Mechanical design of a completely open-foldable dome for EST

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ABSTRACT

In the context of the EST design study for a 4m-class solar telescope and a study for large open-foldable domes of the Dutch Technology Foundation STW, a design is made for the 20 to 30m diameter range. Detailed designs are made for three specific diameter sizes: 23, 28 and 33m. Smaller-size open-foldable domes based on tensioned cloth and in use at the Dutch Open Telescope (7m) and the GREGOR (9m) have proven to be all-weather stable and very effective for good seeing conditions for solar telescopes. The cloth has shown no degradation over the past 14 (DOT) resp. 6 (GREGOR) years of experience and no permanent elongation with the frequent de-tensioning and tensioning during opening and closing. The application of cloth permits a dome design leaving, when opened, the telescope completely free without any structure over the telescope and no massive structures besides or under it. Basis for the new design is the available pre-stretched stable cloth, which is nowadays produced in much stronger qualities than used for DOT and GREGOR. The larger curvature radius requires larger tension in the cloth, but combination with stronger cloth fits for the upscaling. Calculations show that the steel construction geometries of the GREGOR dome can be upscaled with a few adjustments. Bearings and drives remain within normal sizes. Cost calculations show that open-foldable domes of this size are remarkably lower in price than closed domes. In addition, an interesting option is presented for a semi-transparent windshield of which the position can be adapted to the wind direction. This shield gives an effective wind protection of the region around the primary mirror without disturbing the wind flows above the shield and without stagnant air or big eddies behind it. It is storm safe and the costs are only a fraction of the open-foldable dome costs.

Keywords: retractable domes, tent enclosures, tensioned membranes, wind load, spatial structures, astronomical telescopes, open telescope principle, wind flushing

1. INTRODUCTION

High spatial resolution is a primary goal for the European Solar Telescope (EST). The enclosure of a telescope has three functions:

1. Protection of the telescope against bad weather.
2. During the night: keeping the temperature of the telescope structure close to the air temperature at the next morning, when solar observations start again. If used for nighttime observations, the enclosure has to keep the telescope structure's temperature during the day close to the air temperature in the evening.
3. During observations: protection of the telescope against wind buffeting in strong wind in case the telescope structure would be not stable enough.

Furthermore, with an open enclosure during observations, preservation of good local seeing around the telescope is of primary importance for obtaining high-resolution observations.

Consequently, the enclosure design should fulfill all three functions and at the same time cause minimum temperature disturbance of the airflow around the telescope. In the next section we will first discuss the mechanisms by which surrounding air can cause image deterioration. Within this context we will emphasize the difference between day- and

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nighttime observations and discuss the prevention of image deterioration. In section 3 we will give an overview of existing fully-retractable telescope enclosures, necessary to realize the open principle needed to avoid severe image deterioration. In section 4 designs for larger-size open-foldable tent domes are presented and the advantages and disadvantages of the different dimensions of dome diameter (23, 28 and 33 m) are discussed. As a last point, we discuss the advantages of an additionally placed wind shield around the tent dome in section 5. Section 6 summarizes our findings.

2. PREVENTION OF IMAGE DETERIORATION BY SURROUNDING AIR

The spatial-resolution capabilities of ground-based telescopes improved drastically by modern image-reconstruction and wavefront-correction techniques like Speckle Reconstruction, Phase Diversity, Multi-Object Multi-Frame Blind Deconvolution (MOMFBD) and Adaptive Optics (AO). Multiple Conjugate Adaptive Optics (MCAO) still is attaining its full development. 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 feasible final image resolution.

2.1 Mechanisms of image deterioration by surrounding air

To find optimum designs for the enclosure, it is important to understand very well the mechanisms of image deterioration by surrounding air. The raw-image quality is limited by fast refractive-index fluctuations in the light path through the earth's atmosphere, which deform the optical wavefronts. These refractive-index fluctuations are caused by density fluctuations in the air, which in turn can be produced by fluctuations in temperature and pressure. The refractive-index change $\boldsymbol{n}$ is approximately proportional to the pressure $\boldsymbol{p}$ and inversely proportional to the absolute temperature $\boldsymbol{T}$:

$$\boldsymbol{n} = 1 + \boldsymbol{c_\lambda p/T} \qquad (1)$$

where $\boldsymbol{c_\lambda}$ is slightly dependent on the wavelength of the light: for instance, $\boldsymbol{c_\lambda} = 79 \times 10^{-6}$ for 656 nm (H_α) and 81×10^{-6} for 397 nm (Ca II H) if the pressure $\boldsymbol{p}$ is expressed in millibar and the temperature $\boldsymbol{T}$ in degrees Kelvin. Formulas and values can be found in standard handbooks and websites[1].

AO-systems have a limited number of actuators and, consequently, are less effective in correcting refractive-index fluctuations of cells with a relatively small diameter. Wavefront correction is more effective for wavefront deformations on a larger scale of cell diameter in the beam. Calculations made for smaller scale cells with refractive-index fluctuations give a first impression of how harmful temperature and pressure fluctuations can be. Typical temperature and pressure are 10 °C, equivalent to T = 283 °K, and 780 millibar during solar observations at the Canary observatories on Tenerife and La Palma, both at the same height of about 2300 m.

A wavefront deviation of 157 nm is found for a cell of a length of 20 cm and a deviation in temperature of 1 °C from the neighbouring air. This deviation is calculated for the wavelength of 397 nm of Ca II H. This short wavelength is most sensitive to image deterioration. The deviation of 157 nm equals to 0.40 wavelengths for this line and is far too much for diffraction limited imaging. In addition, the light path of the incoming primary beam through the dome opening and inside the dome towards the primary mirror is of the order of 10 m. If this path is filled with randomly moving cells, the number of cells will be 10m/(2×0.2m) = 25. The wavefront deviations add up approximately with the square root of cell numbers. Consequently, fluctuations of 1 °C would cause $25^{½} \times 0.40 = 2.00$ wavelengths deformation of the wavefront. A desirable value would be a deformation contribution by dome seeing of not more than 0.10 wavelengths. The deformation value is approximately proportional to the temperature fluctuations. The permitted temperature fluctuation for 20-cm cells thus becomes (0.10/2.00)×1 °C = 0.05 °C. For cell lengths of 5 cm a similar calculation results in a maximum allowed temperature fluctuation of 0.10 °C, or more generally, the allowed temperature fluctuation is inversely proportional to the square root of the cell size. As argued before, wavefront-deformation corrections by AO-systems are limited by the minimum distance between actuators and minimum required subaperture diameter to get subimages with enough structure in it for measuring its motions. Consequently, there is a lower limit in cell diameter which is still correctable, probably somewhere around 5 cm or somewhat higher.

Fast pressure fluctuations are caused by wind and by airstreams of ventilation systems. Airstreams with a velocity $\boldsymbol{v}$ and gas density ρ can result in pressure fluctuations:

$$\boldsymbol{p} = 0.01\ (\tfrac{1}{2}\ \rho\, \boldsymbol{v}^2) \qquad (2)$$

where the pressure $\boldsymbol{p}$ is expressed in millibar. One millibar corresponds to 100 N/m^2 and explains the factor 0.01 in the formula. The air velocity $\boldsymbol{v}$ is expressed in m/sec and the air density ρ in kg/m^3. A typical value for the air density at the Canary observatories is 0.960 kg/m^3. As an example, a calculation will be made for $\boldsymbol{v}$ = 10 m/sec, which represents a normal wind velocity value for good observational circumstances at the Canaries. In this case $\boldsymbol{p}$ = 0.48 millibar. For a single cell of 20-cm diameter and a wavelength of 397 nm, a wavefront deformation of 27.5 nm is found, corresponding to 0.069 wavelengths. For wind velocities of a few m/sec and higher, the size of the 20-cm diameter fluctuating cells is relatively very small. Consequently, it is very unlikely that natural wind will produce chains of successive air cells of only 20-cm diameter with a largely varying pressure, whereas small cells with temperature fluctuations are able to develop at surfaces with a deviating temperature from the surrounding air. As a result, temperature fluctuations are the primary source of seeing.

Nevertheless, indirectly the wind has a strong impact on the seeing, because the dispersion of temperature fluctuations from heated sources largely is determined by wind influence on the airflows. During daytime solar observations, the ground is heated by the sun. As a consequence, warm air bubbles rise upward, hundreds of meters in absence of any wind. Under such circumstances, none of the solar telescopes will be able to produce sharp images, no matter its construction. Fortunately, already a small breeze will mix the air and at an adequate height above the ground the air temperature becomes sufficiently homogeneous to make sharp solar images feasible. Experiences with the solar telescopes on the Canary Islands learn that wind velocities of 1.5 m/sec and higher can result in sharp images. Excellent observations are obtained with wind velocities between 2 and 20 m/sec (i.e. 7 to 72 km/h). Moreover, it became clear that even wind direction is of eminent importance in combination with the shape of the local landscape. As a result, the telescope has to be placed on a tower of sufficient height, typically 15 m or more.

2.2 Difference between day- and nighttime

It is important to realize that during daytime the seeing is fundamentally different from that at nighttime. A few hours after sunset, the ground is sufficiently cooled by infrared radiation (10 μm wavelength region) to the open sky, such that warm air plumes no longer are rising up. On the contrary, the ground becomes colder than the air above it. The gradual increase of temperature from the ground upward permits a stable air mass around a largely closed enclosure with only a slit to let the incoming primary beam through. As a consequence, good seeing conditions can develop without any wind, which is impossible at daytime during sunshine, as discussed before.

