Large open telescope: size-upscaling from DOT to LOT

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ABSTRACT

The design characteristics of a large open telescope (LOT) are: (i) an open tower with only pure translations of the platform under wind load; (ii) an open telescope construction with extremely stiff geometry and drives; (iii) simple optics with easy aligning and testing, but nevertheless suitable for large auxiliary equipment like spectrographs.

Keywords: solar telescope, seeing, wind, telescope construction, towers, telescope optics, diffraction limited imaging, telescope drives

1. INTRODUCTION

The Dutch Open Telescope (DOT) on the Canary island La Palma consists of a 15 m high open framework tower with an open telescope on top without dome during observations. The wind can blow through the tower and the incoming primary lightbeam; it mixes the air and makes the air temperature homogeneous. No warm air bubbles are forced upwards against the closed wall of a tower and no heat is produced by the tower itself. The DOT produces movies over hours with 0.2 arcsec resolution. These results prove the value of the open principle in improving the local seeing.

The DOT has modest size. We investigate upscaling of the open principle to a large solar telescope with a 4-m class primary mirror. Starting from the DOT construction, we show which difficulties are encountered and which practical design solutions are found for the large sizes. We will come to a total concept during our discussion of the various parts.

The discussed parts are:
- A high open tower with sufficient stability. The DOT tower uses the principle of pure translation of the platform under wind load. With special geometries this principle is maintained in high towers (of the order of 50 m and even more) which consist of a number of stories and can be built in normal framework technique.
- An open telescope construction: the primary beam and mirror exposed to the wind; stiff construction, especially the drives and bearings with inventive design details; no shaking in the wind.
- Simple optics: an axial or off-axis parabolic primary mirror; water-cooled field-stop in the primary focus; a limited number of components in the secondary optics, where both imaging in a multi-wavelength system and a spectrograph are still possible.

2. THE OPEN TOWER

A classical open framework tower is the 150 feet solar tower on Mount Wilson. It consists of an inner framework with an outer one around. The inner framework carries the coelostat. The outer framework should protect against the wind forces. This means that around each inner tube piece an outer tube piece is made. In the many corner points of the framework the outer construction is such, that it does not touch the inner one. This ingenious work was done with rivets. The inner and outer towers have separate foundations. The inner tower has four foundation feet under the four upgoing inner tubes. Each

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ground point of the four upgoing outer tubes rests on a kind of bridge of steel beams. Such a bridge rests on two concrete blocks at its endpoints.

However, the inner tower has a low eigenfrequency of the order of 0.5 Hz and there is coupling between the outer and inner tower through the underground of the foundations. Consequently, with a fluctuating force on the outer tower, the inner tower shakes. The coupling through the foundations takes place with very small displacements in the foundations themselves. But because of the large tower height relative to the base dimensions, these small foundation displacements produce significant vibrations on top of the inner tower.

In general, double towers consisting of an inner tower and an outer one have foundation coupling problems. Consequently, for the DOT we investigated the possibilities of a single tower still stable enough against wind. These investigations resulted in the solution with isosceles triangles.[1,2]

We first calculated a tower in classical framework as indicated in Figure la. This construction is very stiff against translations of the platform, however it turned out to be not stiff enough against rotations of the platform without using a big quantity of iron. We learned from this calculation that a compensation for rotations about horizontal axes (x and y in Figure 1) should be built in the geometric form of the framework. The simplest form of a compensating construction is a horizontal platform on vertical posts as shown in Figure lb. The platform remains parallel to the ground if the posts bend sideward under a wind load. However, this construction is not stiff against rotations about the vertical axis (z in figure 1). Horizontal translations excite rotational vibrations about the vertical axis, which was also confirmed by model experiments.

A framework similar to the construction used for the tubes of large telescopes[3] shown in Figure lc forms a compensating construction which is still stiff against vibrations about the vertical axis. The stiffness against these vibrations is proportional to the square of the top angle α of the vertical triangles. The calculations showed that for our purpose α should be at least 30° as is the case in Figure 1d. Then the platform becomes larger than necessary to locate the telescope and now problems with the deflections of the platform arise.

