Large fully retractable telescope enclosures still closable in strong wind

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ABSTRACT

Two prototypes of fully retractable enclosures with diameters of 7 and 9 m have been built for the high-resolution solar telescopes DOT (Dutch Open Telescope) and GREGOR, both located at the Canary Islands. These enclosures protect the instruments for bad weather and are fully open when the telescopes are in operation. The telescopes and enclosures also operate in hard wind. The prototypes are based on tensioned membrane between movable but stiff bows, which fold together to a ring when opened. The height of the ring is small. The prototypes already survived several storms, with often snow and ice, without any damage, including hurricane Delta with wind speeds up to 68 m/s. The enclosures can still be closed and opened with wind speeds of 20 m/s without any problems or restrictions. The DOT successfully demonstrated the open, wind-flushing concept for astronomical telescopes. It is now widely recognized that also large future telescopes benefit from wind-flushing and retractable enclosures. These telescopes require enclosures with diameters of 30 m until roughly 100 m, the largest sizes for the ELTs (Extreme Large Telescopes), which will be built in the near future. We discuss developments and required technology for the realization of these large sizes.

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

1. INTRODUCTION

Telescopes make the sharpest images when placed in the open air, completely free without any dome or other objects, like a rollaway housing, in the neighbourhood. The reason is that temperature fluctuations in the air around the telescope deteriorate the images because the refractive index of the air changes with the temperature. Objects near the telescope have the tendency to produce air bubbles with deviating temperature. Deviations of 0.1 ºC in the air are already harmful and produce motion of the image and blurring, the so-called 'seeing' to indicate the deterioration of images.

It is practically impossible to keep all nearby objects at a temperature within 0.1 ºC with the surrounding air. The solution is a telescope structure standing completely free above all local objects. An open non-massive telescope structure minimizes the effect on the surrounding air: the air does not have the time to take over the distinct temperature. The refraction-index fluctuations caused by wind due to air-pressure fluctuations are too small to deteriorate the image in normal observing situations with wind speeds up to 20 m/s. However, indirectly the wind has a strong influence on the seeing because of its influence on the dispersion of temperature fluctuations coming from sources with a deviating temperature. Wind improves the seeing when it can move freely through the telescope structure without disturbance of nearby large objects, which would cause large-scale eddies, often referred to with the expression "turbulence". In addition, these large objects could cause wind-gust accelerations with undesired dynamical effects on the telescope structure. To realize this open principle[1] we need a fully retractable dome around a freestanding telescope, such that the air near the ground with a deviating temperature is not stowed upwards to the optical beam entering the telescope.

A consequence of the open principle is the high requirement on the stiffness of the telescope. In standard telescope designs the emphasis is not on stiffness. It is possible to increase the stiffness enormously without increase of the weight[2,3]. It is very well possible to make large telescopes stiff enough for open operation even in strong wind.

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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 the eighties, the European Southern Observatory (ESO) developed an inflatable tent construction[4,5] based on ribs of double cloth, 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 close and open only with depressurized ribs. In the depressurized situation the tent cloth was hold by relatively weak steel bows, which only permitted closing and opening when wind speeds were lower than 5m/s. This low value for the maximum allowed wind speed to close and open the tent made this construction unsuitable for the astronomical observation praxis. ESO built a prototype of this tent and installed it at the observatory in Chile, but it remained unused.

In addition to the requirement of leaving the telescope fully open, there are two more requirements for protection of astronomical telescopes:
(*i*) Closing has to be possible in strong wind without any danger for accidents, because clear sky and good seeing giving sharp images occur in wind speeds up to 20m/s on many sites favourable for astronomical observations. When this weather type changes to 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. This requirement was disregarded in the ESO design.
(*ii*) When closed, the construction should withstand the worst weather situations of its location. Heavy storms, 50m/s and more, combined with situations of heavy ice deposition occur on many of the mountain areas preferred for astronomical observations.

To fulfil all three requirements a tent development was started based on a different principle: no blow up but tent cloth parts cut in a saddle shape tensioned between movable strong bows.