In such a stable nighttime good-seeing situation the enclosure surface can be up to some degrees colder than the air above it due to the infrared (10 μm region) radiation to the open sky. During daytime we could chill artificially the surface of an enclosure to some degrees under the temperature of the outside air using a cooling machine and a tube system in the skin of the enclosure. However, this will not solve the seeing problem during daytime because in this case the necessary wind will move the warmer air over the chilled skin and cold air plumes will arise. These cold air plumes in the incoming primary beam are equally harmful to the image quality as warm plumes.

A second complicating typical daytime effect is that under the required wind conditions the air temperature still continually changes on a time scale of minutes. Measurements show clearly that these temperature fluctuations are much larger during daytime than during nighttime[2]. The solar thermal motor on the earth atmosphere inevitably produces thermal fluctuations on these scales. These temperature fluctuations on itself are not fast enough and, consequently, on a too large spatial dimension to disturb the wavefronts. However, practically it is difficult to follow these temperature fluctuations with the enclosure temperature. The complex temperature regulation installations are costly and produce much additional heat, which has to be removed on a place far away from the telescope. It is not sure that these complex installations will work well enough that seeing will be as good as in case of a completely open design. Especially at the entrance opening there will be a mixing effect of air with different temperatures from outside and inside the dome, which does deform the optical wavefronts and hence, image deterioration will occur. The efficient solution is to keep the primary beam as open as possible to the incoming wind flow, providing homogeneous air temperature from the primary beam to the primary mirror and from there to the primary focus. The primary telescope beam is in that case so to say part of the undisturbed outside air mass. Experiments with windshields[3] gave indications what is open and what not anymore, see also section 5.

Decisive factors for the magnitude of the remaining air-temperature deviations are the magnitudes of the temperature differences of the incoming air to the object surfaces and the length of time the air is nearby these surfaces. The disturbing optical wavefront deformations are proportional to the integration of the temperature deviations over the thickness of the deviating layer. It follows that to minimize the wavefront deformations the objects in the air stream to the optical beam should be as small as possible. Especially, these objects should not cause stagnant air, because then the length of time the air remains nearby objects with deviating temperature increases drastically. The tubes and/or profile beams of an open framework construction of a telescope fulfil the requirement of very short contact with air of the passing wind and no stagnant air. In sunshine, these structure parts will easily show temperature deviations of the order of a degree, hence more than the permitted amount for the temperature fluctuations in the air itself. However, the time that the incoming air is in contact with these objects with deviating temperature is too short for obtaining harmful changes in temperature. The largest object where the air in the primary optical beam passes is the primary mirror. However, this mirror in the size of 4 meter is still small compared to the dome. The air in a wind breeze of 1.5 m/sec - as discussed minimal required to overcome ground effects - will pass this mirror within 3 seconds. An option for a region in the size of the primary mirror is air suction to enlarge the effect of wind flushing over the primary mirror. The sucked air has to be transported for dumping to a place sufficient far away from the telescope. This air will get additional heat produced by the sucker, which blows into the outlet. Hence, outlet enough far from the telescope is important. Similarly, air blowing for artificial wind near the telescope is not advisable, because normal air blowers produce air with much temperature fluctuations originating from the heat production in the motor, fan bearings and in addition with fast moving blowers by the air compression. Compared to the primary mirror, application of air suction for a whole dome would become a difficult and costly task.

Summarized, high-resolution solar observations need anyhow a natural wind flow to avoid image deterioration by warm air from the ground. The same wind flow can also be used to keep the air temperature homogeneous in the primary telescope beam. This wind flow should not encounter any disturbances of nearby large objects, which would cause large-scale eddies, often referred to as 'turbulence'. Furthermore, these large objects could cause wind-gust accelerations with undesired dynamical effects on the telescopes. To realize the open principle[4,5] of the primary telescope beam, a fully retractable dome around a free-standing telescope is needed.

3. FULLY RETRACTABLE DOMES

Two types of fully retractable domes can be distinguished.

3.1 Domes using solid segments, which are moved downward

Examples of this type are the Vacuum Tower Telescope (VTT) on Tenerife for solar observations and US Air Force Telescopes at Kirtland Air Force Base, New Mexico (3.5 m) and at Maui Space Surveillance Complex, Haleakala, on the Hawaii Island Maui (3.67 m Advanced Electro-Optical System AEOS) for nighttime observations. The design of the solid segments for these two examples is completely different. The VTT dome is half a cylinder with a horizontal axis at the bottom side. This half cylinder is split into 6 segments, which rotate downward around the horizontal axis. The AEOS dome is a cylinder with a vertical axis. On top, there is a large-scale slides construction. After opening the latter, the cylinder can move downward with the opened slides. For both constructions, a large closed part remains under the telescope platform of the required tower in case of a solar telescope.

3.2 Domes using cloth segments, which are folded together

A solution for a retractable dome is an enclosure of strong tent cloth, which folds completely together to a ring of small cross section when opened. It will leave the telescope entirely free in the open air. In addition, the heat capacity of such an enclosure is very low and adapts fast to changing air temperature.

In the eighties, the European Southern Observatory (ESO) developed an inflatable tent construction[6,7] based on double-clothed ribs, forming a kind of tubes, which were blown up by pressurized air. On the one hand, the tent got its strength by the blowing up, on the other hand, it could only open and close when ribs were depressurized. In the depressurized situation the tent cloth was held by relatively weak steel bows, which only permitted opening and closing when wind speeds were lower than 5 m/sec (i.e. 18 km/h). This low allowed value made the construction unsuitable for astronomical observation praxis. ESO built a prototype of this tent and installed it at the observatory in Chile, but it remained unused.

From the ESO experimental dome can be learned that closing the tent dome has to remain possible in strong wind without any danger for accidents, as clear sky and good seeing with sharp images occur in wind speeds up to 20 m/sec. When this weather type changes into bad weather with clouds and rain, the tent construction has to be closed. The largest forces occur halfway the closing and the construction should be able to withstand these forces. Unfortunately the latter requirement was disregarded in the ESO design.

In the nineties, the Dutch Open Telescope (DOT) was developed with financial support of the Technology Foundation STW in the Netherlands. The DOT became the pioneering demonstrator of the open-telescope technology for high-resolution solar observations. A tent development was started based on a different principle: no blow up, but use of tent-cloth parts cut in saddle shape and highly tensioned between movable strong steel bows. The cloth is curved in one direction in the half-sphere shape of the tent, whereas in the perpendicular direction, it is curved just in the opposite direction, hence negatively curved. Static roofs are known, based on this tensioning principle, and also belong to the manufacturing program of Poly Nederland, the Dutch company which made the cloth parts first for the ESO-tent and later for the DOT. The DOT enclosure is the first tent-cloth construction suitable for closing during strong wind, see Figure 1.

Figure 1. Dutch Open Telescope (DOT) with open-foldable enclosure of cloth segments. *Left:* enclosure open, leaving the telescope completely free in natural flushing of the wind. *Right:* enclosure closed with strongly tensioned cloth segments. Practically no snow or ice sticks on the tent cloth due to its smooth coating, whereas much snow and ice are visible in the ladder and elevator framework (see also Figure 3).