Figure 2a shows the principle of the framework we have chosen for the DOT. It combines a large top angle α with a small platform. The construction consists of a platform in the shape of a rhombus, the points 13-14-15-16, supported by the four broad-based triangles 1-14-4, 3-13-2, 6-15-7 and 8-16-5. Each pair of parallel triangles gives stiffness in one direction and parallel guidance to the platform in the perpendicular direction. Figure 2b shows the complete framework. The platform is implemented as a pyramidal framework in order to obtain sufficient stiffness. The telescope is to be mounted on the angular points 13, 14 and 16. Connections between the base points 1 to 8 give a stiff framework in the base plane, which prevents shifts of the base points and simplifies the assembly.

Figure 5 shows the tower on La Palma with the telescope on top of it.[4,5] The correctness of the compensation effect which holds the platform parallel was proven by interferometric measurements.[2] With a wind velocity of 10 m/sec the platform translations are 0.1 mm, the height differences between the corner points less than 1 μm.

Many variations on the construction shown in Figure 2 are possible. However, all suitable constructions have the following characteristics in common. The platform is supported by three or more triangles that are isosceles and stand vertical. The top of an isosceles triangle deflects parallel to the basis, if it is loaded by a force parallel to the basis. The top of a vertical triangle deflects in a horizontal line if it is loaded by a force perpendicular to the plane of the triangle. Consequently, the top of an isosceles vertical triangle deflects in a horizontal plane if it is loaded by a horizontal force of arbitrary direction. Three or more of such triangles give a parallel horizontal guidance to the platform in all directions provided that not all triangles are parallel to each other.

For the sake of completeness we mention that instead of vertical isosceles triangles other supporting means can be used which deflect in parallel planes under horizontal loads such as pyramids. One possible combination is for instance a symmetric pyramid, a vertical isosceles triangle and a vertical post. Even solutions with non-symmetric triangles and/or pyramids are possible if the parallel deflection planes are not chosen horizontally but these solutions are of less practical value.

Figure 3 shows one of the variations. This tower consists of three vertical isosceles triangles ABD, BCE and CAF, which bear the platform DEF[2]. The telescope is mounted on triangle GHI which is fastened to the platform DEF by three triangles. The lower part of the telescope mount becomes situated under the platform plane DEF. In this way the torque on the platform by wind load on the telescope is reduced. The tower with three triangles is easier to assemble than the existing tower with four triangles because the latter needs a flat plane for the 8 base points or one of the base points has to be adjusted. The reason is, that the three-triangle tower is statically determinate and the four-triangle tower statically indeterminate. This makes the three-triangle tower principle specifically suitable for (temporary) towers on uneven ground without an expensive foundation.

The three-triangle principle is applied to a tower of 7.5 m height on the South Pole[6], see Figure 4, and - in the same size order - to the site testing towers for the Advanced Technology Solar Telescope (ATST) site selection. These modest sized towers have only a top platform, DEF in Figure 3, which supports the relatively small instruments, hence no framework with corner points GHI as in Figure 3.

The 15 m long tubes of the DOT-tower have a diameter of only 245 mm. This slender shape has the advantage of a high transparency of the tower to the wind. From measurements with semi-transparent windshields[7,8] it was found that the transparency has to be 80% or more in order not to disturb significantly the airflow by the wind.

The disadvantage of the slender tubes is a lower eigenfrequency for transverse vibrations. The eigenfrequency of the DOT-tower tubes is 6 Hz. This eigenfrequency is high enough to avoid the excitation by wind buffeting, because the energy in the power spectrum of wind decreases rapidly between 1 and 10 Hz.

However, if the frequency of the vortex oscillations[9] (which produce the so-called Von Kármán trails of eddies[10]) becomes equal to the mechanical eigenfrequency, then the relatively small force of the vortex oscillations will still excite vibrations. Some practical formulas are given in Table 1. For the tubes of the DOT-tower the two eigenfrequencies become equal for a wind velocity of 7 m/sec.

