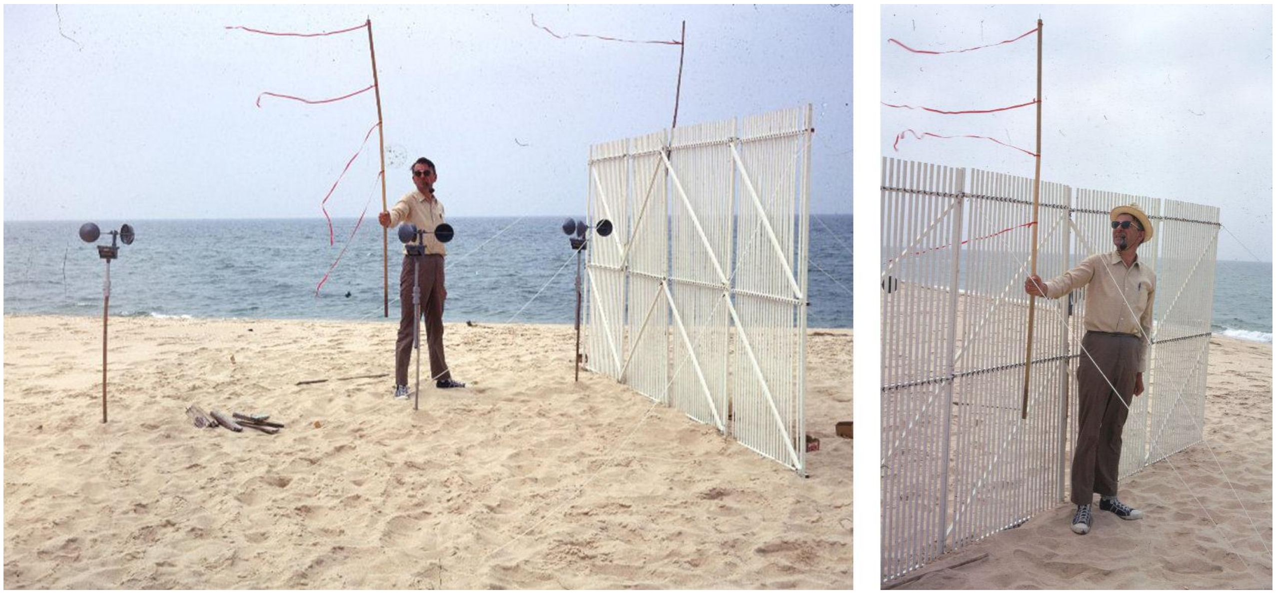

Fig. 8. Tests with semitransparent shields on the beach of the same lagoon island (see fig. 7). *At right*: Kees Zwaan in front of the shield, at the side from where the wind is coming. *At left*: Kees behind the shield. The stick with 4 ribbons shows the effect of the shield.

Consequences of the open telescope principle are high requirements on the stiffness of mount and drives against wind shaking. Most standard telescopes do not possess sufficient stiffness. However, it is possible to increase the stiffness enormously without an increase of the weight [11,2].

The standard small telescopes used for site testing in the JOSO campaigns also were not stable enough for operation in wind. We developed special semitransparent screens to protect these telescopes. Essential for these screens are the vertical boards, which provide a reduced stratified air stream without large-scale eddies behind the screen[12,13]. Fig. 7 shows Kees Zwaan behind such a site-testing telescope, while in fig. 8 we are doing tests with these screens. It was found that 50% transparency gives a very effective windshield for nearly no wind conditions at a distance behind the shield of 40 times the board width (= 20 periods). With respect to seeing, the use of such a shield is the best compromise if the telescope is not stable enough for a completely open operation. Certainly, it is better than domes, which are half open towards the downward side of the wind. The shields are successfully applied at the McMath telescope at Kitt Peak[14], at Antarctica and at the horizontal Solar Telescope at Sayan Observatory near Irkutsk (Siberia). As an important additional result of these tests, it was found that the transparency has to be 80% or more in order not to disturb significantly the airflow by the wind.