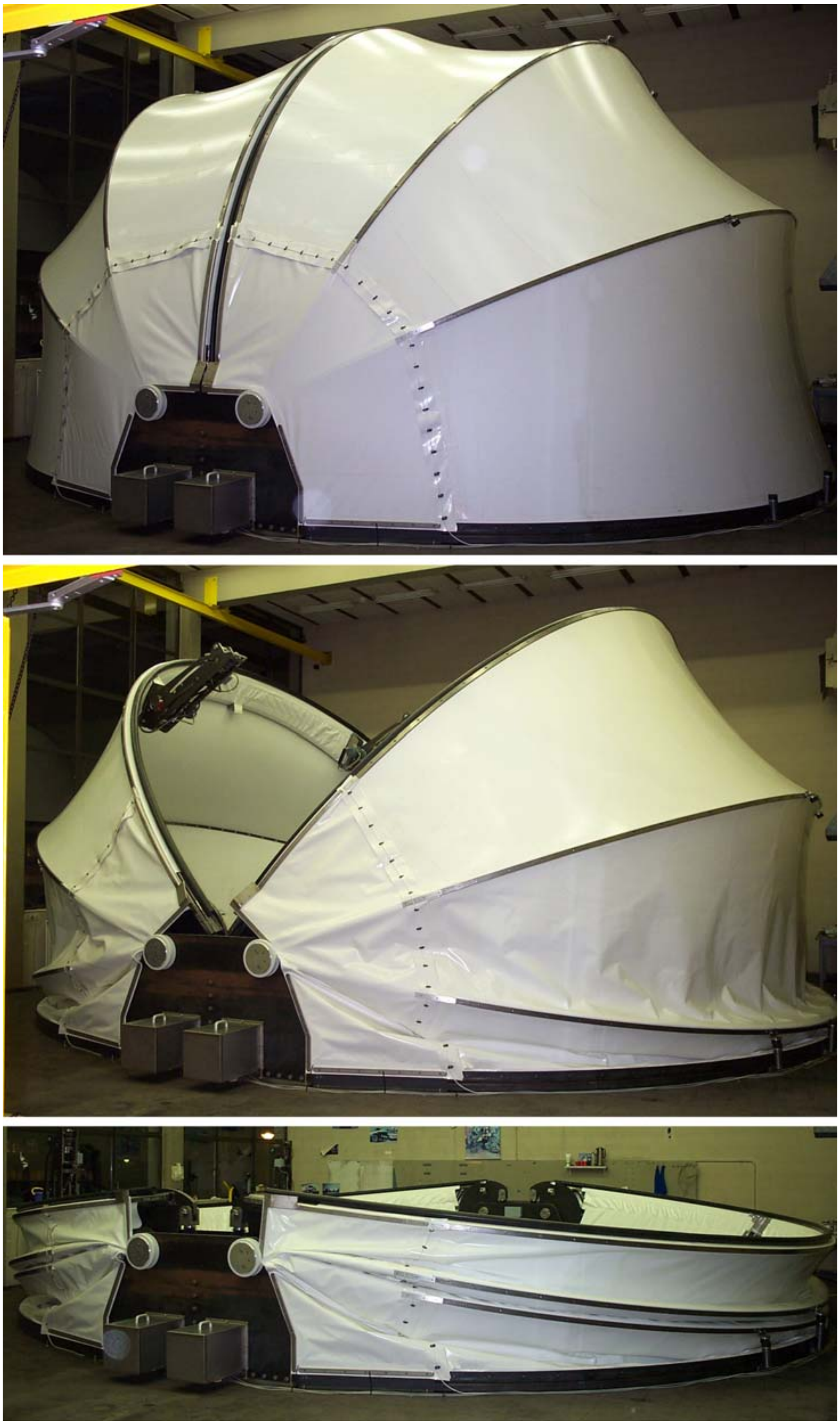

Figure 2. GREGOR-enclosure test assembly at the workshop of Delft University of Technology. *Top:* closed. *Center:* half open. *Bottom:* open.

The DOT tent with its 7-m diameter has a single cloth layer. The GREGOR enclosure with a 9-m diameter represents a further development with several improvements, see Figure 2. It has two cloth layers with 5 to 10 cm air space in between and, consequently, a better thermal isolation, clearly shown by measurements on both enclosures[2].

Opening and closing experiences in strong wind exist up till velocities of 90 km/h (25 m/sec) and never gave problems with both enclosures. To drive the main top bows a very compact system near the hinges with electrically driven actuators has been designed. The other bows between the different cloth parts are not driven, only hinges are placed at the bow ends. Still, the upper cloth segments are sufficiently tensioned during opening and closing due to the weight of these in-between bows. The construction avoids flapping of the cloth during opening and closing without need of a complex drive system for the in-between bows.

Both enclosures survived without any damage hurricane Delta of 28 November 2005. The 1-minute mean at maximum was 245 km/h (68 m/sec) at the GREGOR site[8]. Storms can be accompanied by heavy snow and huge ice deposition from undercooled clouds. However, snow and ice deposition on the cloth is not severe, in fact much less than on the other buildings. This is due to the outside cloth coating with a smooth PVDF layer. In combination with the half-spherical shape of the tent, this results in most snow and ice gliding down, see Figures 1 and 3.

Figure 3. *Left:* GREGOR after snowfall. On top of the 20-m high tower is the closed, completely open-foldable telescope enclosure of 9-m diameter. On the tent cloth no snow is present because it slides downward over the smooth coating of the cloth. *Right:* DOT at the same time as shown in the right part of Figure 1, but seen from another side. Snow and ice in ladder and elevator framework are clearly visible from this side. No snow or ice is present on the cloth of the enclosure on top. In addition, the coarse framework of the large tubes remained clean, as the photo shows.

Temperature measurements inside and outside the DOT- and GREGOR-enclosures indicated that the air surrounding the telescope takes over the outside air temperature within a few minutes after opening[2]. The high-resolution movies of the solar surface made by the DOT[9,10] demonstrate the excellent seeing, reached with the completely open-foldable tent dome.

4. DESIGN OF LARGE-SIZE OPEN-FOLDABLE TENT DOMES

The excellent results obtained with the DOT- and GREGOR-domes stimulated a design development of open-foldable domes of a much larger dimension in the diameter range of 20 to 30 meter. Important fact is the longterm reliable operation of the DOT enclosure since June 1996 (14 years) and the GREGOR enclosure since August 2004 (6 years) without any degradation of the cloth. It proves the reliability of the UV-light protection by the PVDF top layers on both sides of the cloth, which is considerably exposed to the UV radiation of the sun at a height of 2300 m. Storm stability requires high tension in the cloth in closed situation of the enclosure. This tension for the closed state was not reduced over the years by the frequent cloth release and tensing during opening and closing.

Designs were made for three dome diameters: 23, 28 and 33 m. The left-hand part of Figure 4 shows from top to bottom the 23-, 28- and 33-m dome designs around a tentative EST telescope design, which is expected to be mechanically large enough to house the different options for the optics.

The 23-m version in the left top panel can house the telescope in parked position when the telescope is eccentrically within the dome and parked horizontally or with an elevation of up to 12°, or somewhat more, depending on the telescope's exact design. The telescope is placed eccentrically to the west side, such that the telescope itself points to the east in its parked position, ready to find the sun in the morning.

The 28-m version in the left middle panel of Figure 4 is large enough that the telescope is able to turn around the azimuth axis over 360° within the closed dome, when its elevation is limited to 10° above the horizon, or somewhat more, depending on the telescope's exact design. Azimuth regions with a limited elevation are those where the telescope is pointing to the areas of the rotation shafts of the bows. A logical dome-orientation choice would be one with the rotation shafts to the north and south. In that case, the telescope can be parked with a higher elevation to the east or west. In the late afternoon, the dome could even be closed over the telescope in observing position. Afterwards, the telescope could be moved within the closed dome downward to 10° elevation and rotated around the azimuth from west to east, ready for observing the next morning. With the 23-m enclosure, this motion is possible with an opened dome, because then the enclosure bows are completely below the telescope floor, see also the right-hand top panel of Figure 4 and the right-hand bottom drawing of SECTION A-A in Figure 5. The right-hand middle panel of Figure 4 shows the situation with the opened 28-m enclosure of a summer observation in the late morning. Here, the primary mirror is high above the platform floor and free reachable by the natural airflow of the wind, because the elevation axis is located below the primary mirror.

The 33-m dome version in the left bottom panel of Figure 4 permits free motion of the telescope in all positions and directions within a closed dome. The right bottom panel of the same figure shows the telescope in a vertical position right-up in the closed dome. In this panel an optional windshield of 6 m height and covering 180° azimuthally is added. The shield can be oriented to any direction by rotation over a circle rail. These optional windshields for shake protection of the lower part of the telescope including the primary mirror will be discussed in more detail in section 5.

Figure 5 shows projection drawings using the dimensions of the 23-m tent dome: the left part with a closed enclosure, the right part with an open enclosure. The SECTION A-A of the open enclosure at the right bottom part of the figure clearly shows that the whole optical primary beam can be reached freely by natural wind airflow without regions of stagnant air. Hence, the air moving through the primary beam does not get time to change temperature on telescope surfaces with a deviating temperature. This is the basic requirement in order to avoid instrumental seeing, as explained in section 2.

Figure 6 shows projection drawings with the dimensions of the 28-m enclosure in the left part and those of the 33-m enclosure on the right side, both in a closed-enclosure situation. The open situation is similar to that of the 23-m enclosure in Figure 5 and is not shown here. In particular, Figure 6 offers a comparison of the dimensions of the 28- and 33-m version with that of the 23-m one in Figure 5. Note that, similar to Figure 4, here also the reduction scale of the drawings increases with the dome diameter.