Eigenfrequency of transverse vibrations of a round tube

$$\nu_m = c/8\pi \; (E/\rho)^{1/2} \; (D^2+d^2)^{1/2}/l^2$$

- ν_m = mechanical eigenfrequency in Hz
- c = constant depending on the connection of the end points
  - $c = \pi^2 = 9.87$ for both ends pin-connected
  - $c = (5/4\,\pi - 0.00039)^2 = 15.42$ for one end pin-connected, one end fixed
  - $c = (3/2\,\pi + 0.01765)^2 = 22.37$ for both ends fixed
- E = modulus of elasticity for tension of the material; for steel $E = 2\times10^{11}$ Newton/m^2
- ρ = density of the material; for steel $\rho = 7.85\times10^3$ kg/m^3
- D = outside tube diameter in meter
- d = inside tube diameter in meter
- l = length of the free tube part in meter

Eigenfrequency of vortex oscillations:

$$\nu_v = s\,v/D$$

- ν_v = vortex eigenfrequency in Hz
- s = Strouhal number, about 0.2 for round tubes
- v = wind velocity in m/s
- D = outside tube diameter in meter

Table 1: Some practical formula.

The geometry of the DOT-tower is such, that the tubes pass each other closely near half the height of the tower. Consequently, rubber dampers could easily be placed at half the height of the tower; see Figure 5. One of each pair of crossing tubes is brought to an eigenfrequency which is a little bit higher by small perpendicular tubes at a height of 2.5 m: the eigenfrequency is brought from 6 Hz to about 7 Hz, see Figure 6. Because of the frequency difference, the two tubes cannot vibrate together without deformation of the damper in between. In this way an effective suppression of any vortex oscillation of the slender tubes is achieved.

Both the dampers and small tubes are perpendicular to the main tubes and are flexible to deformations in the direction along the big tubes. They cannot produce a significant force along the main tubes. Consequently, they do not disturb the compensating construction, which holds the platform parallel.

The eigenfrequency of the transverse vibrations of a framework tube or beam is proportional to the diameter and inverse proportional to the square of the length, see Table 1. Consequently, with a constant D/l the eigenfrequency will decrease with increasing length l. When the height of a tower becomes significantly higher than the 15 m of the DOT-tower, the construction of isosceles triangles of single tubes will not work anymore. There are two solutions. The first one is: going to legs of the triangles which consist of framework on their own. Then the principle of the isosceles triangles remains valid. The second one is to find geometries which can be built in stories of framework and still show the parallel motion of the top platform under wind load, hence no rotations of the platform.

The key to these geometries in stories is the fact that perpendicular tubes to the main up-going tubes do not disturb the elongation or compression on the main tubes, hence the compensation effect remains intact. It is the principle already applied in the small tubes and dampers for the DOT. Also the top of the combined ladder and elevator guidance of the DOT is connected by perpendicular strips to the main structure.

In Figure 7 a tower construction of two stories is shown. It consists of two interweaved tower constructions. The vertical posts A-Θ, B-Φ, C-Ψ and D-Ω form a tower conform the principle of Figure 1b. The second tower has in the first story the triangles ABF, BCH, CDJ and DAL, and in the second story the triangles FHM, HJN, JLO and LFP. The second tower is stiff against translations and rotations around a vertical axis of its top square MNOP. These stiffnesses are passed on to the first tower by the perpendicular connections MΘ, MΦ, NΦ, NΨ, OΨ, OΩ, PΩ and PΘ in the top floor, and by FE, FG, HG, HI, JI, JK, LK and LE in the first floor.

The tower platform for supporting a telescope is a separate framework which is only connected to the corner points Θ, Φ, Ψ and Ω. Four triangles ΘΦQ, ΦΨR, ΨΩS and ΩΘT connect the platform QRST to ΘΦΨΩ. The corner points Θ,Φ,Ψ,Ω remain on the same height when the tower deforms under wind load. Consequently, the platform QRST does not incline under wind load: the compensation effect of the four vertical posts is working. The four triangles ΘΦQ, ΦΨR, ΨΩS and ΩΘT form a connection from the outside tower to the space inside the second tower without touching the latter. A completely free area is available above the platform square QRST, as is illustrated in the topview of Figure 7.

The distances between the corner points become too long for single connecting tubes or beams if the height of the tower is increased. However this geometry is suitable for framework in between without disturbing the compensating effect. Figure 8 shows a construction where each of the two stories is splitted up in two substories, hence all together a four-story framework.

Now the lower part of the second inner tower consists of four pyramids pointing downward: AFLZ, BHFZ, CJHZ and DLJZ. They lean against each other along the lines FZJ and HZL. In the pyramids an arbitrary number of substories can be formed. Beams perpendicular to the vertical posts come from each sublevel. The construction of Figure 8 contains one sublevel. In this way the free distances between corner points can be reduced to the desired length.