2. FIRST PROTOTYPE: DOME ON AN OPEN TOWER FOR THE DOT

The Dutch Open Telescope (DOT)[6] of the Utrecht University (UU) at the La Palma Observatorio del Roque de los Muchachos (ORM) of the Instituto de Astrofísica de Canarias (IAC)[13] is primarily a solar telescope. In the case of solar observations, the solar radiation heats all objects and likewise the ground. This enlarges the temperature fluctuations in the air and hence the seeing problems. Wind becomes an important factor to get good seeing, not only for solar observations but also for nighttime observations, especially during the first half of the night when objects and ground have not lost yet their heat obtained during daytime.

The dome of the DOT is half a sphere with a diameter of 7 m and consists of six cloth segments. Two stiff bows lie against each other in the centre over the top of the half sphere. On each side of the stiff bows are three cloth segments with in-between two bows of only curved tubes. The cloth segments with greatest distance to the top bows are fixed to a base circle on a stiff platform on top of an open framework tower. The dome can be opened by moving apart and downward the two top bows.

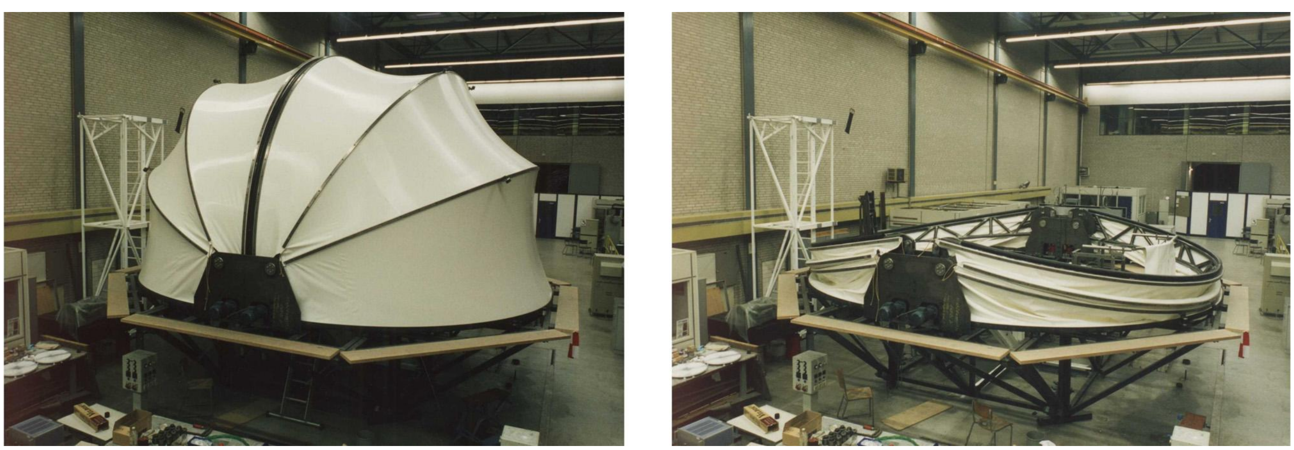

Fig.1. Test assembly of DOT-tent at the workshop in Delft. *Left:* tent closed; *Right:* tent open.

Fig. 2. The Dutch Open Telescope (DOT) on La Palma. *Left:* open dome for solar observations. *Right:* closed dome in winter; there is ice in ladder/elevator framework, however practically no ice sticks on the cloth due to its smooth outside coating.

Test assembly was at the workshop of the Technology University Delft (TUD), see fig. 1 for a closed tent (left) and the tent in an open position (right). Fig. 2 shows the tent on top of the DOT-tower at the observatory on La Palma: the left picture shows the tent open while the DOT is observing the sun, the right one shows the tent closed.

The tent cloth parts tensioned between the bows have a saddle shape. 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 other direction, hence negatively curved. Static roofs based on this tensioning principle are known, but the DOT-tent is the first construction suitable for closing during strong wind.