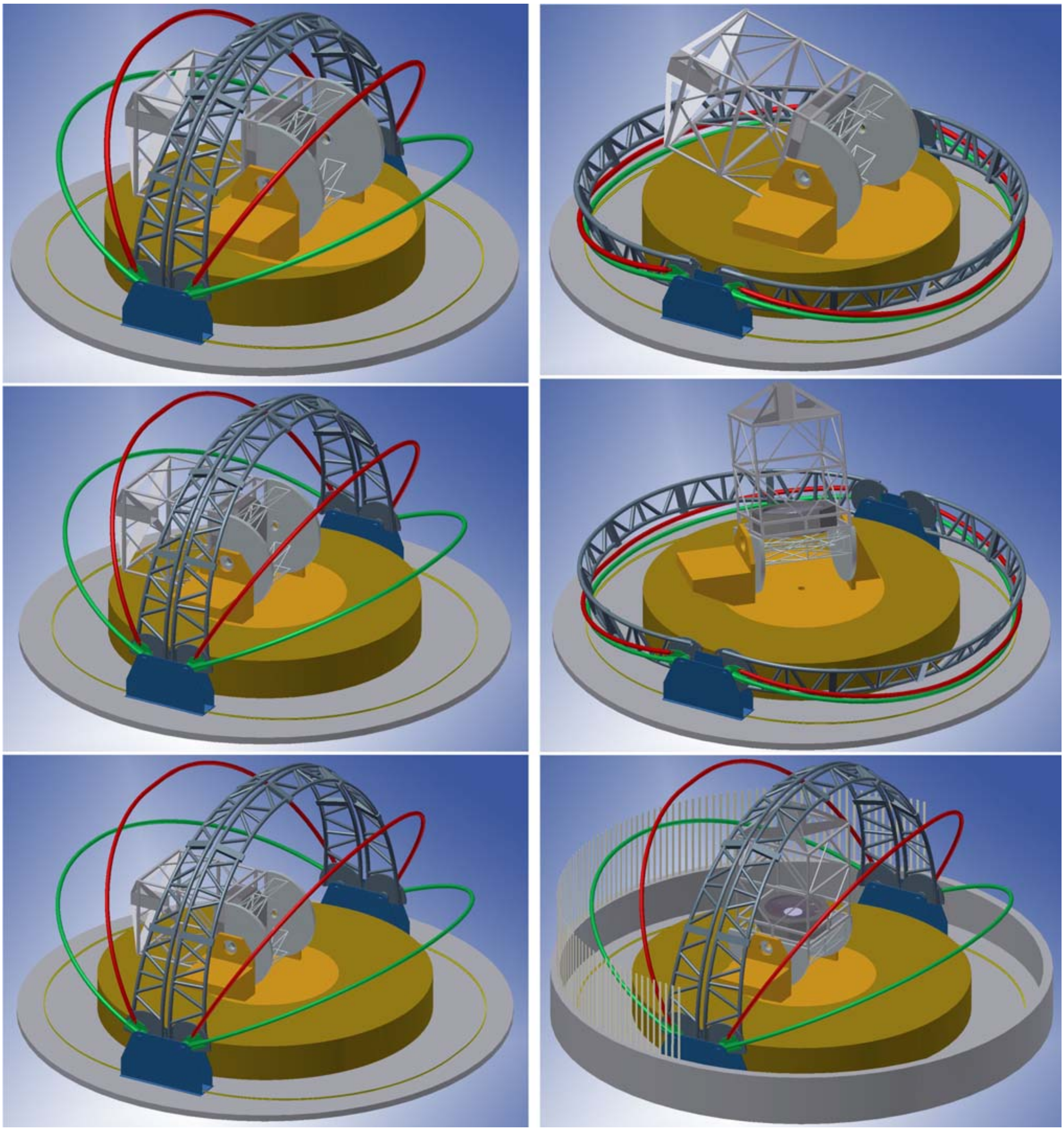

Figure 4. Three different designs of large-size open-foldable tent domes, from top to bottom: 23-, 28- and 33-m diameter. Note that the reduction scale of the drawings increases with dome diameter from top to bottom panels, actually the dome diameter in all drawings is equal, but the telescope size becomes smaller from top to bottom.

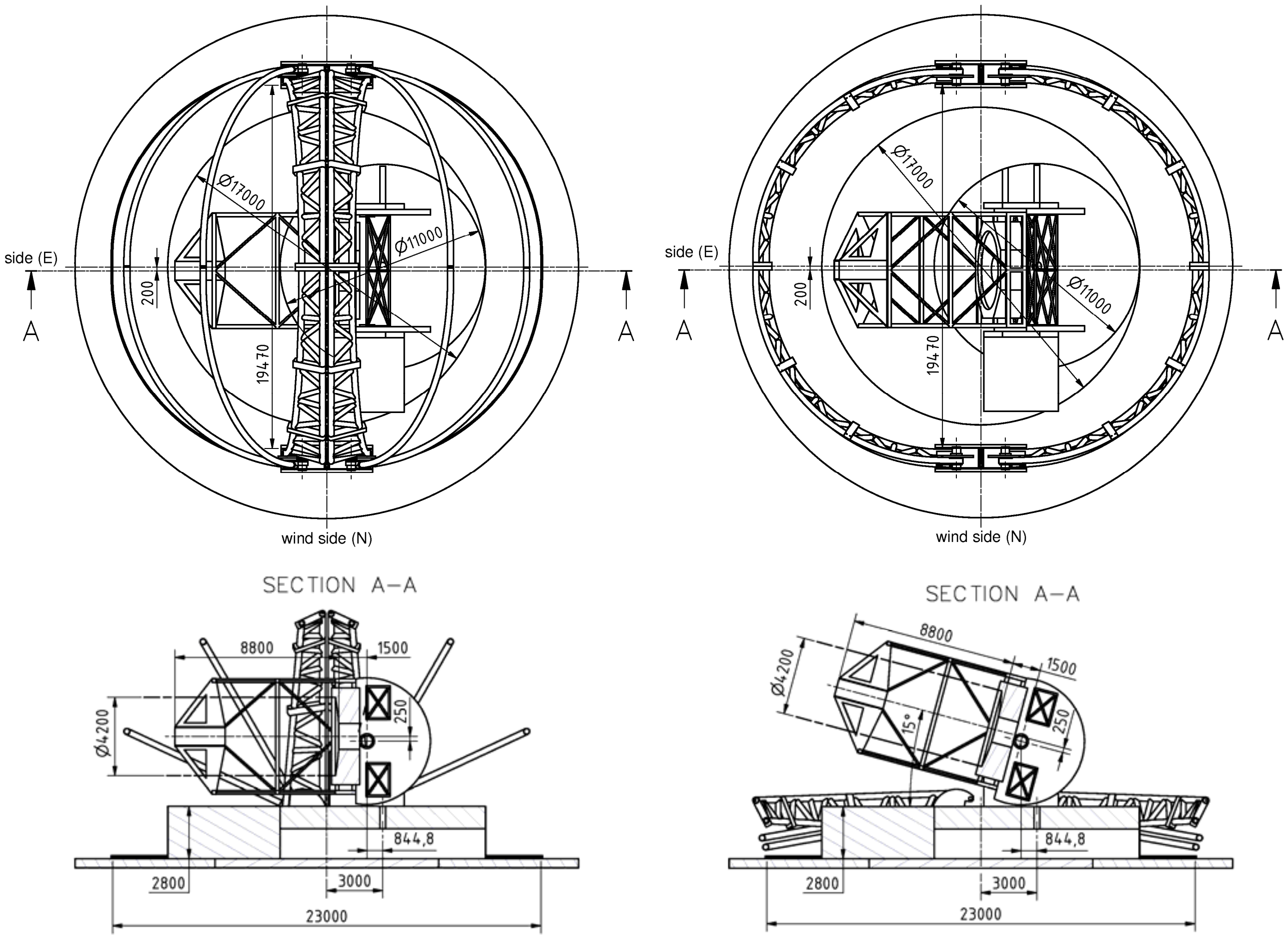

Figure 5. Projection drawings of the 23-m tent dome with a closed (*left*) and open (*right*) enclosure.

The scheme of the supporting steel structure for the cloth for the large domes is similar to that of the DOT- and GREGOR-domes. There are two main bows in a strong and stiff framework of steel tubes. These main bows run over the dome top in a closed situation. The sealing between these two main bows consists of a rubber tube on each of them. The rubber tubes are pressed together when the dome is closed. The main bows are driven by electrical actuators near the rotation shafts of the bows. Furthermore, there are two in-between bows at each side of the main bows. These bows consist of single steel tubes and are hanging between the high-tensioned cloth in the closed situation. Hence, on each side are three tensioned cloth parts, altogether 6 parts, each of which is spanned in a saddle shape. Each part is composed of strips, welded together to form the inward saddle shape when tensioned. Note that the in-between bows are not driven. When the enclosure opens by the downward movement of the main bows, the in-between bows will hang on the upper two cloth parts at each side. The weight of these in-between bows is sufficient to keep the upper cloth parts tensioned in wind speeds up to 30 m/sec (105 km/h) during opening and closing. As a result, only the lowest cloth parts near the dome floor are not tensioned. Experiences with the DOT- and GREGOR-enclosures show no flapping problems with these lowest cloth parts. Due to the saddle shape, these cloth parts always move inward and the cloth is heavy enough that no flapping arises. For the larger domes discussed here, a heavier cloth is planned. The framework main bows need more space inward than the single tube in-between bows. Figure 7 demonstrates for different enclosure sizes that the main bows pass with ample space over the parked telescope: 993 mm free space for the 23-m enclosure and 1980 mm for the 28-m one.