Similarly, the top part FHJL-MNOP can be divided in substories. In the construction of Figure 8 there are two substories. The level in between is situated under the platform floor QRST and does not disturb the framework between QRST and the top-corner points ΘΦΨΩ.

The shorter lengths between the corner points allow relatively larger diameters of the connecting elements, tubes or beams. If the diameter is larger than 1/35 of the length, vortex oscillations can only occur for wind speeds higher than 20 m/s, i.e. speeds higher than during observations. In addition, the eigenfrequencies are higher than 10 Hz and no dangerous oscillations can occur. Consequently, no dampers are necessary. For comparison, the diameter of the DOT-tubes is 1/61 of the length and in that case dampers are necessary as discussed before. In Figure 8 an example of a framework for a telescope foot is drawn. The triangles QRV, RSW, STX and TQU support the square UVWX, where for instance the azimuth bearing is located.

The details of the design of the corner points and connecting beams are important to get maximum stiffness, including a maximum compensation effect for the inclination of the platform. For instance, a large momentum of inertia of the beam cross-section for the beams in the platform QRST and the connecting beams of the top square MNOP, a relatively large momentum of inertia for the vertical posts AΘ, BΦ, Cψ and DΩ, and a relatively low momentum of inertia for all the perpendicular connections to the vertical posts.

The platform QRST forms a very stable base. Moments on the telescope are brought to the maximum width of the outer tower. The forces and deformations along the vertical posts by moments are minimized. A telescope construction half under the plane ΘΦΨΩ and half above this plane minimizes the moment to this plane due to wind forces on the telescope. Because of the completely open area above the square QRST, the platform is suitable for mounting any shape of telescope. The part under the level of the plane MNOP can be used for an optical lab, such as the rotating Coudé labs in the case of the ATST.[11]

3. TENT PROTECTION

The telescope can be protected by a completely open foldable tent construction similar to the tent construction of the DOT. The DOT-tent on La Palma survived storms with wind gusts of more than 120 miles/hour; design figure is 165 miles/hour. Closing (and opening) is possible till 70 miles/hour. Several times we had good observations with 50 miles/hour and closed afterwards the tent. The DOT-tent resisted heavy snow and ice formation without problems. The ice deposition on the cloth itself is not severe, much less than on the other buildings. This is due to the coating of the cloth on the outside with a smooth PVDF layer. In combination with the shape of the tent of half a sphere, this has as a result that most of the ice and snow glide downward. Figure 12 shows the DOT after ice formation by clouds. The steel construction shows the normal ice formation, icicles in the direction of the wind, but the cloth is relatively clean from ice.

The Gregor telescope[12] on Tenerife will get a tent protection, which is a further development of the DOT-tent. Its diameter will be 9 m (the diameter of the DOT-tent is 7 m). The bows of the Gregor-tent will be driven by the same size of electrical actuators as in the DOT-tent. Gregor uses the full capacity of 200 kN of these actuators, DOT only 130 kN. Standard actuators are made up to a capacity of 2500 kN. The necessary capacity is proportional to the square of the diameter. Consequently, standard actuators can drive tents up to a diameter of 32 m.

A ring through the tower points MNOP is the logical shape of a base for the tent construction. The telescope platform QRST is insensitive to deformations to the tower points MNOP. Hence, forces from the tent ring to these points MNOP do not influence the telescope position. The sensitive points ΘΦΨΩ are outside the ring. Here again, the connection of the outer tower to the telescope platform through the inner tower, without touching it, shows its advantage.

4. TELESCOPE CONSTRUCTION

The ATST is a telescope based on advanced technology, which can be put on the open tower. We will discuss here a somewhat simpler design, based on the open telescope design of the DOT with full access of the airflow by wind to the primary beam (Figure 13) and simple optics.