The completely open-foldable dome based on strongly tensioned cloth is an essential part of the open design. A comprehensive measuring program has been set up to investigate the deformations under wind load of the GREGOR and DOT domes[15,16]. These measurements will provide the necessary information for the development of large-size domes[17].

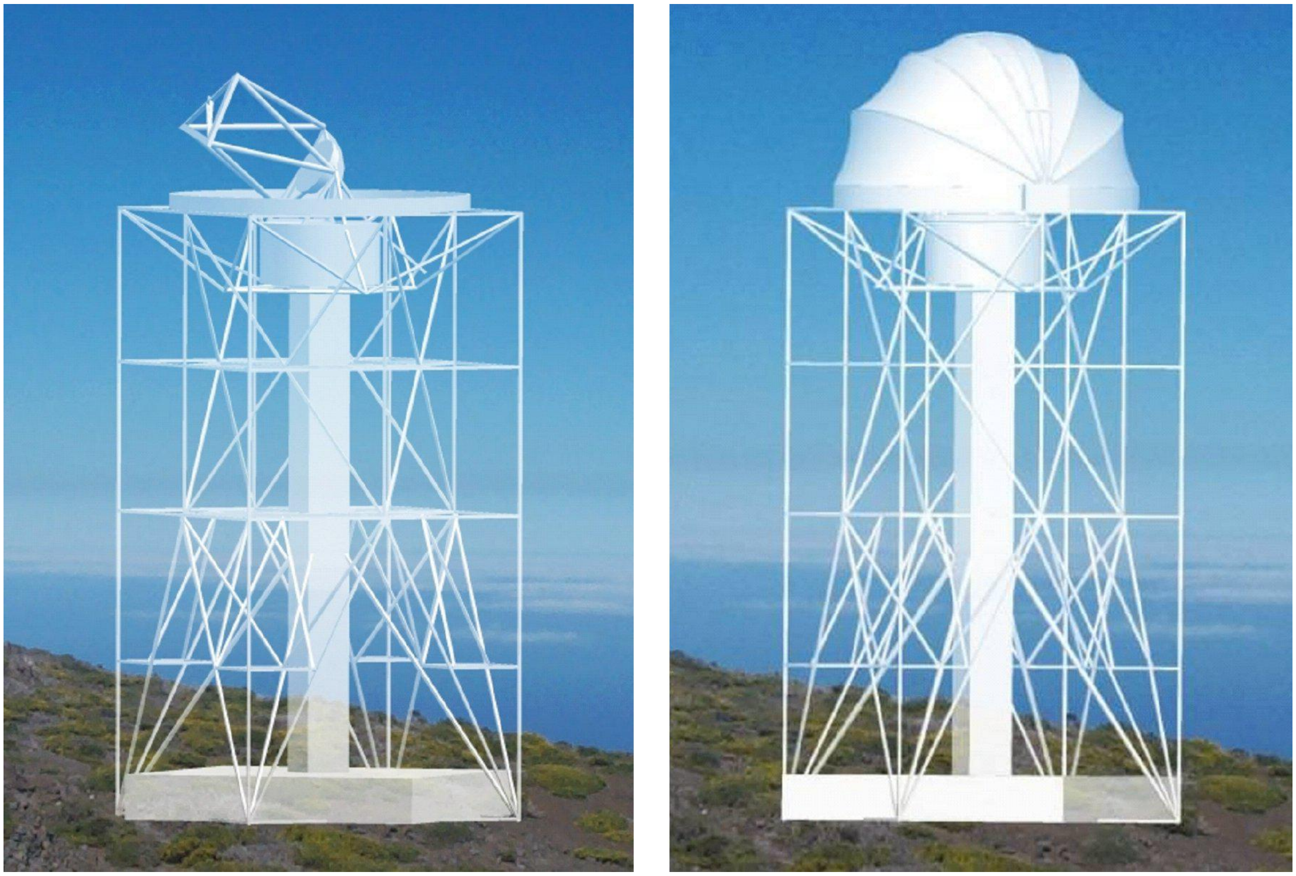

Fig. 9. Concept for a large high-resolution solar telescope. *Left*: in operation completely open; *right*: with closed canopy.