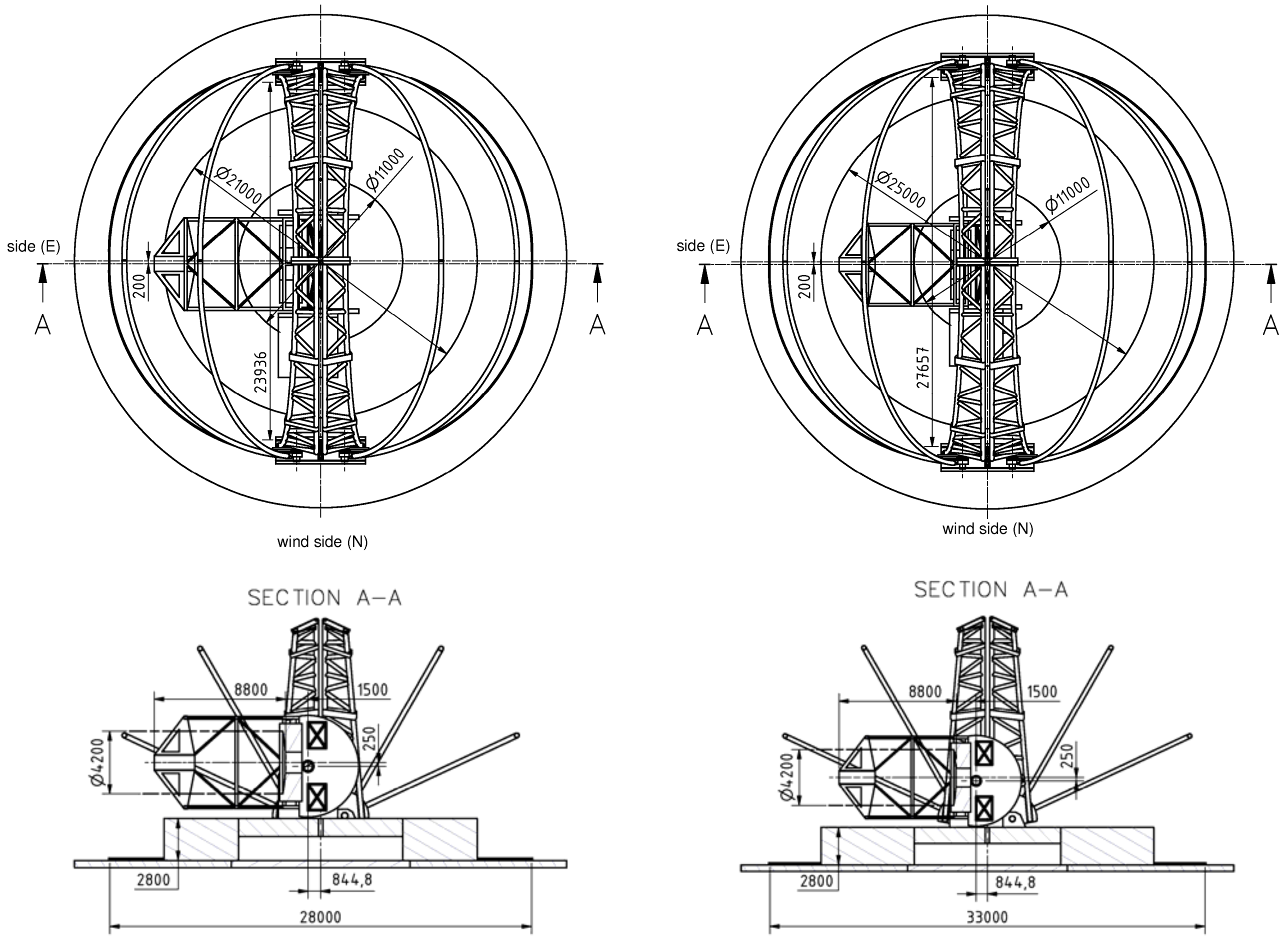

Figure 6. Projection drawings of the 28-m enclosure (*left*) and the 33-m enclosure (*right*) in a closed situation. Note that, similar to Figure 4, the reduction scale of the drawings increases with the dome diameter.

Furthermore, a large elevator is planned for transport of the primary mirror and other large parts inside the building. In the case of an open tower – like the DOT-tower – or a partly open tower, the plan is to make the elevator, staircase and optical path in closed shafts or in a combined shaft[11]. Figure 8 shows for the 28-m enclosure the way in which the elevator can be located at the west side of the telescope platform. The figure also shows more details of the platform, like staircases and fences. The center part of the platform, which moves with the azimuthal motion of the telescope, is higher than the outer part. In this way, the telescope – pointed horizontally – moves over the fences and also can move over the elevator. A mechanical hinge arm construction is being designed to move the primary mirror with its support cell downward and at the same time turning over to a horizontal position. In this way the primary mirror plus cell can be removed from the parked telescope to a carriage and to the elevator. However, for this handling some framework elements of the telescope construction will have to be removed, but the structure will retain enough strength without the removed elements. Of course, for the observations these elements have to be replaced to get maximum stiffness for the telescope structure. An alternative way to move the primary mirror from the telescope to the elevator platform is to use an outside crane while the enclosure is open. Such an outside crane would be fastened on the side of the tower. When not in use, the crane arm is folded downward under the telescope platform level. Hence, the parked crane will not disturb the seeing during observations.

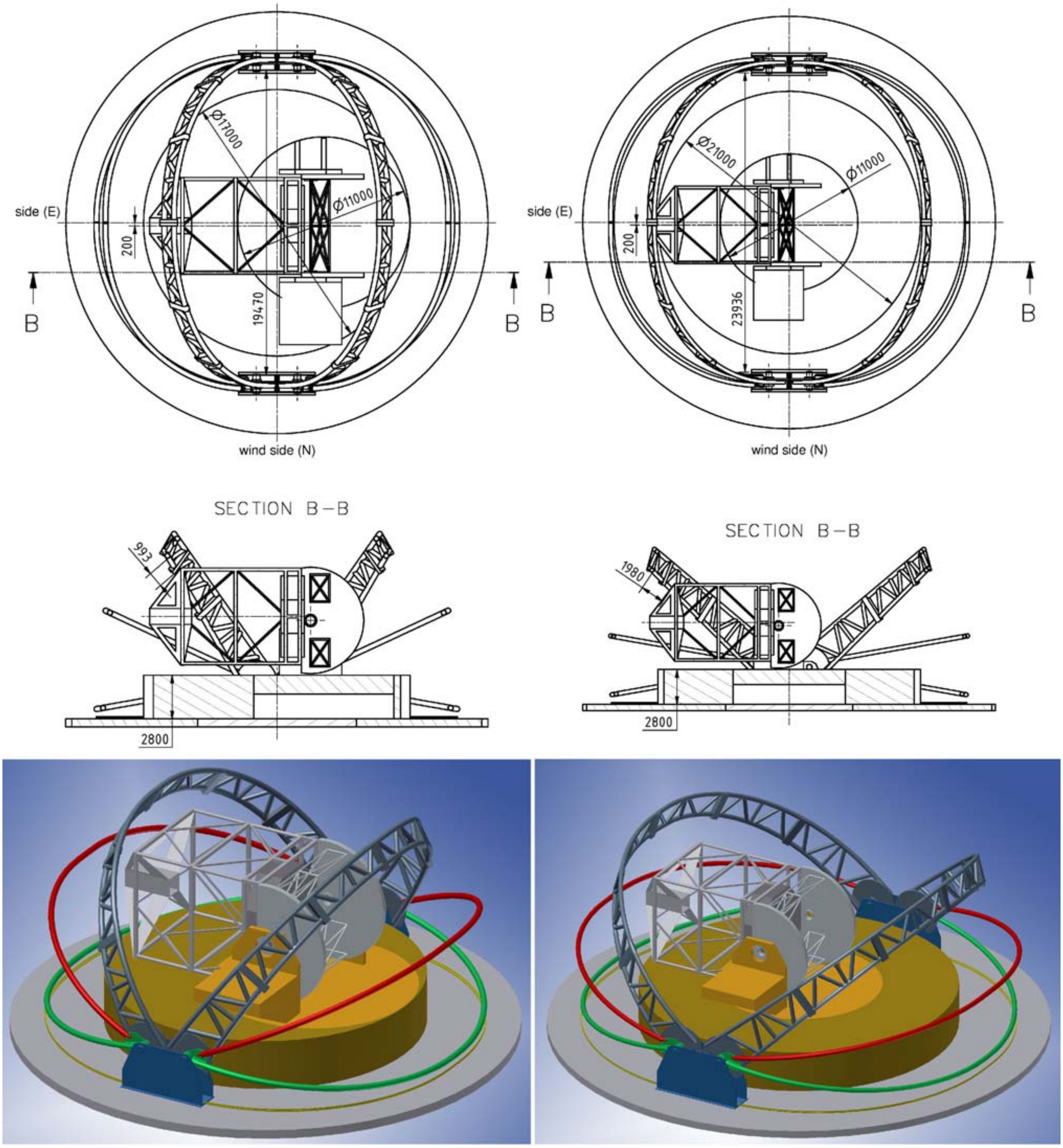

Figure 7. Enclosure bows over the parked telescope. *Left*: the 23-m enclosure with the eccentrically placed telescope. *Right*: the 28-m enclosure with the centered telescope. *Top*: top-view drawings. *Center*: SECTIONS B-B show exactly the free space between main bows and telescope.