The present size of the mechanical part of the DOT is suitable for mirrors up to a diameter of 1.40 m. The geometry is intrinsically so stiff that upgrading to a mirror diameter of 4 m is no problem. Two keys are needed for the extreme stiffness: (i) the stability of the framework parts is reached by proper application of some construction rules, which can be condensed in the principle "everywhere are triangles"[13] ; (ii) the stability of the drives is reached by special gear design, which gives line contact between the teeth of meshing gears under a relatively low load.[14]

The DOT-telescope has a polar mount. The same mount construction can be used for an alt-azimuth mount simply by rotating the polar axis vertical. The structure of the polar or azimuth wheel can now be lowered into the space below the top plane MNOP of the tower and the fork can be shifted to the center of the azimuth wheel. These changes lead to a still stiffer overall geometry, which is an advantage for a Large Open Telescope (LOT).

Figure 9 shows a layout for the optics. An off-axis parabolic mirror as proposed for the ATST[11] would fit excellently into a LOT design. If that would not be possible because of technical or financial reasons, an on-axis parabolic mirror will give a very good alternative. Essential is a low obscuration percentage of the incoming primary beam by the secondary optics and its support.

We have good experiences with the low obscuration of 10% of the DOT. The decrease of the optical modulation transfer function – specifically in the frequency range half way of the diffraction limit - is approximately proportional to the obscuration fraction. The secondary optics is supported by plate shaped structures with the small-edge sides pointing to the incoming beam. All edge sides carry slightly broader baffle strips, which avoid stray light from the large plate surfaces by grazing incident sunlight.

It is even possible to construct a support where the diffraction light is spread out regularly in all directions, see Figure 11. The structure is stiff in all directions because it is composed of triangles. In the case of a DOT-like asymmetric telescope-tube framework half a circle of triangle structures will be used.

We follow the optical scheme in Figure 9. In the prime focus a water-cooled diaphragm combined with air suction like in the DOT[5] is placed. The field is about 1/10th of the solar diameter reducing the heat to 1/100th for the secondary optics. Behind the diaphragm there is a second on-axis parabolic mirror with short focal length. A small parallel beam comes from this mirror. Two parabolic mirrors in cascade have no coma; consequently, the whole field of three arc minutes is diffraction limited. Directly behind the water cooled diaphragm there is a flat mirror with a hole. This mirror reflects the light to another flat mirror directly besides the second parabolic mirror. The second flat mirror reflects the light to a third flat mirror, which reflects the light along the elevation axis. This axis is situated behind the primary mirror.

A suitable place for a polarization package (encoder) is between the second and third flat mirror, near the third mirror. This package may include optical components for producing a telecentric path of rays and a reduction of the beam size suitable for the polarization elements. For this purpose it is also possible to add a lens near the second flat mirror, just beside the water-cooled diaphragm.

In the cross point of the elevation axis and the azimuth axis there is a fourth flat mirror, which reflects the light downward into a Coudé lab directly under the telescope. Figure 10 shows a total concept of open tower and telescope. In the Coudé lab is reimaging with a small aperture image for adaptive optics and splitting up in several channels.

Along the azimuth axis there is a big tube – three to four meter diameter – from the Coudé lab directly under the telescope to a second Coudé lab on the ground. In this tube is a smaller tube, about 1m diameter, for guidance of the light beam. The long way of about 50 m from the second parabolic mirror to the second Coudé lab will not require additional optics before FM6 in the case of smaller fields in the order of 1 arc min, which will often be sufficient for high resolution spectrographs. There are several solutions for use of the full 3 arc min field in the second Coudé room. Which solution is the best depends on the wavelength range. Infrared light has a high reflection on mirrors, is less sensitive to the shape deviations in the mirrors, consequently, more secondary mirrors of medium size decrease the image quality not so much. Under the telescope and in the first Coudé room is space available for such a system. Visible light permits the addition of lenses, which can be put in the light path, as already indicated for the polarization package. Aberrations of these lenses are not a problem because the f-ratio after the second parabolic mirror is small. In addition, small beam diameters are favourable for visible light to avoid internal seeing. For visible and certainly for blue light it is advisable to evacuate the tube.

Elevator, ladder and cables are also situated in the large tube along the azimuth axis. This tube forms a closed connection between the two Coudé labs, protected against all weather influences.

The second Coudé lab on the ground can really be large because the design of the lower part of the tower gives a maximum of free space between the four base points.

5. CONCLUSION

We have presented a complete concept of a really open telescope with the advantages of optical labs of the evacuated telescopes. The optical concept consists of simple components, which can be easily tested as separate parts. Alignment of the components is relatively simple and not extremely critical. The concept is such, that hardly any compromises are necessary, neither in the open construction nor in versatile use of the telescope.

