

Unique design of the Dutch Open Telescope

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Introduction

The Dutch Open Telescope (DOT) is a telescope mainly used for high-resolution solar observations at the Observatorio Roque de los Muchachos (ORM) at a height of 2350m above sea level on the North-West Canary island La Palma, where the seeing can be excellent for high-resolution observations of the sun.

The DOT is of a special construction with open telescope on an also open tower to minimize the local thermal disturbance of the air above and in the telescope, where the primary beam is coming to the primary mirror. This is the basis of the advanced capabilities for large-field high-resolution images, sharp over the whole field during hours for movies showing the dynamic processes on the sun.

The drawings in **Figure 1** show the principle of the open telescope on the top of the open tower. The photos in **Figure 2** show the realized telescope with completely open-foldable dome on the tower.

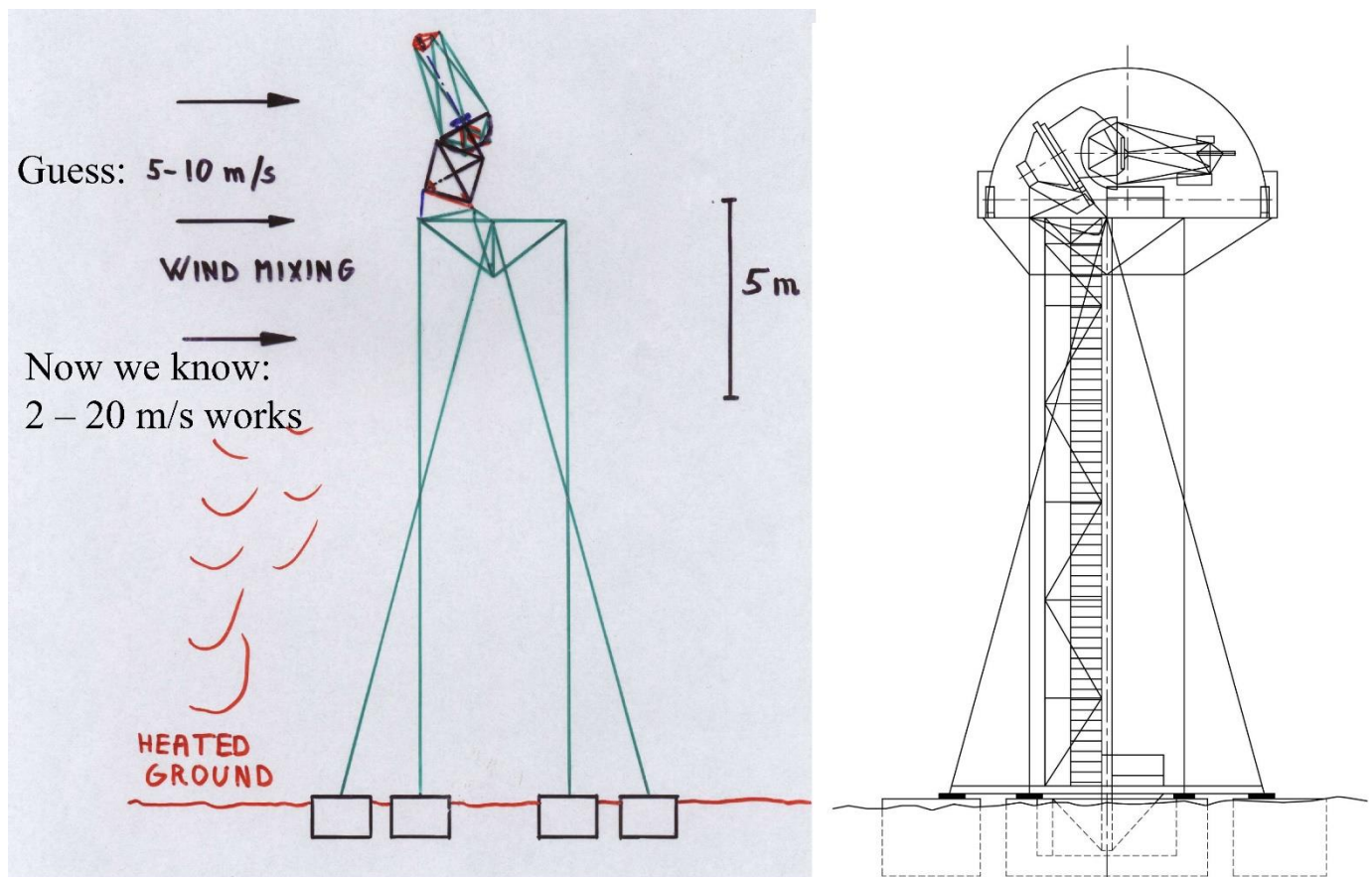


Figure 1. The open tower principle which followed from the site test measurements of Kees Zwaan. **Left:** Conceptual scheme. **Right:** Design scheme with open-foldable dome and telescope in parked position. Measurements with masts up to 30m height showed the mixing effect of wind. Large improvement of the seeing was in the height path from 10 to 15m. So a height of 15m was chosen for the open tower. See further *ref. 1*.

1. The open tower

The challenge was an open frame tower, yet sufficiently stable for accurate pointing stability of 0.1 arc second (0.000 028 degrees, or in radians 0.000 000 48) when observing in the necessary wind up to 20 m/s with always gust behavior, so varying wind force on the tower with telescope.



Figure 2. The DOT on its open steel framework tower with a height of 15m. The **left picture** shows the enclosure open while the DOT is observing. The **right picture** shows the enclosure closed as protection against bad weather. A framework is around the ladder with every 2.5m a platform, where the climbing side changes. Consequently, fall height inside the framework at maximum 2.5m and safe climbing without safety belt.

At first glance it seemed impossible to make a very open steel tower sufficiently stiff. An active stabilization system for the telescope on the tower platform seems logical and has been investigated. The result was that with existing systems you could not get further than 2 arc seconds (0.000 56 degrees). This is sufficient for platform stabilization for radar antennas, for example, but not for high-resolution solar observations. The image acquisition and processing methods, like adaptive optics being an active system in the telescope optics, can in principle compensate for small image movements due to telescope tilts. These image movements provide a kind of magnification of the scintillation. However, the less disruption including fast small image movements, the further you go in achieving better final images. More information about the active systems is in **ref. 2**.

Astronomical objects are far away and consequently a pure translation of the telescope does no harm. Any construction will show a certain deformation under wind load to produce a counter-force. The trick is to choose the geometry of the construction in such a way, that the counter-force to the wind is, as good as possible, generated by a pure translation of the platform relative to the ground. Elements for parallel motion to the ground are:

1. Vertical posts. In both horizontal directions, x and y, the construction is weak, but in the vertical direction z it is stiff. A force on the top point of a vertical post with horizontal component gives a large

deflection in horizontal direction, but the vertical component of the force gives only a very small vertical deflection. Consequently, the motion of the top point is nearly parallel to the ground.