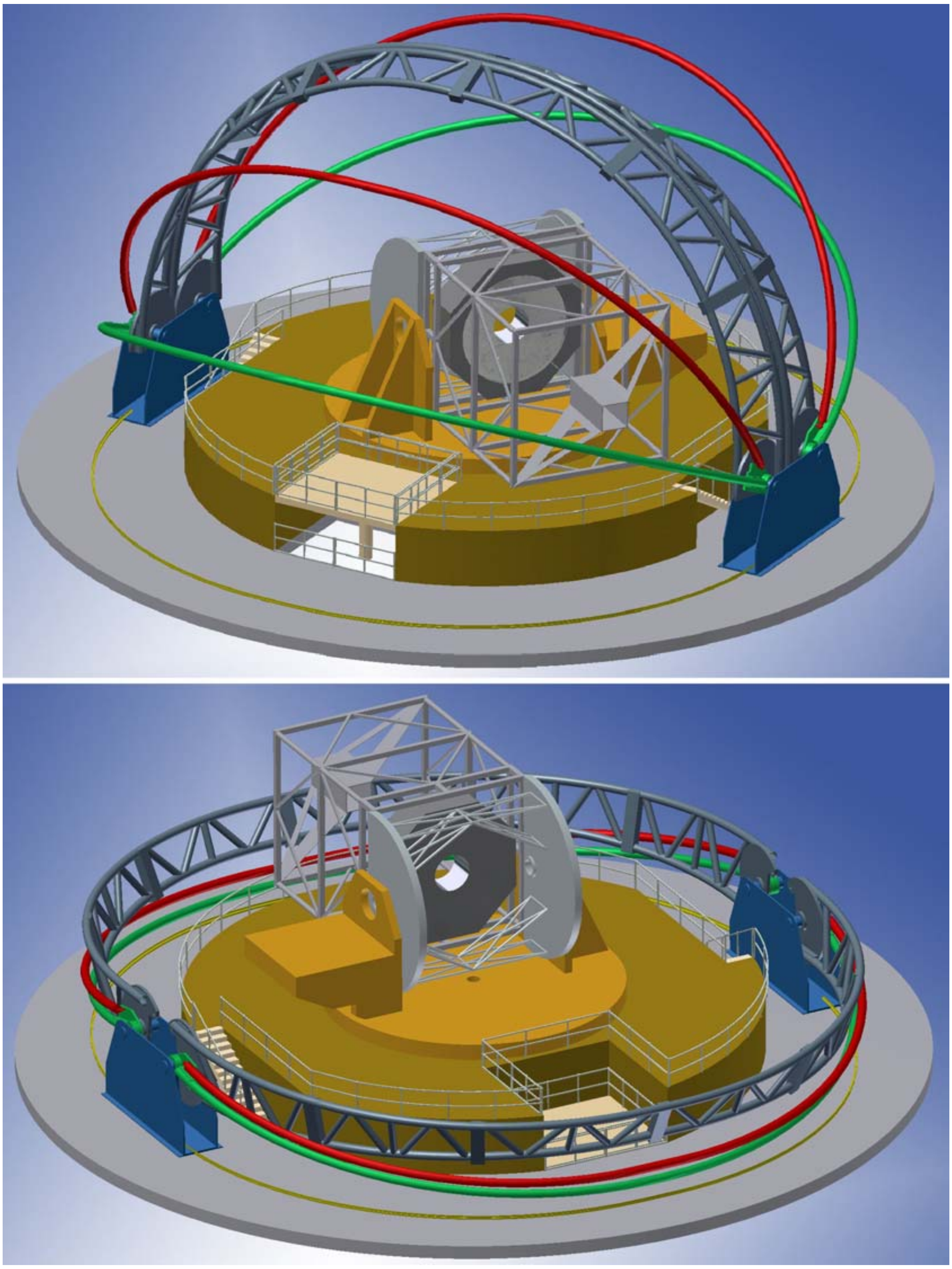

Figure 8. Telescope platform for the 28-m enclosure. *Top*: closed, telescope orientation south-west. *Bottom*: open, telescope orientation east. For a description of details like elevator, see text.

Even in the 23-m enclosure with an eccentrically placed telescope, there remains enough space for a large elevator in the platform. Figure 9 shows how this elevator can be located sideward of the east direction. The telescope can be parked to the other side of the east direction leaving the elevator platform free for access from above. And of course, the telescope can also move over the lift platform above the fences, as the position of the telescope foot is high enough.

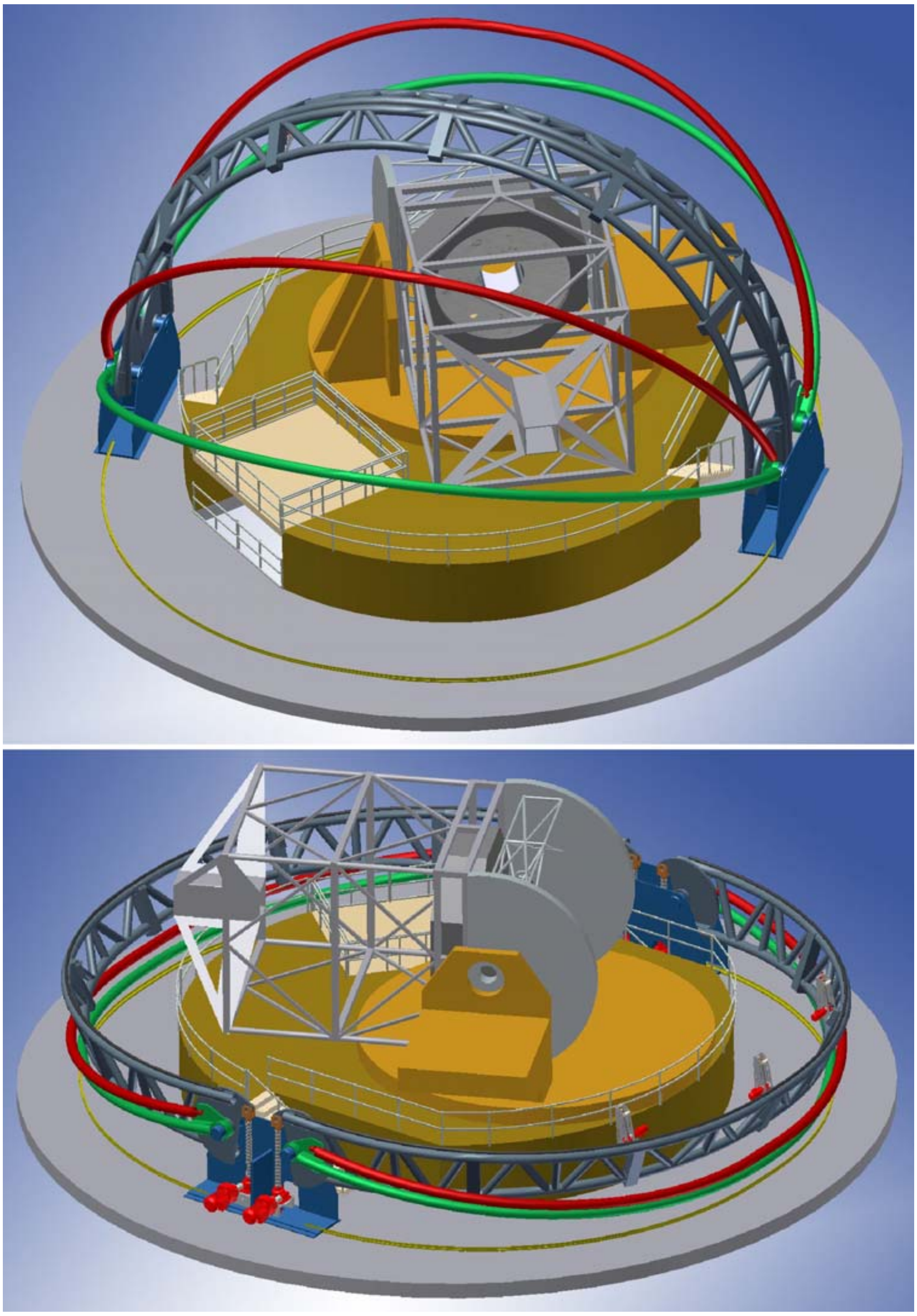

Figure 9. Telescope platform for the 23-m enclosure with lift platform, staircases and fences. *Top*: closed, telescope orientation east-north-east. *Bottom*: open, telescope orientation east-north-east with main-bow actuators visible.

The bottom part of Figure 9 shows the 23-m enclosure in open position. In addition to lift platform, staircases and fences, this view shows also the main-bow actuators near the rotation shafts of the bows. Plates and protection covers are taken away to make the actuators visible. Calculations indicate that the load of 30 m/sec (108 km/h) wind velocity dominates over the weight load of the bows on the actuators for smaller dome sizes, like those of DOT and GREGOR. Since the surface increases with the second power of the diameter, wind load does too. In principle, the weight of the bows increases with the third power of the diameter in order to keep the maximum tensions in the steel at the same level for the maximum storm load in closed situation. Consequently, the weight load of the bows on the actuators during opening and closing dominates over the wind load for very large dome sizes. Calculations show that for a diameter around 25 meter the wind load and weight load are equal, viz about 1000 kN (100 metric tons) in the chosen geometry of actuator arm length relative to dome size. However, wind and weight load do not reach their maximum value at the same time. Hence, actuators of 1700 kN will do the job. The 23-, 28- and 33-m domes require respectively 1500, 2250 and 3500 kN. The design offers the possibility to use two smaller actuators next to each other instead of a single actuator at each end of a main bow. This keeps the required actuator design within the commercial range of existing actuators, even for the 33-m dome. In addition, the bottom part of Figure 9 shows the three clamps at the right-hand-side main bow, in use to bring the cloth at full tension in the closed situation, providing storm resistance (used value in calculations 70 m/sec, i.e. 252 km/h, with in addition a normal engineering safety factor of 1.4 for the force). The clamps are placed at the top and 30° from the top on each side, where parts of the main bows are coupled by screw connections. Each main bow is splitted into six parts, reducing the size of the parts to be suitable for dip-zinc coating, followed by powder coating in a white color with titanium dioxide pigment. Each clamp is designed for a maximum 200 kN clamp force, sufficient even for the 33-m dome size. Figure 10 shows the clamp mechanism and illustrates its movement during opening.