The two Coudé labs permit an extremely flexible use of the telescope with many auxiliary instruments, including large spectrographs, but also access to the light close to the telescope.

Figure 14 shows the total concept on the Observatorio del Roque de los Muchachos. On the left side from left to right: the Nordic Optical Telescope, the Swedish Solar Telescope and the DOT. On the right side: the William Herschel Telescope. Observation rooms with many computers producing heat are located in a separate building on safe distance from the telescope tower, near the road at the bottom of the image.

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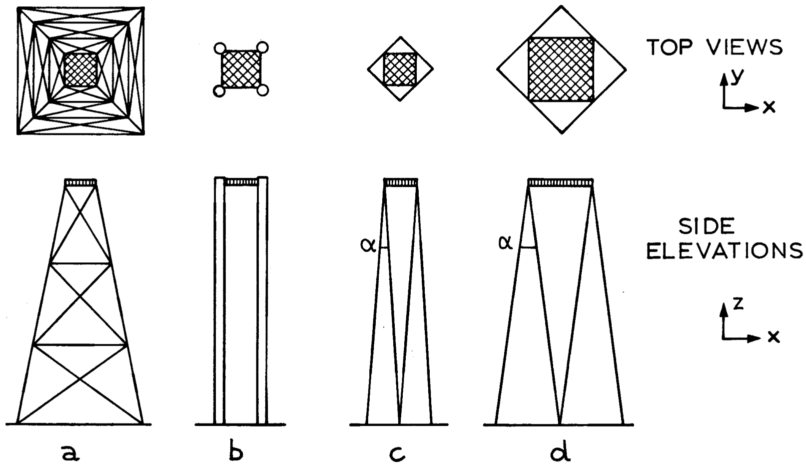

Figure 1: Various tower constructions: *a.*classical framework; *b.*platform on posts; *c.*4-triangle truss with small platform and small base; *d.*4-triangle truss with large base and large platform.

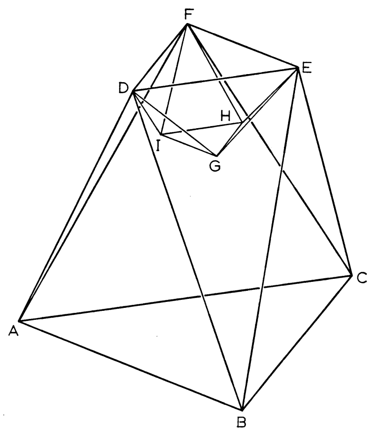

Figure 3: Three-triangle tower.

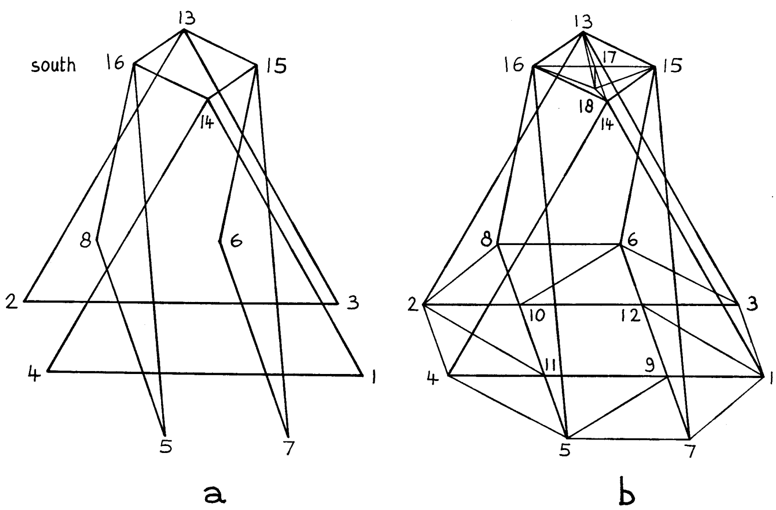

Figure 2: Tower construction with large base and small platform; *a.*principle of the construction; *b.*the complete framework.


Figure 4: Three-triangle tower at the South Pole.

Figure 5: The DOT tower on La Palma.