Several essential inventive ideas made the realization of such a strong, movable tensile construction feasible. To drive the main top bows a very compact system near the hinges with electrically driven actuators has been designed.

The bows between the different cloth parts are not driven. There are only hinges at the bow ends. Still, during opening and closing, the upper cloth segments are tensioned because of the relatively large weight of these in-between bows, reached by a large wall thickness. This construction avoids flapping of the cloth during opening and closing without the need of a complex drive system for the in-between bows. Experience taught us that closing the tent during wind speeds around 20m/s is not a problem at all.

Storms can be accompanied with heavy ice deposition. However, the ice deposition on the cloth is not severe, much less than on the other buildings. This is due to the outside cloth coating of a smooth PVDF layer. In combination with the shape of the tent of a half-sphere, this has as a result that most of the ice glides downward (see fig. 2 at right). The steel construction shows the normal ice formation, icicles in the direction of the wind, but the cloth is relatively clean from ice.

Originally, the DOT was planned without a bad-weather protection around the whole telescope. Only local protection of the optical parts was foreseen. However, experienced observatory employees warned against the terrible weather situations, which occasionally occur at the observatory with huge ice deposition from under-cooled clouds combined with heavy storm. The tent dome contributed significantly to the success of the DOT: a combination of completely open during observations with a safe protection during bad weather. The DOT reaches regularly a spatial resolution of 0.2 arc seconds. Films of the solar surface made by DOT can be seen on the DOT website[6].

3. IMPROVEMENTS: DOME ON A CLOSED TOWER-BUILDING FOR THE GREGOR

There was a lot of scepticism from the surrounding scientific world whether the DOT-tent would survive the severe weather situations that occur at the observatory on La Palma during wintertime. Now that the tent is in safe operation for a couple of years, the scepticism changed into a serious interest in the tent construction.

The GREGOR[7] is a new larger open solar telescope, which has replaced the smaller Gregory vacuum telescope on an existing closed tower building at the Tenerife Observatorio del Teide (OT), also operated by the Instituto de Astrofísica de Canarias (IAC)[13]. The weather situations on the OT observatory are similar to those on the ORM observatory on La Palma and we were asked to construct a dome, which is a further development of the dome of the DOT.

The diameter of the GREGOR dome is 9 meter. Between the two main top bows, there are two clamps instead of the single clamp in the smaller 7-meter dome of the DOT. The tension force is divided over the two clamps, which are placed 4.6 meter apart in the top of the dome. This gives less deformation to the bows than a single clamp. A second advantage is a larger free height in-between the two clamps in the centre of the dome than in the case of a single clamp. This allows the GREGOR telescope to be moved into an upright position inside the closed tent.

The test assembly of the GREGOR dome at the workshop of the TUD can be seen in fig. 3 and 4. The dome in closed, half open and open position, seen from the outside is shown in fig. 3 in the top, centre and bottom part, respectively. Fig. 4 shows the closed dome seen from the inside.

Images of the GREGOR dome on top of the tower building located at the OT observatory are shown in fig. 5 and 6. Fig. 5 at left shows a total view of the closed dome and tower. The GREGOR telescope structure inside the closed dome can be seen at the right of fig. 5. The telescope structure with open dome seen from the inside is shown in fig. 6.

The thermal insulation of a single tent cloth is not so good. Consequently, when the DOT is in the clouds sometimes condensate is present inside the tent and from time to time, a few drops fall from the bows on the telescope. For the DOT, this is not a problem because special attention was given to moisture insensitivity of the telescope structure.

For the GREGOR dome, we developed a system with a second tent cloth, which gives a better thermal insulation. The second cloth is fastened to the inside of the bows. This second cloth is tensioned in precisely the same shape as the outside cloth, giving a layer of air between the two clothes with more or less everywhere the same thickness. Special attention has to be given to the fastening of the inside cloth, because it gives pulling forces to the fastening screws and bending forces to the fastening strips, whereas the outside cloth spanned over the outside of the bows gives a pushing force on the bow, and on the fastening parts there are mainly shear forces.