2. Isosceles triangles in a vertical plane. In the plane of the triangle the construction is stiff, both in horizontal and vertical direction. Perpendicular to this plane it is weak, but the motion of the top point is nearly parallel to the ground just as for the case of the vertical posts. The isosceles triangle will carry horizontal wind force on the platform in its plane because of its stiffness in that direction. In a weak direction it has not to carry anything, because the wind load on the platform in that direction will be carried by other parts of the construction which are stiff in that direction. Special to the isosceles triangle is, that the deflection of the top point in its stiff plane under a horizontal load is also horizontal. This holds for the assumption that the material area of the cross section of both legs of the triangle is equal, which is of course the case if both legs are tubes or beams made of the same material. Under a horizontal load one leg gets a pull force and the other leg a push force of equal strength. Consequently, the elongation of one leg and the shortening of the other are equal and a little geometry leads to the conclusion that the deflection of the top point is horizontal.

A combination of enough elements for parallel motion results in a platform, which moves parallel to the ground and which is very stiff against rotations around all horizontal axes. However, the platform needs also to be stiff against rotations around the vertical axis. This last requirement is fulfilled when at least three isosceles triangles are used, which are not all three parallel or nearly parallel. In addition, the top angles of these triangles have to be large enough, the angle depending on the required stiffness. Top angles of 30° , or more, result in a very high stiffness. The **Figures 3 and 4** show how we came to the geometry of the DOT tower.

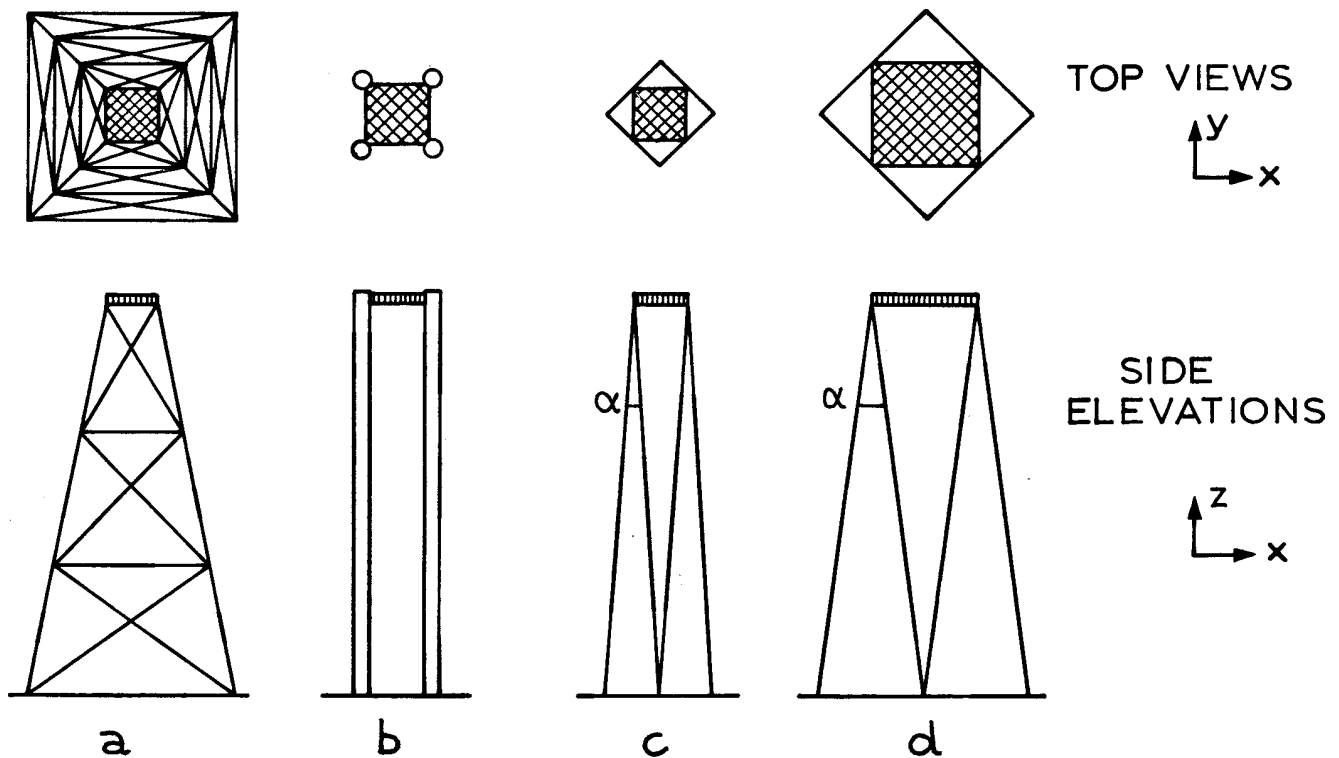


Figure 3. The way to the design of open tower with high tilt stability of the platform in gusty wind:

- a.** Classical framework. 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 should be built in the geometric form of the framework.
- b.** Platform on posts. 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.
- c.** 4-triangle truss with small platform and small base. Small triangle top angles are not stiff enough.
- d.** 4-triangle truss with large base and large platform. Top angles of 30° give enough stiffness, however larger platform then corresponding to the size of the telescope mount.