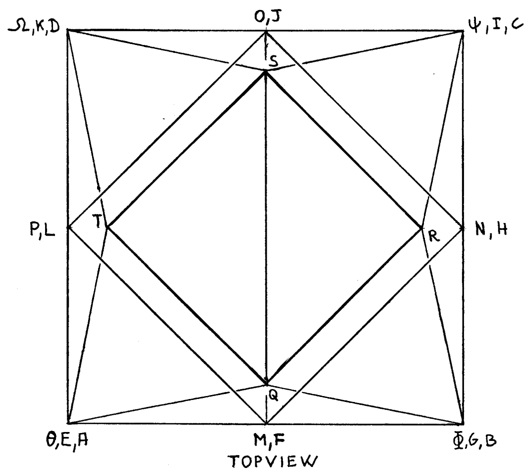

Figure 6: The base of the DOT tower with small perpendicular tubes.

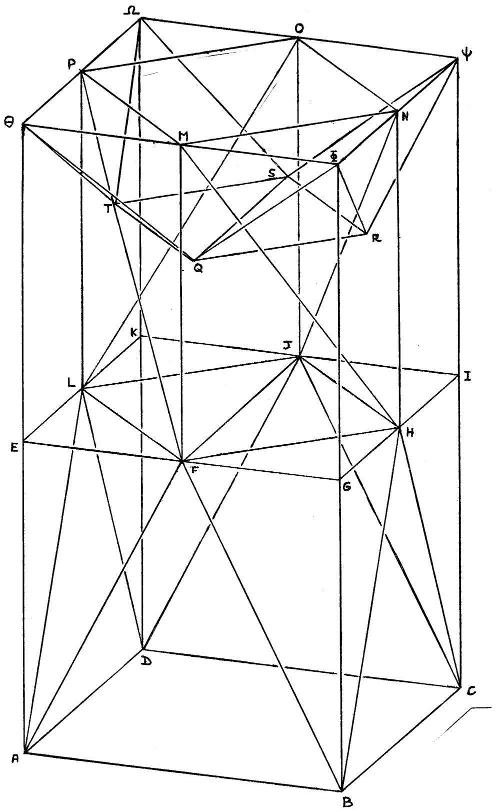

Figure 7: Principle of compensating framework in stories.
A two-story framework. Dimetric Projection (DIN5) and Topview.

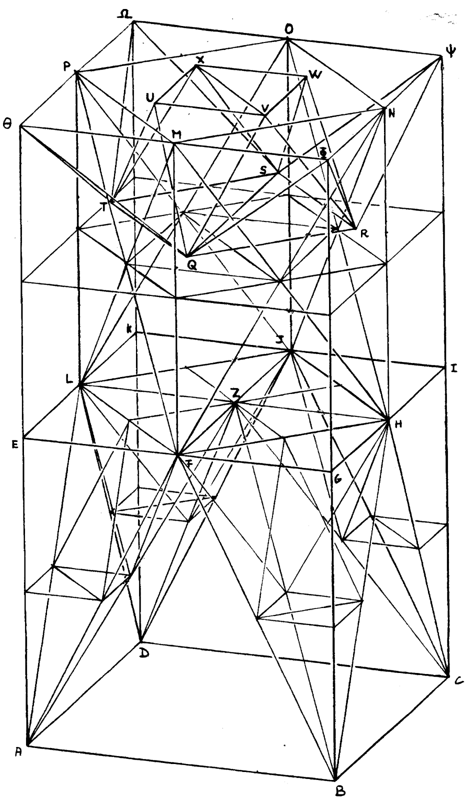

Figure 8: Complete framework of tower in four stories.
Dimetric Projection (DIN5).