The DOT-tent closes perfectly between the two main top bows and protects against rain from above. However, around the rotation shafts of the bows the cloth does not close everywhere. Consequently, in these regions the wind can blow some wetness into the room inside the tent. This is not a problem for the DOT because the telescope is located considerably higher than the leakage regions, and in addition because of the special attention to moisture insensitivity of the telescope structure as mentioned before. For the GREGOR dome, we developed additional cloth parts on the outside in the areas around the rotation shafts of the bows, which provide a good sealing.

The GREGOR dome withstood trouble free the extremely high wind load during hurricane Delta on November 28, 2005. A weather station of the meteorological state institute (Agencia Estatal de Meteorología) is situated nearby the

GREGOR and was on the downward side of the WNW-wind direction during Delta. Consequently, the GREGOR was exposed to at least the wind speeds measured at this station. The 1-minute mean at maximum was 245 km/hr (i.e. 68 m/s or 152 miles/hr)[8]. The GREGOR site is exposed to relatively high wind speeds due to the shape of the landscape. Several times opening and closing of the dome occurred at wind speeds of 90 km/hr (i.e. 25 m/s or 56 miles/hr), always without any problem.

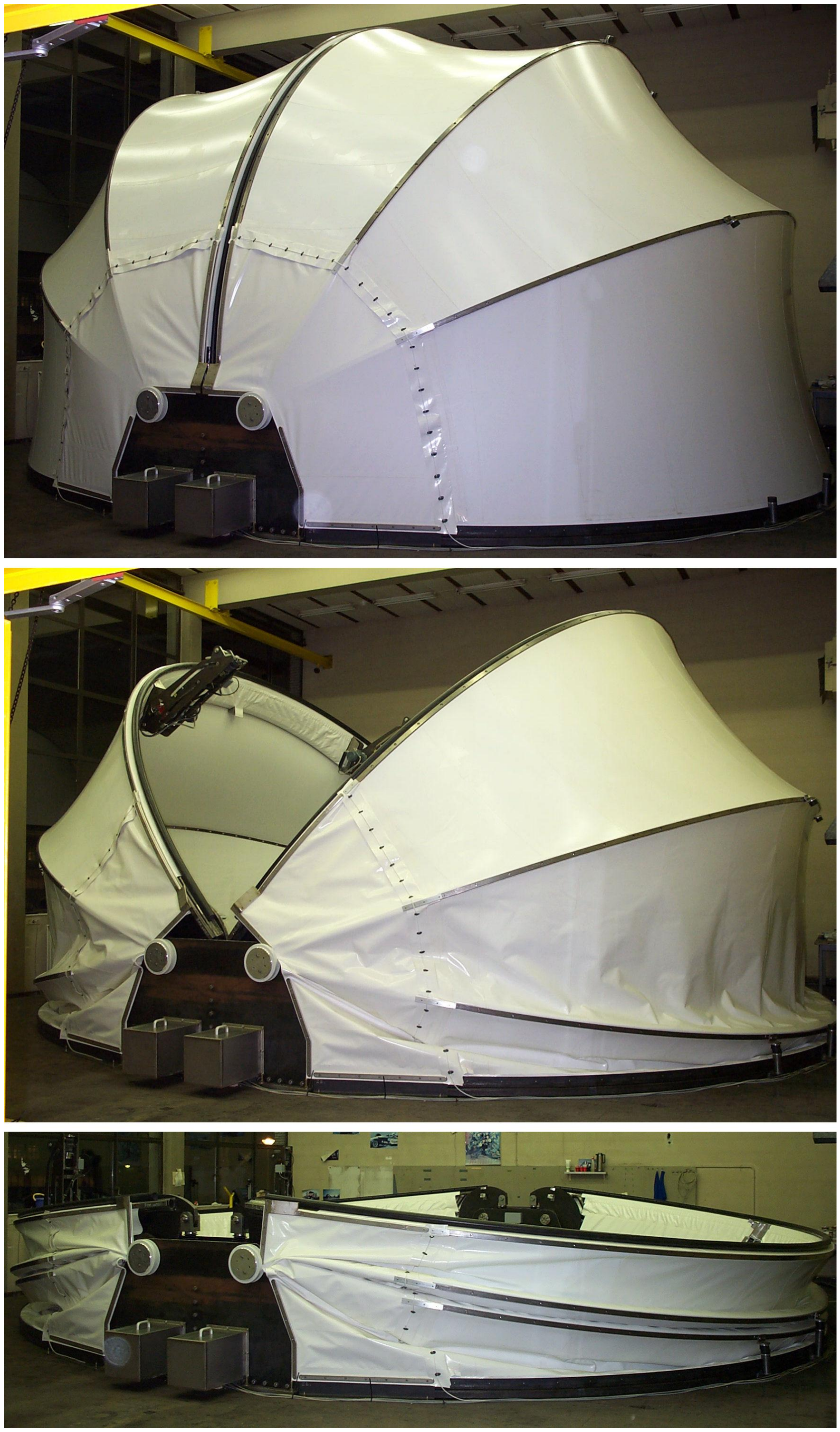

Fig. 3. Test of GREGOR-tent in Delft in closed (*top*), half open (*centre*) and open (*bottom*) position.

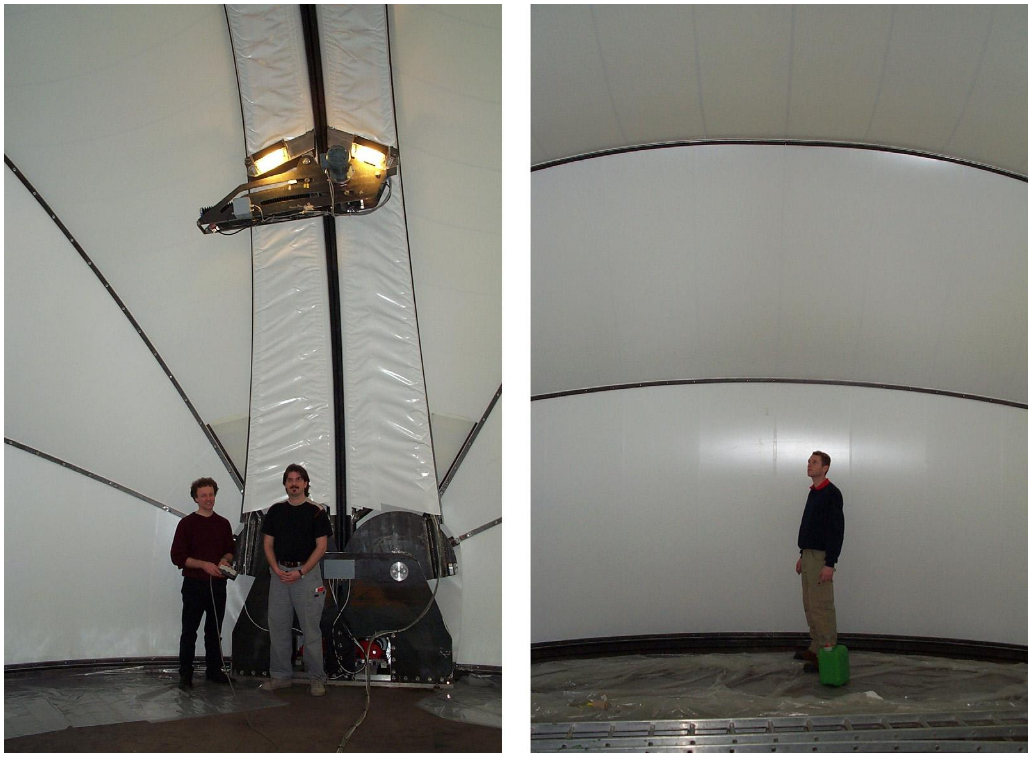

Fig. 4. GREGOR test in Delft. The closed dome seen from the inside. *Left:* front part with drive units. *Right:* side part.