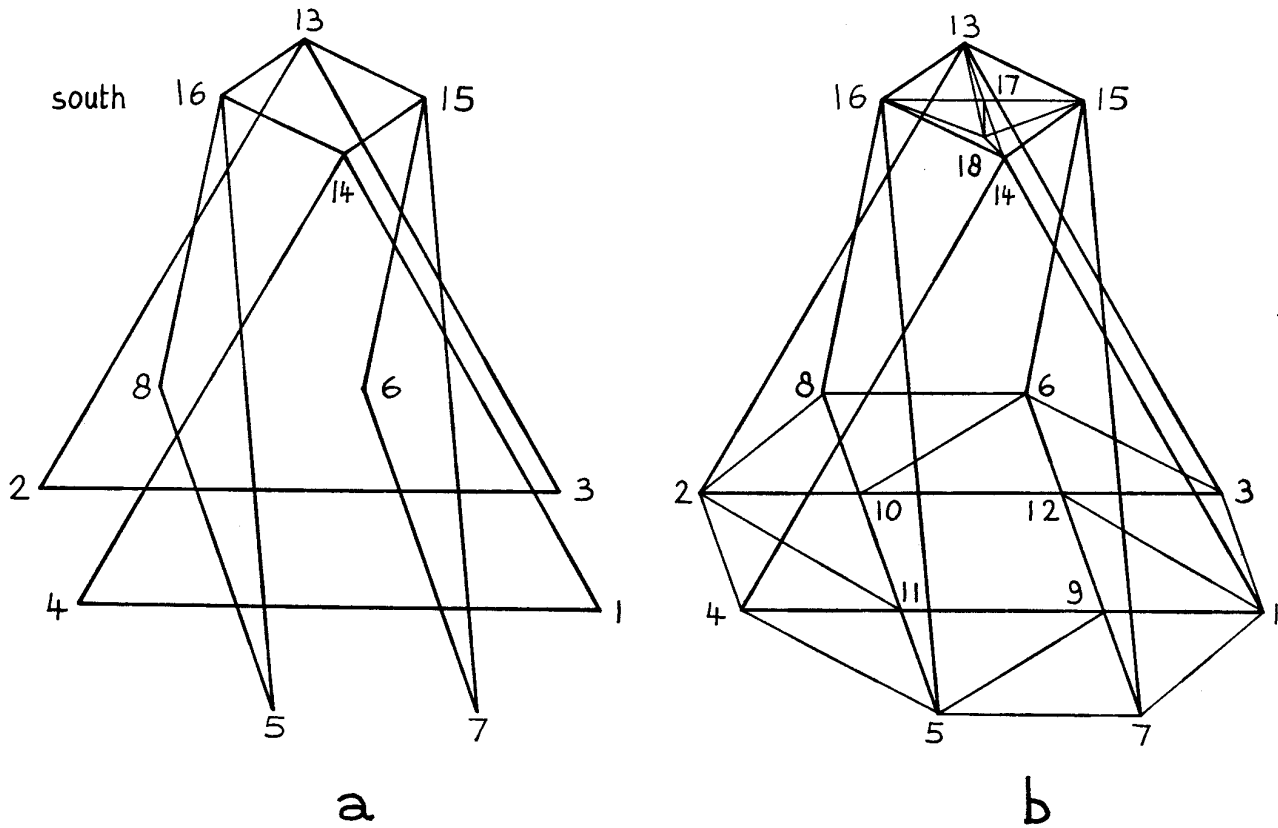


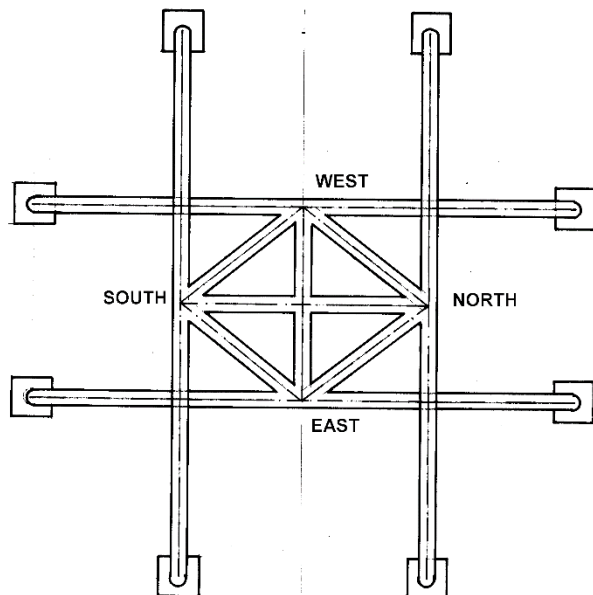
Figure 4. Large top angles combined with smaller platform adapted to the telescope-mount size.
a. Principle of the framework: Platform in the shape of rhombus 13-14-15-16, supported by the four broad based triangles 3-13-2, 1-14-4, 6-15-7 and 8-16-5. Each pair of parallel triangles provides stiffness in one direction and parallel guidance to the platform in the perpendicular direction.
b. The complete framework: The platform is implemented as a pyramidal framework with the apex (top) downward in order to obtain sufficient stiffness. The telescope is to be mounted on the angular points 13-14-16, see the sketches in **Figure 1**.

The dimensions of the DOT tower are shown in **Figure 5** with also the dimensions of the upward tubes and beams used for the other connections.

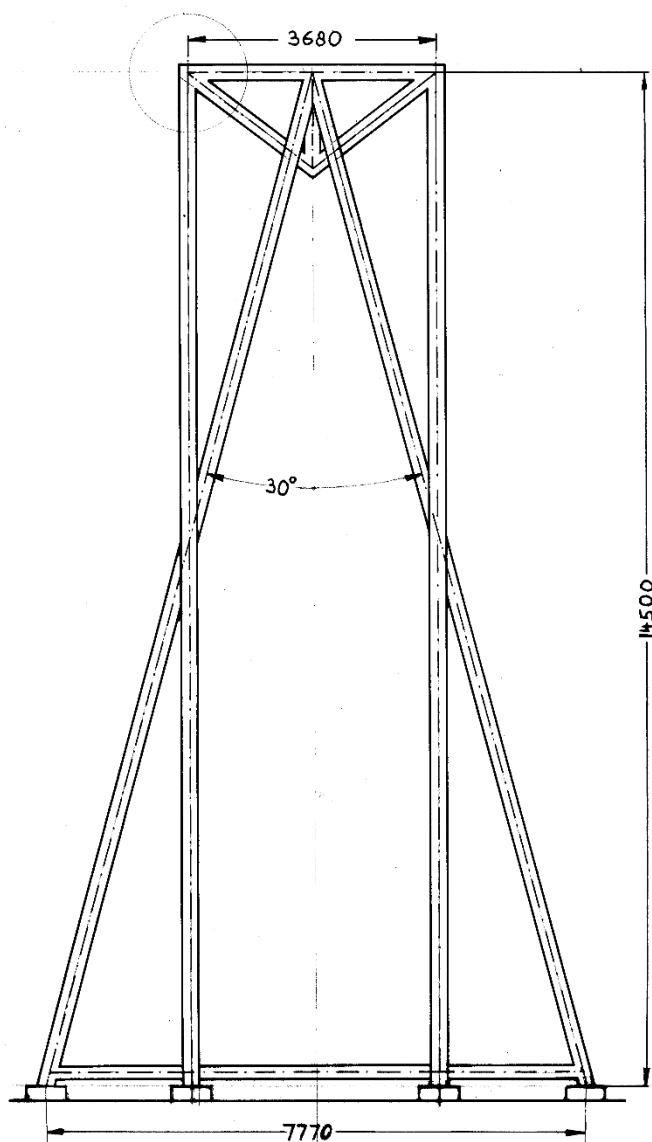
For the stiffness of the overall construction it is very important, that the center lines of the connecting elements, tubes $\varnothing 244.5\text{mm}$ and coupled CNP22 beams, go through a single point in the corner points of the framework. A deviation equal to the diameter of the tube gives already a reduction of the stiffness with a factor 2. The construction of corner points with center lines through a single point gives more work but is very well possible. The sketch on the left side of **Figure 6** shows the basic equations and illustrates it for a welded connection. The same holds for screwed connections: there are good solutions but they are laborious. However, it gives you important advantages: high stiffness and strength combined with low weight. In addition, the surface exposed to the wind becomes small, hence smaller wind forces and better seeing. The photos on the right side of **Figure 6** show how we realized it for the tops of the vertical triangles of the DOT tower. Test assembly on the field of the radio telescope in Westerbork is shown in **Figure 7**.

Joints in the corner points have to be as stiff as possible without hinging. There are 2 reasons for fixed ends of the tubes: higher resonance frequency of transverse vibrations and less shortening of the tubes by transverse deflection of the tubes. Formulas for calculation of the resonance frequency are in the upper part of **Table 1** with the results for the long upward tubes of the DOT tower.