4. CONCLUSIONS CONCERNING FUTURE HIGH-RESOLUTION SOLAR TELESCOPES

Development directions for application of the mechanical, thermal and optical ingredients for large 3- to 5-m mirrors are the following:

- Open constructions with principal stiff overall geometries and in addition carefully designed joints to maintain geometry stiffness. An extremely stiff, still relatively lightweight, wind-stable construction can be realized. The DOT possesses a mount, which is in fact suitable for a 2.5-m diameter mirror, see fig. 4 in ref[18]. The 45-cm mirror was originally a first experiment in this mount. The outstanding results demonstrate that the large mount does not disturb the images when there is natural wind flushing. A large mirror would have less light absorption and consequently less heating than the large mount now without a mirror in front. Installation of a larger mirror on the DOT, together with the observation experience using it, would be an excellent test and preparation for the construction of a large solar telescope. No changes to dome and tower would be required for mirror sizes up to about a 1.5-m diameter. A design with a 1.4-m mirror has already been worked out and could be brought into operation pretty fast if funding would become available[18].

- Larger enclosures based on the completely open-foldable tent construction. Simultaneous wind- and deformation measurements on the DOT and GREGOR enclosures will provide the knowledge for computer calculations and development of large-sized enclosures. Additional seeing measurements will provide more insight into the effects of an open, half-open or only partly-open dome on the wind turbulence and seeing.

Fig. 9 shows a design for a large high-resolution solar telescope with the ingredients summed up above. The canopy leaves the telescope completely open during observations. Under telescope and canopy is an open tower. Directly under the telescope is an optics room. From there a closed shaft goes downward to a large optical lab at the ground. In the shaft is an evacuated tube for the transport of the image and space for cables, staircase and elevator. A light beam of a diameter of a few tens of cm allows image transport to the ground over many tens of meters without loss of resolution and field[18]. The optical room and relatively slender shaft will not disturb significantly the open principle, as experienced with the SST. The large optical lab at the ground permits a multitude of observational instruments.

ACKNOWLEDGMENTS

Further developments are supported by grants from the European Union for a design study for a European Solar Telescope (EST) and by the Dutch Technology Foundation STW for the open-foldable tent construction. Technical support comes from the DOT[19] and GREGOR[20] groups. The GREGOR is operated by the German consortium of the Kiepenheuer Institut für Sonnenphysik, the Astrophysikalisches Institut Potsdam, the Institut für Astrophysik Göttingen and other national and international partners at the Observatorio del Teide (OT) on Tenerife. The DOT is operated by Utrecht University at the Observatorio del Roque de los Muchachos (ORM) on La Palma. Both observatories are operated by the Instituto de Astrofísica de Canarias (IAC)[22] in Spain. The DOT has been built by instrumentation groups of Utrecht University, the Central Workshop of Delft University (now DEMO-TU-Delft) and several firms with specialized tasks with funding from STW. The DOT team enjoys hospitality at the solar telescope building (SST)[21] at ORM of the Royal Swedish Academy of Sciences.

REFERENCES

[1] Hammerschlag, R.H., Jägers, A.P.L. and Bettonvil, F.C.M., "Large Open Telescope: size-upscaling from DOT to LOT", in *Innovative Telescopes and Instrumentation for Solar Astrophysics*, Proc. SPIE 4853, 294-305 (2003).
[2] Hammerschlag, R.H., Bettonvil, F.C.M. and Jägers, A.P.L., "Towers for telescopes with extreme stability, active or passive?", in *Optomechanical Technologies for Astronomy*, Proc. SPIE 6273, 50-63 (2006).
[3] Lanford, E., Swain, M., Meyers, C., Muramatsu, T., Nielsen, G., Olson, V., Ronsse, S., Vinding Nyden, E., Hammerschlag, R. and Little, P., "Concept study and validation of Antarctic telescope tower", in *Advances in Stellar Interferometry*, Proc. SPIE 6268, 36-47 (2006).
[4] Rutten, R.J., Hammerschlag, R.H., Bettonvil, F.C.M., Sütterlin, P. and de Wijn, A.G., "DOT tomography of the solar atmosphere", Astronomy and Astrophysics 413, 1183-1189 (2004).