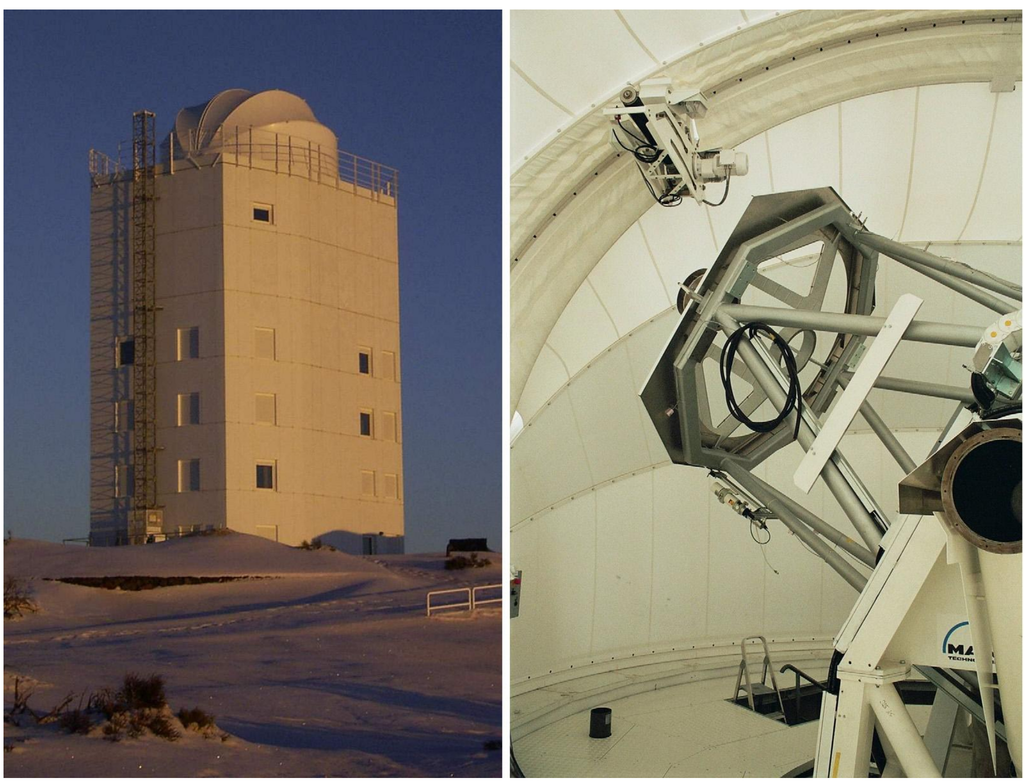

Fig. 5. *Left:* Total view of the closed dome and tower. *Right:* GREGOR telescope inside closed dome.