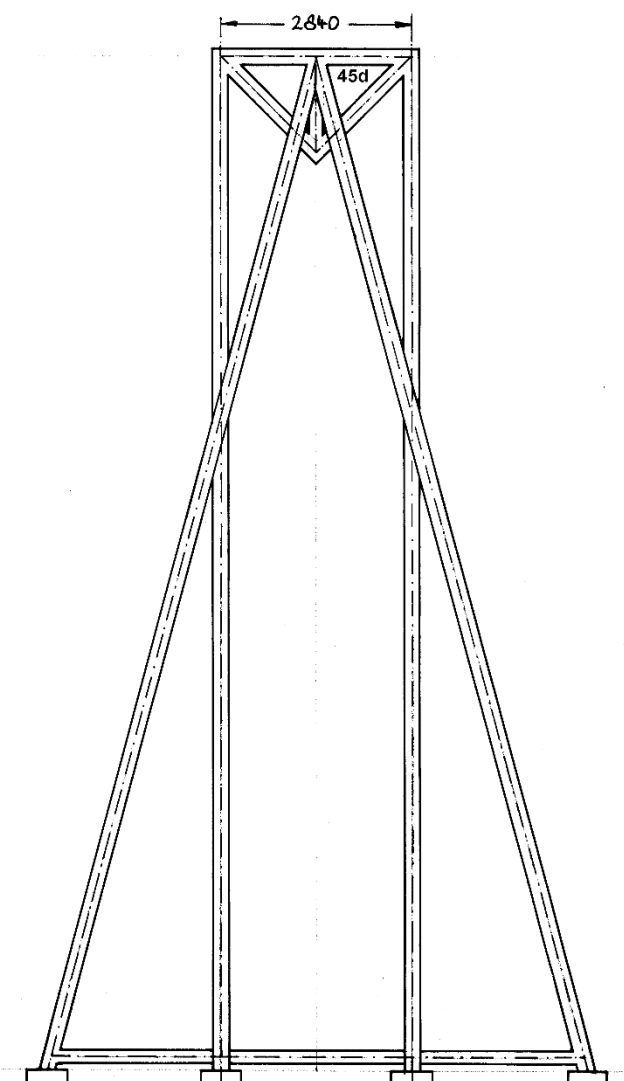
The resonance frequency of the long upward tubes could be measured with an interferometer setup on the tower. **Figure 8** shows the measuring results and **Figure 9** the interferometer setup. **Figure 10** shows a first interferometer laboratory setup with the basic explanation of the optical and electronic system for measuring dynamic shifts of the interference fringes.



TOPVIEW



EASTVIEW



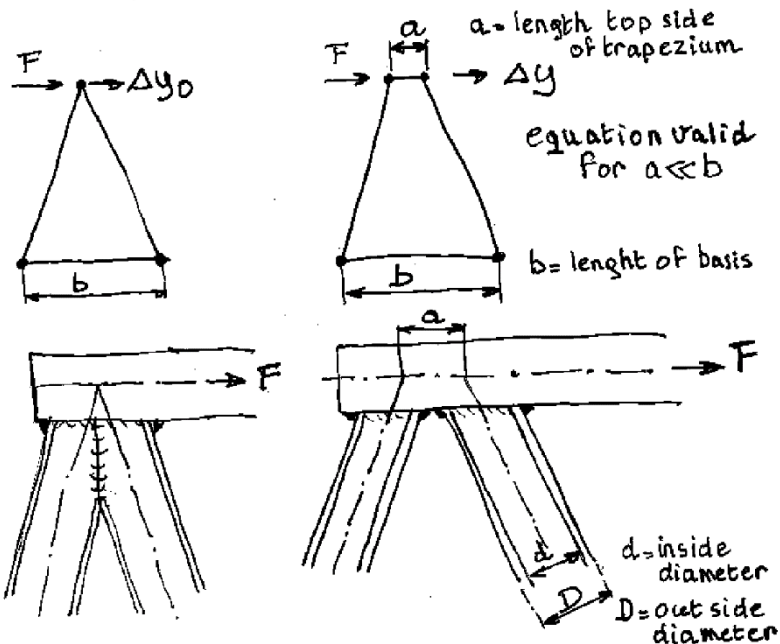
NORTHVIEW

Figure 5. Dimensions of the DOT tower. Dimensions in mm. The upward connections are round steel tubes, outside diameter 244.5mm, wall thickness 10mm. The other connections consist of 2 coupled beams of the type CNP22, 220mm high. More in formation in **ref. 2a DOTtowerInfo**.

$$\Delta y = \Delta y_0 \left\{ 1 + q \left[\frac{a^2}{D^2 + d^2} \right] \right\}$$

Δy = translation of "triangle" top

Δy_0 = translation of real triangle
if load effects the mathematical cornerpoint.



q = numerical coefficient ≈ 2

$d \approx D$
thin wall
tube

$a \approx D \Rightarrow \Delta y \approx 2 \Delta y_0$

$a \approx 2D \Rightarrow \Delta y \approx 5 \Delta y_0$

practise
often for
easy
welding or
screwing.

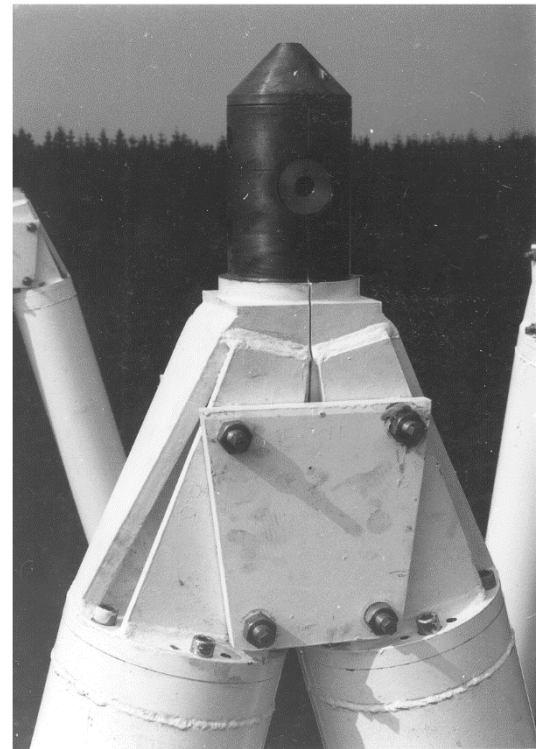
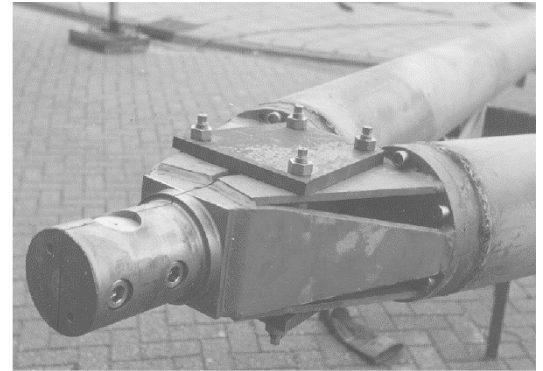


Figure 6. For the stiffness of the overall construction, it is very important, that in all the corner points, the center lines of the connecting elements go through a single point, the mathematical corner point. A deviation equal to the diameter of the tube gives already a reduction of the stiffness with a factor 2, see the **sketches, left** center lines through single point, **right** with distance a equal to the tube diameter D . The construction of corner points with the center lines through a single point gives more work but is very well possible. The sketches illustrate it for a welded connection. The same holds for screwed connections: there are good solutions but they are laborious. However, it gives you important advantages: high stiffness and strength combined with low weight. In addition, the surface exposed to the wind becomes small, hence smaller wind forces and better seeing.