[5] Rutten, R.J., Bettonvil, F.C.M., Hammerschlag, R.H., Jägers, A.P.L., Leenaarts, J., Snik, F., Sütterlin, P., Tziotziou, K. and de Wijn, A.G., "The Dutch Open Telescope on La Palma", in *Multi-Wavelength Investigations of Solar Activity*, Proc. IAU Symp. 223, 597-604 (2004).

[6] Hammerschlag, R.H., Bettonvil, F.C.M., Jägers, A.P.L. and Nielsen, G., "Towers for Antarctic Telescopes", in *1st ARENA Conference on Astronomy at CONCORDIA*, EAS Publication Series 25, 265-272 (2007).

[7] Dunn, R.B., "An Evacuated Tower Telescope", Applied Optics 3, 1353-1357 (1964).

[8] Dunn, R.B., "Sacramento Peak's New Solar Telescope", Sky and Telescope 38, 368 (1969).

[9] Scharmer, G.B., Bjelksjö, K., Korhonen, T., Lindberg, B. and Petterson, B., "The 1-meter Swedish Solar Telescope", in *Innovative Telescopes and Instrumentation for Solar Astrophysics*, Proc. SPIE 4853, 341-350 (2003).

[10] Hammerschlag, R.H., Bettonvil, F.C.M., Jägers, A.P.L. and Scharmer, G.B., "Large bearings with incorporated gears, high stiffness and precision for the Swedish Solar Telescope (SST) on La Palma", in *Optomechanical Technologies for Astronomy*, Proc. SPIE 6273, (2006).

[11] Hammerschlag, R.H., "Construction Outlines of the Utrecht Open Solar Telescope", in *Solar Instrumentation: What's Next?*, ed. R.B. Dunn, 547-582 (1981)

[12] Hammerschlag, R.H. and Zwaan, C., "An Efficient Wind Shield for the Protection of Telescopes", Pub. Astron. Soc. Pacific 85, 468-469 (1973).

[13] Hammerschlag, R.H. and Zwaan, C., "Semitransparent Windshields", JOSO Annual Report, 61-66 (1973).

[14] Pierce, A.K., "A Windscreen around the Heliostat of the McMath Solar Telescope", Solar Physics 107, 397-398 (1987).

[15] Jägers, A.P.L., Sliepen, G., Bettonvil, F.C.M. and Hammerschlag, R.H., "Fast foldable tent domes", in *Astronomical Instrumentation*, Proc. SPIE 7018, *Advanced Optical and Mechanical Technologies in Telescopes and Instrumentation*, paper 7018-64 (2008).

[16] Sliepen, G., Jägers, A.P.L., Bettonvil, F.C.M. and Hammerschlag, R.H., "Contactless sub-millimeter displacement measurements", in *Astronomical Instrumentation*, Proc. SPIE 7018, *Advanced Optical and Mechanical Technologies in Telescopes and Instrumentation*, paper 7018-49 (2008).

[17] Bettonvil, F.C.M., Hammerschlag, R.H., Jägers, A.P.L. and Sliepen, G., "Large fully retractable telescope enclosures still closable in strong wind", in *Astronomical Instrumentation*, Proc. SPIE 7018, *Advanced Optical and Mechanical Technologies in Telescopes and Instrumentation*, paper 7018-60 (2008).

[18] Hammerschlag, R.H., Bettonvil, F.C.M., Jägers, A.P.L. and Rutten, R.J., "Aperture Increase Options for the Dutch Open Telescope", in *The Physics of Chromospheric Plasmas*, ASP Conf Series 368, 573-592 (2007).

[19] DOT website: http://dot.astro.uu.nl

[20] GREGOR website: http://www.kis.uni-freiburg.de/index.php?id=163&L=1

[21] SST website: http://www.solarphysics.kva.se

[22] IAC website: http://www.iac.es