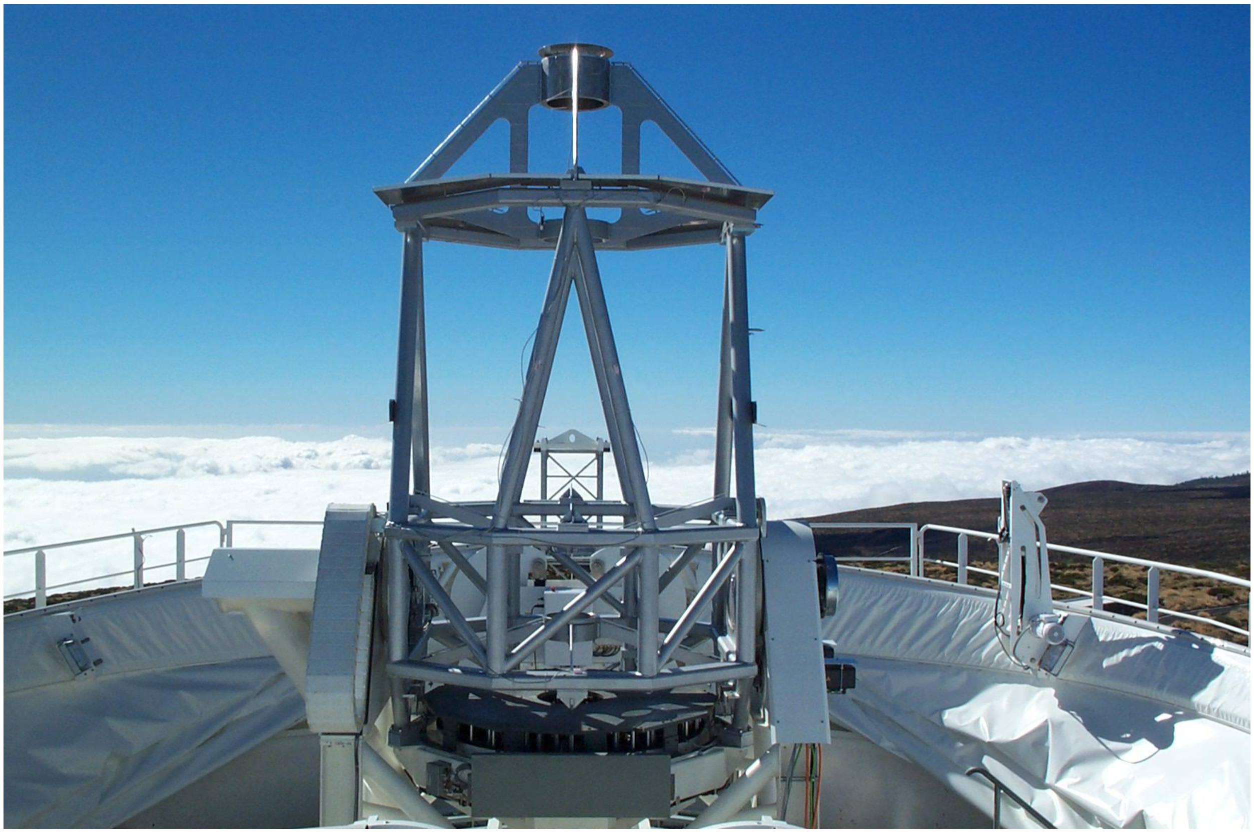

Fig. 6. The GREGOR telescope structure with open dome seen from the inside.

4. LARGE DOME SIZES AND CONCLUSIONS

The DOT and GREGOR domes prove that a completely open foldable tent construction can withstand the severe weather situations on the favourable mountain sites for astronomical observations. The construction permits routine opening and closing in strong wind.

The moderate sized domes for DOT, ∅7m, and GREGOR, ∅9m, were developed using limited calculations. For larger sizes, more precise analyses are necessary of the dynamic behaviour of the combined steel and cloth structure. The construction movable in very strong wind gives additional problems for the calculations compared to the known static membrane constructions. The ability to move gives more freedom of motions, for instance free rotatable bows between the cloth segments. In addition, the mechanical properties of the drive machinery have to be incorporated. The behaviour is different in closed and half open position. This is especially the case in gusty wind situations.

Measurements on real constructions in strongly gusty wind and storm will give much more information than wind tunnel experiments. The DOT-tent on La Palma and the GREGOR-tent on Tenerife give the unique possibility to set up a measuring program for verifying the calculations. Many measuring points inside the tent give the deformations of the tent construction relative to the stiff floor of the tent. A measuring system around the tent has been set up consisting of fast response anemometers for registration of the wind gusts from all directions.[9,10]

The following questions will have to be addressed. How big is the largest size we can realize? What are the limitations? In which way do the latter depend on the maximum wind speed for half open position during closing and for the closed situation? What are the changes to be made compared to smaller tents?