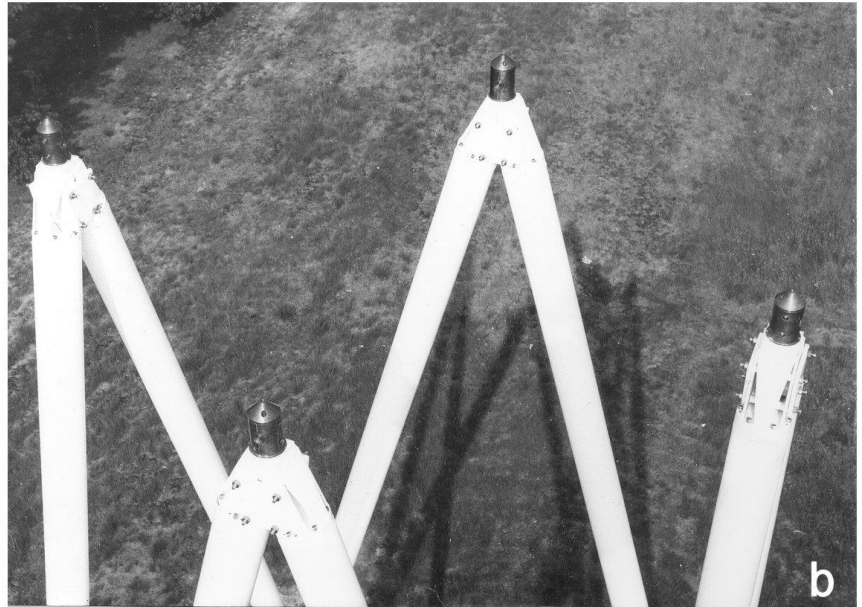
The **photos on the right side** show how we realized the top corner points for the DOT tower.

Top photo: Fabrication in the workshop of the Technical University in Delft.

Bottom photo: Test assembly on the field of the radio telescope in Westerbork. The platform corner points fit over the cylindrical shaped tops, see next **Figure 7**.

The cylindrical top of a triangle consists of one half of each leg. The two halves are stiff connected with 2 high tensioned M24 bolts and in addition somewhat lower 2 connection plates from both sides with $\varnothing 20$ mm pins of high strength material. Consequently, the joints of the triangle tops are also stiff and transport moments. More in formation in **ref. 2a DOTtowerInfo**.

The formulas for triangle construction setup were confirmed by a laboratory construction with an interferometer setup. **Figure 10** shows this construction setup with the basic explanation of the optical and electronic system for measuring the dynamic shifts of the interference fringes.



Test assembly of the inner platform
on the 4 triangles in Westerbork
a. 4 triangles assembled
b. the tops of the triangles
c. the inner platform is hoisted to the
triangle tops

Figure 7. Test assembly of the inner platform on the 4 triangle tops. It was at the site of the Radio Telescope of Westerbork in the Netherlands. Cone-shaped end pieces are mounted on the tops of the triangles. Such a cone top is in detail visible in **Figure 6** on the photo in the right bottom. These cone tops make it easier for the clamp holes in the platform to find the triangle tops. This inner platform is a stiff framework in the shape of a 4-sided pyramid with its top down. The connecting elements consist also of double CNP22 beams. All the corner points are stiff with transfer of moments, because the center lines of the connecting elements go through single point in each corner.

The connections of the inner platform to the tops of the 4 triangles consist of clamps around the cylindrical tops of the triangles. Each clamp has 2 high tensional M24 bolts of quality 12.9, which means tensile strength 1200 N/mm^2 , elastic limit $0.9 \times 1200 = 1080 \text{ N/mm}^2$.

Resonance frequency of transverse vibrations of a round tube

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

v_m = mechanical resonance frequency in Hz

c = constant depending on the connection of the end points

$$c = \pi^2 = 9.87 \text{ for both ends pin-connected}$$

$$c = (5/4 \pi - 0.00039)^2 = 15.42 \text{ for one end pin-connected, one end fixed}$$

$$c = (3/2 \pi + 0.01765)^2 = 22.37 \text{ for both ends fixed}$$

E = modulus of elasticity for tension of the material; for steel $E = 2 \times 10^{11}$ Newton/m²

ρ = density of the material; for steel $\rho = 7.85 \times 10^3$ kg/m³

D = outside tube diameter in meter, DOT tower $D=0.2445$ m

d = inside tube diameter in meter, DOT tower $d=0.2245$ m

l = length of the free tube part in meter, DOT tower $l=15.011$ m ($14.5/\cos 15^\circ$)

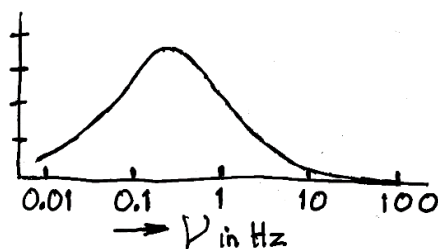
Calculated resonance frequency for the DOT tower

$v_m = 2.92$ both ends pin connected

$v_m = 4.57$ one end pin-connected, one end fixed

$v_m = 6.63$ for both ends fixed, $v_m = 6.5$ for calculation with weight of rings 2.34m from foot plate

$v_m = 5.8$ measured value, see **Figure 8**, slightly lower than the calculated value for both ends fixed, because the CNP22 beams of the platform have some bending flexibility. The interferometer setup on the tower to measure the resonance frequency is shown in **Figure 9**.



Power spectrum
of wind gust

Wind Gusts

The power spectrum of wind gusts decreases rapidly from 1 to 10 Hz, see the image on the left side.

Due to the wind gust behavior, it is advisable to have the resonance frequency not much lower than 5.8 Hz.

Slender Tubes Advantage

Less slender tubes with larger diameter would give higher resonance frequency. The slender shape of the tubes $l/D = 15.011/0.2445 = 61.4$ has the advantage of a high transparency of the tower to the wind without upward flow of the warmer air near the ground towards the telescope. This benefits sharp telescope images of the sun.

Vortex Oscillations

If the frequency of the vortex oscillations, see **ref. 3 section 5.3.1. Vortex oscillations**, which produce the so-called Von Kármán trails of eddies, see **ref. 4 section 82 The Kármán Trail**, becomes equal to the mechanical resonance frequency, then the relatively small force of the vortex oscillations can excite vibrations.

Frequency of vortex oscillations:

$$v_v = s v/D$$

v_v = vortex frequency in Hz

s = Strouhal number, about 0.2 for round tubes

v = wind velocity in m/s

D = outside tube diameter in meter, DOT tower $D=0.2445$ m

The calculated wind velocity for vortex oscillations of 5.8 Hz around the DOT upward tubes is $v = 7.1$ m/sec. We have seen such a vibration one time on half tower height from the ladder, being near a tube, during the DOT construction on La Palma before we had mounted the dampers.

Vibrations are reliably prevented with dampers between the tubes, see **Figure 11**.

Table 1. Some practical formula for the calculation of vibration frequencies of round tubes, with the results for the slender upward tubes of the DOT tower.