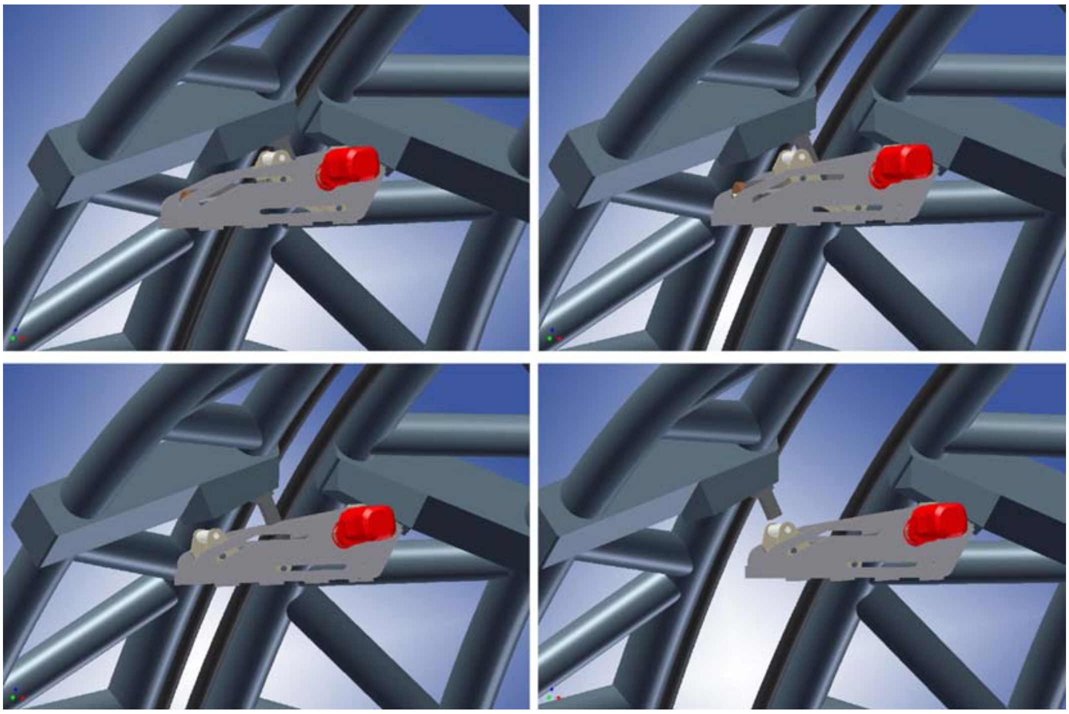

Figure 10. Movement of the clamp mechanism at the main bows during opening of the tent enclosure. *Top left*: clamp closed. *Top right*: clamp partly opened. *Bottom left*: clamp completely open and pen moved downward. *Bottom right*: the actuators move the main bows further down and the hook on the left main bow passes over the pen.

The DOT- and GREGOR-domes have a tension force on the cloth of about 2 kN/m. The larger dome sizes require a higher tension because of the larger wind force per meter cloth, due to the larger distance between the bows and, in addition, a larger radius of the curvatures. The wind force on the whole dome increases quadratically with the dome diameter. However, the length of cloth attachment to the bows increases linearly with the diameter. As a result, the force per meter cloth increases only linearly with dome diameter. A cloth tension of 8 to 10 kN/m is planned to be provided by the three clamps in the closed dome. Nowadays, new cloth is on the market which is stronger than that used for the DOT- and GREGOR-domes. Brake tension of this cloth is 200 kN/m in warp direction and 160 kN/m in weft direction. Repeated tensioning and relaxing tests are made up to 20% of these breaking strengths and the planned 8 to 10 kN/m for the EST-dome is only 5%. Figure 11 shows the Foshan Olympic Stadium in South China. It is an example of a static construction covered with large parts of the new cloth and comparable to the size of the cloth parts for an EST dome.

Figure 11. Foshan Olympic Stadium with cloth parts comparable to the size needed for an EST enclosure.

5. OPTIONAL WINDSHIELD

An optional windshield can be placed around the dome for protection of the lower part of the telescope with the primary mirror and its support cell. In the bottom right part of Figure 4 it was already shown how such a shield can be placed around the dome. In addition, Figure 12 shows a drawing of such a shield with an indication of some dimensions. The shield can rotate around the dome on a railway.

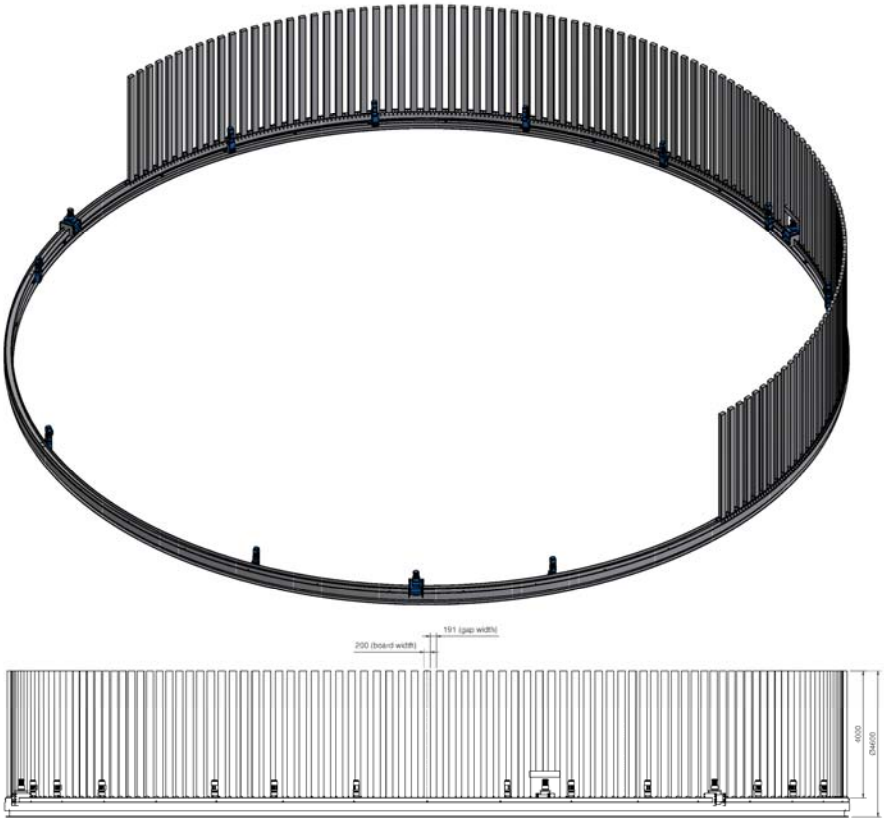

Figure 12. Drawing of an optional windshield around the EST dome for additional protection of the lower telescope parts.

Figure 13 shows a windscreen consisting of two parts of different height: the lower part 4 m and the higher part 6 m. The two parts, each covering 90° around the enclosure, can rotate separately. The figure shows the situation in which the telescope looks over the low shield to the upcoming sun in the east, while the high shield protects against the wind from the north, a situation which can provide very good seeing at the Canary observatories. Wind is fluctuating rapidly in direction and in the case of north-eastern or eastern direction the lower shield part will still protect the telescope as good as possible.

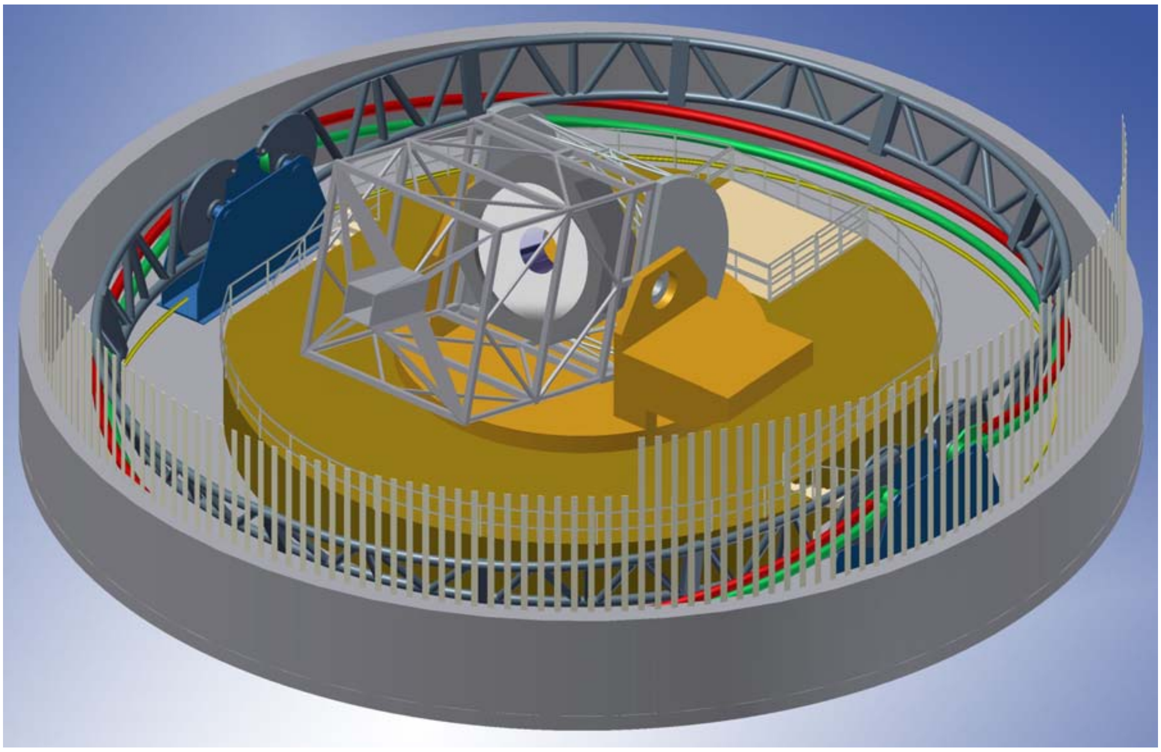

Figure 13. Windscreen around tent dome and consisting of two parts of different height.