The starting configuration to answer these questions is the basic geometry of the DOT- and GREGOR-domes. As explained earlier, these domes are half a sphere consisting of six tensioned cloth segments, three on each side of two stiff framework bows over the top of the half sphere. Only the two top bows are actively driven by motors, each one over somewhat more than 90 degrees downward to its side, leaving the telescope completely free in the open air. The two bows between the three cloth segments on each side move downward due to gravity. These in-between bows keep the still raised cloth segments tensioned during opening and closing and in the situation that one or both sides of the tent are left partly upward. The weight of the in-between bows is sufficient to keep the raised cloth segments tensioned up till a wind gust peak velocity of 30 m/s.

In closed situation the in-between bows are kept into position by the cloth. This means that a storm load over the whole half of the dome between a top bow and the ground half circle contributes to the load on the cloth. The span in this respect is 90°, i.e. $(\pi/4)d$, where d = diameter of the dome. Of course, the in-between bows give a certain support to the cloth, compared to a completely free span. Nevertheless, the cloth has to carry the load. Consequently, the strength of the cloth limits the dome size in the case of the design where only the top bows are motor driven. Using the common tensioned polyester cloth for such a design, dome diameters up to 30 m will likely be feasible.

Larger dome sizes will require motor driven in-between bows. Alternatives are in-between bows, which are fixed in the closed position of the dome and make the dome strong enough against storms. During operation the wind load is much lower. Remind that the load is approximately quadratically proportional to the velocity. During operation the cloth can carry the in-between bows. The relatively simple system with only driven top bows can be maintained in that case.

We also investigated drive systems for larger sized domes. The required actuator size increases quadratically with the dome diameter when geometric configuration and relative dimensions of the parts are kept the same. The 7-m DOT dome requires 13 metric ton actuators, while the 9-m GREGOR uses 20 metric ton actuators. Standard electric actuators are available up till 250 metric ton, which corresponds to a dome diameter of 32 m, i.e. the same order of limit to the size as mentioned above. Larger dome sizes will need more complex but very well performable designs. Also hydraulic systems, available for much higher loads, are an interesting option.

On-site measurements on the DOT- and GREGOR-domes are essential for the development of the extremely large dome sizes of 30 m to about 100 m based on the described principle. It could be an excellent option to be added to the alternatives described elsewhere[11]. The advantages of the design presented in this paper are the described better seeing conditions, the light weight and not being more expensive than the other alternatives. The lightweight construction makes the foundation significantly easier, which also reduces largely the total costs. New insights into calculation methods are expected from the interaction between the precise dome measurements and refinement of the calculations.

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REFERENCES

[1] Hammerschlag, R.H., Bettonvil, F.C.M., Jägers, A.P.L. and Sliepen, G., "Cornelis Zwaan, open principle, and the future of high-resolution solar telescopes", in *Astronomical Instrumentation*, Proc. SPIE 7012, *Ground-based and Airborne Telescopes*, paper 7012-21 (2008).

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

[3] 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).

[4] Bonneau, A. and Zago, L., "Inflatable domes for astronomical telescopes", in *Advanced Technology Optical Telescopes III*, Proc. SPIE 628, p. 342 ff (1968).

[5] Bonneau, A. and Zago, L., "Design and construction of the inflatable dome prototype", in *ESO Conference on Very large Telescopes and their Instrumentation*, Vol. 2, 867-874 (1988).
[6] DOT website: http://dot.astro.uu.nl
[7] GREGOR website: http://www.kis.uni-freiburg.de/index.php?id=163&L=1
[8] Martín Léon, F. et al., "Estudio de la tormenta tropical 'Delta' " (Capítulo III, p. 6) at http://www.aemet.es/es/divulgacion/estudios/ (2006).
[9] 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).
[10] 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).
[11] Quattri, Q., Hautum, M. and Pedretti, A., "Enclosures for a 100m telescope: Baseline conceptual design and alternatives", in Proc. SPIE 6267, *Ground-based and Airborne Telescopes*, 112-123 (2006).
[12] SST website: http://www.solarphysics.kva.se
[13] IAC website: http://www.iac.es