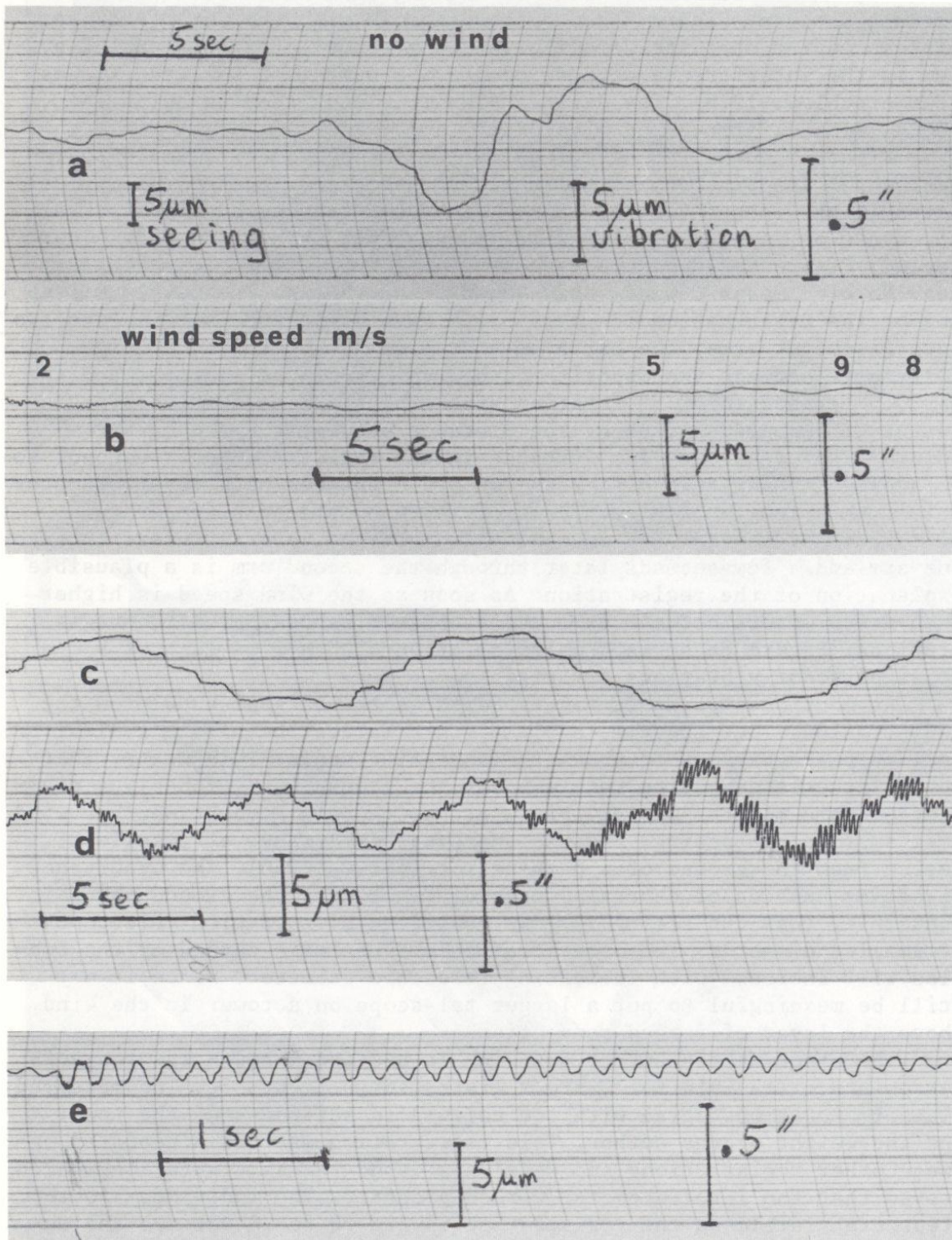


Figure 8. Measuring results with the interferometer on the test-assembled DOT tower at the site of the Radio Telescope of Westerbork in the Netherlands shown in **Figure 9**.

The bar of $5\mu\text{m}$ seeing indicates $5\mu\text{m}$ path difference between the two interferometer arms.

The bar $5\mu\text{m}$ vibration stands for $5\mu\text{m}$ height change between the two opposite platform corner points with reflecting mirrors, see **Figure 9**.

The bar of $.5''$ indicates the effect of $.5''$ tilt change of platform, height change divided by the distance of the corner points.

a. Without wind and shining sun the warmer air near the ground comes upward and produces seeing bubbles. A bubble of some meters and a few degrees explains this bubble.

b. The seeing bubbles disappear with wind of 2m/s or more. A wind gust of 9m/s gives no vibration and tilt change less than $0.1''$.

c. Walking across platform. **d.** Stamping over the platform. Weight of person + clothes is 75kg .

e. Slap on upward tube with rubber hammer. Registration shows vibration frequency of 5.8Hz .