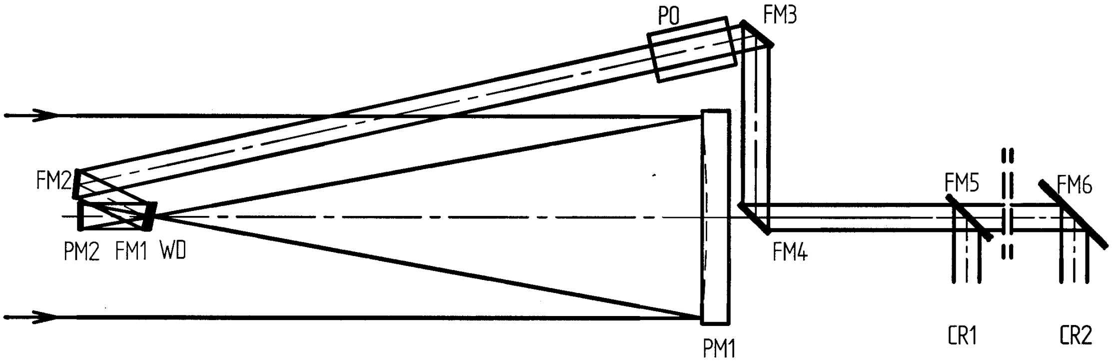

Figure 9: Layout of the LOT optics. PM1 and PM2 = Parabolic Mirror 1 and 2; WD = Water-cooled Diaphragm; FM1 to FM6 = Flat Mirror 1 to 6; PO = Polarization package; CR1 and CR2 = Coudé Room 1 and 2. Drawing is not on scale.

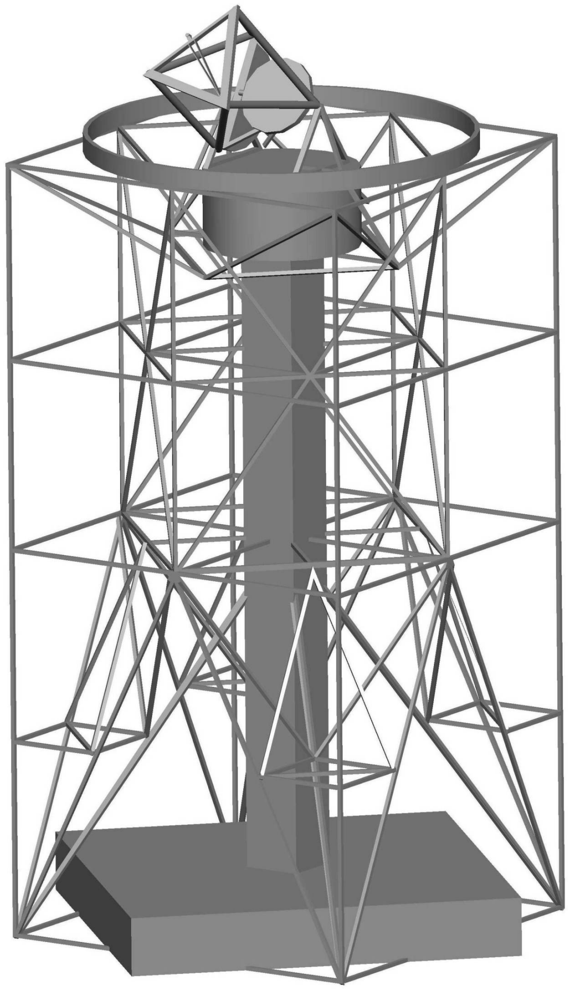

Figure 10: Complete concept of the open tower and telescope.

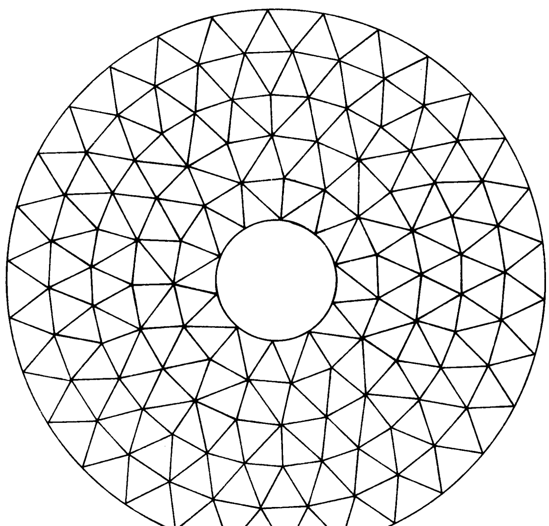

Figure 11: Example of a support structure for secondary optics with spreading of diffraction light in all directions.

Figure 12: The DOT after ice formation by clouds. The cloth is relatively clean from ice.

Figure 13: The open structure of the DOT telescope. To the left the primary mirror, to the right the secondary optics (in the telescope top), which for the DOT includes a multi-channel system.

Figure 14: Total concept on the Observatorio del Roque de los Muchachos.