The shield can be made with posts which are screwed to the ring carriage. In this way the individual posts can be removed or replaced by others of a different height. Hence, changes of the shield following from usage experiences, can be made quite easily. The posts and the railway ring are dimensioned to be storm safe, just like the enclosure construction. A typical cross-section is rectangular steel tube of 200×120 mm with wall thickness of 6 mm for the 4-m high shield and 200×200 mm square tube with wall thickness of 6 mm for the 6-m high one. The width of 200 mm for the posts is needed for the effectiveness of the shield in protecting the telescope. To make this understandable, we will give underneath a short explanation of these semi-transparent windshields.

A closed windshield produces a volume with almost stagnant air behind the shield. Behind and above this stagnant air a turbulent region with counter flows develops. The wind-protected area behind the shield is very limited. The stagnant air and the large-scale eddies with counter flows will cause long lengths of stay of air near objects of deviating temperature.

However, a semi-transparent windshield consisting of vertical boards with spaces in-between offers a good compromise. Eddies are formed directly behind the windshield. The kinetic energy of the wind is largely transferred into these eddies, which loose their energy over some distance behind the shield. A model of the wind-speed reduction behind such a shield is given in Figure 14. In area 1 of the figure there is a decrease of the wind speed through the hierarchy of eddies. At a distance of about 20 board periods (p) behind the shield, the eddies have lost most of their energy. The energy dissipation through the hierarchy of eddies causes some rise in the air temperature, but calculations show that this rise is too small to effect the image quality for wind velocities during observations, ranging up to 20 m/sec.

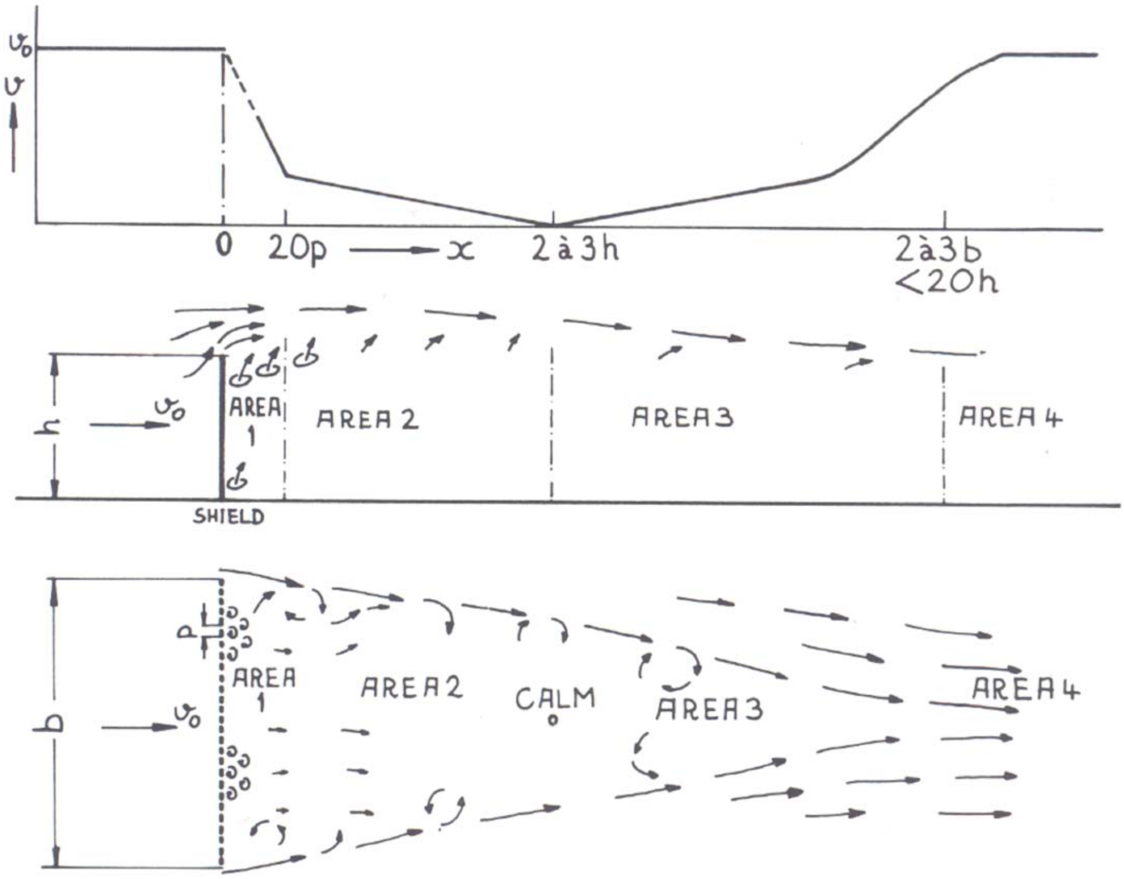

Figure 14. Model for the wind-speed reduction behind a shield consisting of vertical boards.
Top: graph of wind speed as a function of place before and behind the shield. *Center*: side view of area before and behind the shield. *Bottom*: top view of this area.
b = shield width, h = shield height, p = board-gap period, v_0 = wind speed in front of the shield, v = wind speed behind the shield, x = distance behind the shield.

The eddies have vertical rotation axes parallel to the boards. Consequently, there are only horizontal velocity components and no air mixing in vertical direction will occur. The eddies are, so to speak, spinning tops, which keep the spin axis vertical. A shield with horizontal boards is less effective, because eddies with horizontal axes are generated. The eddies contain vertical velocity components, which permit energy transport from the wind flow above the shield into the eddies. As a result, behind the shield the wind speed will be reduced less and the turbulence extends over a larger volume than in the case of vertical boards. A shield with vertical boards produces an almost horizontally stratified air mass with a minimum of turbulence. This is also confirmed by wind-tunnel measurements and by field measurements in real wind with its usual variability[3]. In addition, these shields are successfully applied for the protection of telescopes[3].

6. CONCLUSIONS

The nowadays available stronger cloth makes the construction feasible of completely open-foldable domes with diameter sizes into the 30-m range, using similar steel construction geometries as those of the smaller DOT- and GREGOR-domes. The geometry consists of two main bows and two in-between bows on each side. The incomplicacy of this geometry results in relatively inexpensive domes for the larger sizes, because the number of parts does not increase with size. The most important advantage of the open-foldable domes compared with slit domes or domes with many ventilation doors is their much better air-temperature homogeneity around the telescope. After opening a completely open-foldable dome, the air temperature around the telescope is in equilibrium with the surrounding air within a few minutes[2]. Consequently, an expensive climate installation with large energy consumption, as proposed for large solar telescopes in ventilated domes, is not required for an open-foldable dome. As a result, the open-foldable dome also is very attractive from costs point of view. A more general discussion of ventilated domes and open-foldable domes is given in another conference paper on the EST[12]. Another advantage of the open-foldable dome is the smaller mass. For instance, for the 23-m version a weight of 58000 kg is calculated. The optional rotatable windshield would add 17000 kg. The lower mass simplifies the construction of a tower with high eigen-frequency for stability in wind gusts.

The choice between a 23-, 28- or 33-m dome is also a choice between the case of most often very good seeing (the smaller one) and more operation space around the telescope (the bigger one). Open-foldable domes minimize the disturbance around the telescope, but the smaller the dome the smaller the carrying construction at the dome base and consequently, the smaller the chance that the wind flow along the dome base reaches the incoming optical beam. Wind flows often are not horizontal but inclined upward along the mountain slope, strongly depending on wind direction, gustiness and surrounding landscape shape. Moreover, this fact limits the value of simulations and wind tunnel experiments. An eccentric location of the telescope in the dome reduces the required size of the dome and it should be considered to what extent full-circle azimuthal rotation within the closed dome is important. Figure 9 demonstrates that an eccentrically placed telescope still offers enough space for a large transport elevator for the primary mirror. In addition, a 23-m platform already is large enough to construct an extremely stable tower underneath, even in open steel framework, which is favourable from the point of view of seeing[11].

If the telescope does not get sufficient stability for operation in strong wind, then the semi-transparent windshield with vertical boards offers a very good compromise between protection and still obtaining enough airflow for temperature homogeneity of the air around the telescope. The air-temperature homogeneity will be better than in a ventilated dome.

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