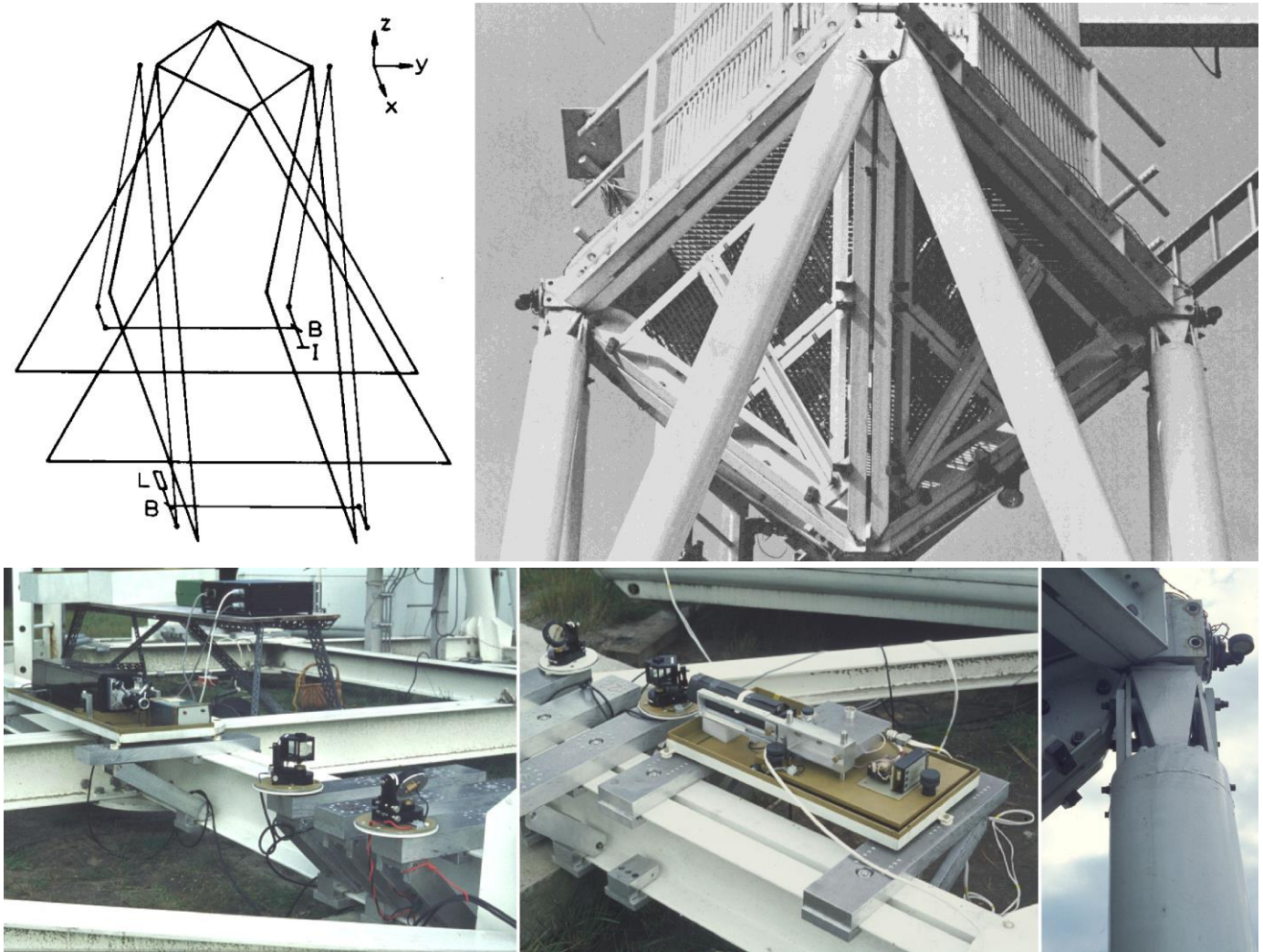


Figure 9. Top Left: Scheme of the interferometer for measuring the rotations of the tower platform around the horizontal x axis. The tower construction is indicated with the principal framework of **Figure 4a**. The light beams of the interferometer are drawn with a bit thinner lines. The symbol L indicates a laser, B a beam splitter, I the interference pattern and the dots on the corners indicate deflection mirrors. The laser beam is split into two beams, which are reflected to two opposite corner points of the platform. The beams go from the corner points to a second beam splitter, which combines the two beams. Behind the second beam splitter, an interference pattern of fringes is formed. A change Δ of the path difference between the two beams causes a shift of the interference pattern over Δ/λ fringes, where λ is the wavelength of the laser light. The interferometer has nearly equal paths in the two arms. Therefore, a low-cost HeNe laser, light wavelength 632.8 nm, with some longitudinal modes could be used. A rotation of the platform about the horizontal x axis changes the path difference. Rotations about the y and z axis and all translations of the platform do not change the path difference. The interferometer measures only the x component of the rotations.

Bottom Left: Photo of the laser with beam expander, the first beam splitter and the back of the mirror, which reflects the light upward to the mirror on the left side corner point of the platform.

Top Right: Platform photo with the two beam reflecting mirrors on two opposite corner points.

Bottom Right: Right side corner point of platform with mirror. Details visible by enlarging image.

Bottom Center: The photo shows the mirror, which reflects the light from the right side top mirror to the second beam splitter, where the two beams are combined to an interference pattern. The light goes through a tube of black paper to the optical and electronic system with three photocells for measuring the shift of the interference fringes. The fringes are also visible through an eye piece, which is visible on the horizontal top plate of the system. This system was tested in a first interferometer setup, which confirmed the formulas in **Figure 6** for construction stiffness. This first interferometer setup is shown in **Figure 10** with basic explanation of the optical and electronic system for measuring dynamic shifts of interference fringes. **Ref.5 and 6** give more information.

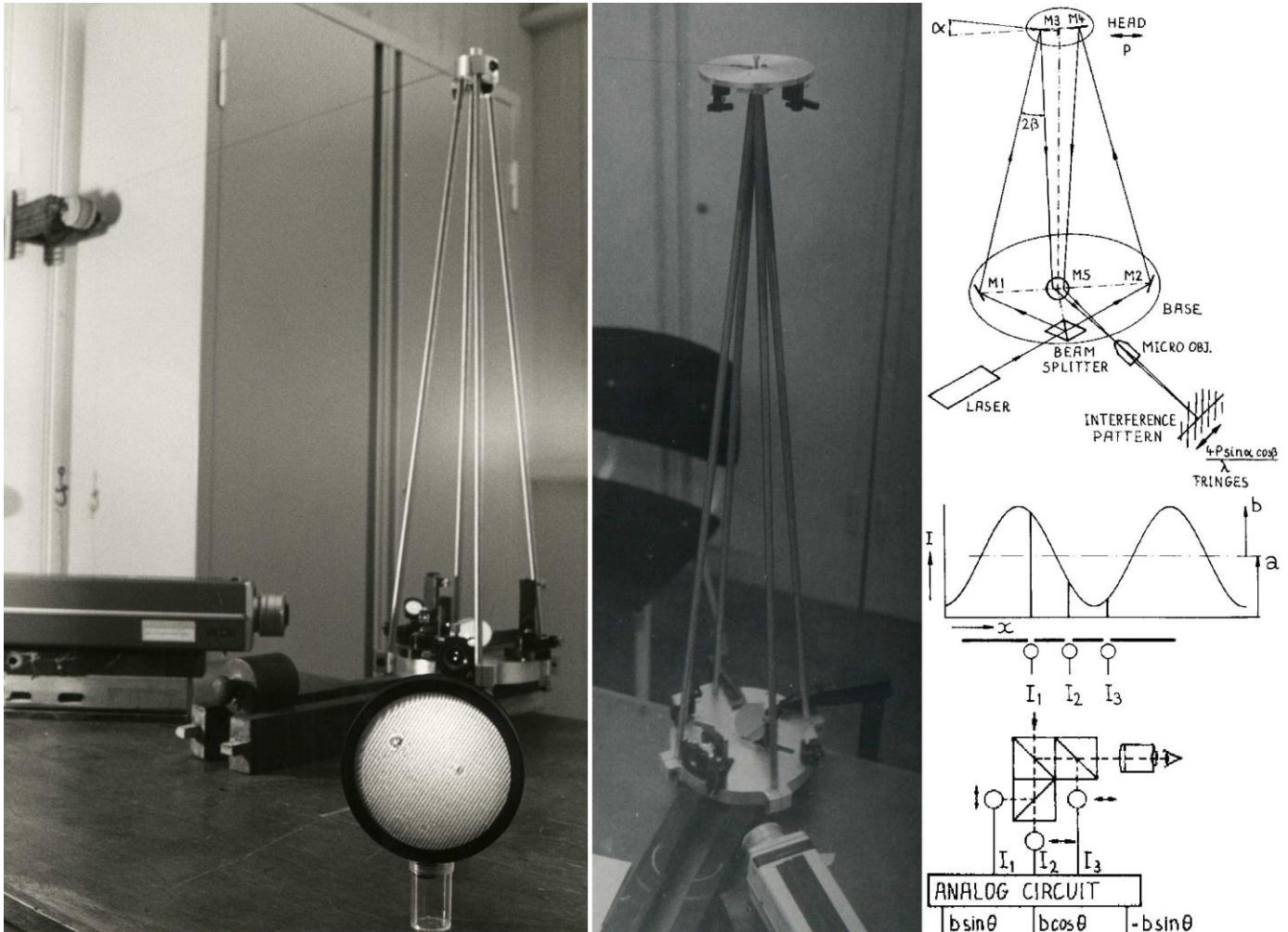


Figure 10. First interferometer laboratory setup, which demonstrated for the construction stiffness, the essence of real triangles with the center lines of the connecting elements through a single point in the triangle corner points, see **Figure 6**. This setup was used for the development of the opto-electronic system for measuring fast shifts of the interference fringes, see **Figure 8 and 9**.

Right top: Optical scheme of the interferometer on a pyramidal construction. Horizontal translation of the top with mirrors M3 and M4 in the line from M3 to M4 causes a path difference between the two interferometer arms and consequently a shift of the interference fringes.

Left: The interferometer on the model of the pyramidal construction of 4 upward rods with on top an uncomplicated connection with the rods ending next to each other in a thick top plate. Left the HeNe Laser ($\lambda = 632.8\text{nm}$). Right the pyramidal construction with on the base plate the beam splitter, the mirrors M1, M2, M5 and the micro objective. The mirrors M3 and M4 are attached to the underside of the top plate. In front, the interference fringes are visible on a ground glass. The top is loaded by a cord, which goes down over a wheel on the left side and ends in a hook for attaching of weights. The loading can be gradually increased by putting the weight on a scale, which is slowly lowered with a lifting table. The interferometer is only sensitive to deformations within the pyramid construction, which contains all parts of the interferometer. Displacement of the top of $1\mu\text{m}$ relative to the base plate causes a shift of the fringes over 0.6 line distance. The measurements showed that this construction was 6 times less stiff than expected for a pure triangle construction, as **Figure 6** shows.

Mid: The pyramidal construction was changed to a construction with the center lines of the 4 upward rods ending in single point. Such a construction is more complicate, as is shown in **Figure 6**. The measurements with the interferometer showed that this construction is indeed 6 times stiffer in agreement with the equations in **Figure 6**.

Right center: The shift of the interference lines is detected with 3 photocells.

Right bottom: The optical system for the 3 photocells, consisting of 3 beam splitters, giving 4 beams with an eyepiece in the 4th beam. The place of the photocells can be adjusted to the direction and distance of the interference lines. This system is visible in **Figure 9** bottom center. See further **ref. 6**.

Air flowing against a wing of an airplane produces on the underside eddies. Over the upper side, the air flows over the wing surface without eddies and sucks the wing upward. Wind air flowing against a round tube produces eddies alternately from one side to the other side of the tube with an alternately changing suck force on the tube. The frequency of the changes depends on the diameter of the tube and the wind speed. These changes of the eddies are called vortex oscillations.

The long upward tubes of the tower can start vibrating, if the frequency of the vortex oscillations becomes equal to the resonance frequency for transverse vibrations of the tubes. The upper part of **Table 1** shows the formula for calculating the resonance frequency for transverse vibrations of the tubes. The lower part of **Table 1** shows the formula for calculating the vortex oscillations frequency and the results of the calculations for the long slender upward tubes of the DOT tower.

The tube can vibrate with 5.8 Hz when the wind velocity is 7.1 m/sec. The suck force is much smaller than the pressing force of storm. Hence, these vibrations are not a threat to the construction, but are not desired in connection with the necessary tilt stability of the tower platform with telescope during the observations.

Reliable prevention of vibrations of the upward tubes is realized by rubber dampers between the tubes, where two tubes pass each other closely at about half the height of the tower. With equal resonance frequency of the two tubes, transverse vibrations of the two tubes with damper together are still possible. The solution is changing the resonance frequency of one of the two upward tubes somewhat. Then, the two tubes cannot vibrate without deforming the damper.

Small tubes perpendicular to the four upward tubes of the two North-South triangles are added at a distance of 2.34 meter from the ground plates. The lateral resonance frequency of these upward tubes increases from about 6 to 7 Hz. The 90° angle between additional tube and upward tube is essential, because then the additional tube does not take over a part of the force along the upward tube. The bending force of the additional perpendicular tubes in order to follow the longitudinal elongation or compression of the large upward tubes is neglectable. So, the additional tubes do not disturb the principle for parallel platform motion, which serves the tilt stability under wind load.

The dampers are shown in the upper part of **Figure 11**. The lower part of **Figure 11** shows the construction of the additional small tubes perpendicular to the large upward tubes. Detailed information about the damper construction with the flexible rubber plates is in **Figure 11a**.

The tower platform consists of two parts. The inner part, **Figures 4 and 7**, supports the telescope and needs the extreme tilt stability. An outer part platform is around the inner part. This part carries the completely open-foldable dome for protection of the parked telescope against bad weather.

A drawing of the outer platform around the inner platform with the completely open-foldable dome is in **Figure 12** with the closed and open situation of the dome with dimensions included.

The dome on the outer platform is completely open during observations and the remaining surface of the open dome is nearby the platform floor. Hence, the moments from the outer platform to the inner platform because of wind are only small during observations. Consequently, the completely open dome and outer platform do not disturb the extreme tilt stability of the telescope on the inner platform during observations.

We did not choose the option with large platform as indicated in **Figure 3d** because of the following three reasons:

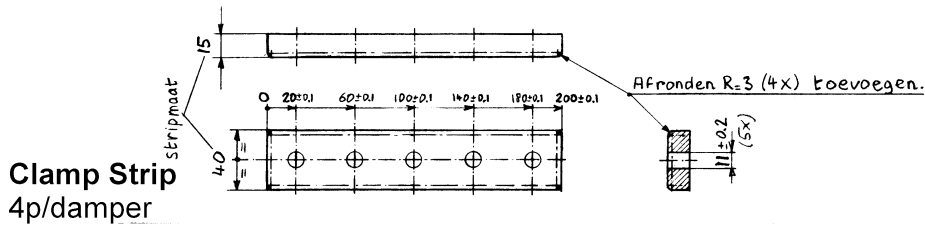
1. A large platform must be of very stiff construction to bring the wind forces on the telescope construction to the outside four support points on the four upward triangles without tilt of the telescope. The platform becomes a massive construction, less transparent to wind and very heavy.
2. The upward tubes are very slender for very high transparency of the tower for the wind. With the triangles shifted towards each other, it is possible to place effective dampers between the upward tubes at half height of the tower as is shown and described in **Figure 11**. With a large heavy platform on triangles at the outside, it would be difficult to place dampers in such an easy way.
3. The bases of the perpendicular upward triangles end together on the same four places. The ground under the bases has to be very stiff to keep the principle of parallel motion of the platform.

When the ground under the base foots of the tower truss in **Figure 3d** deforms somewhat under load, then parallel motion of the platform without tilt under wind force is disturbed. Explanation: A wind force on the platform parallel to two of the four triangles is carried by these triangles with downward force on the triangle foots on the side where the wind goes to and upward force on the side where the wind comes from. The downward and upward forces are equal for an isosceles triangle. The downward and upward shifts of the foots are equal if the ground under the foots is of the same structure. Then the tops of the two triangles taking the horizontal force will remain horizontal. However, both foots of one perpendicular triangle will go upward and both foots of the other perpendicular triangle will go downward. Consequently, the platform will get a tilt in the direction of the wind. For perpendicular wind-force direction, the function of the triangles is interchanged with a tilt in the perpendicular direction. For wind direction in between, the wind force can be decomposed into two forces perpendicular to each other. These two perpendicular forces cause two perpendicular tilts of the platform. Together, the two tilts cause a tilt in the direction of the wind, because the tower structure is a linear system in the dependence between wind force and tilt. The ground under the DOT location is loose lava sand that deforms somewhat downward under load. The tower design in **Figure 4** has separated foot places for the perpendicular upward triangles. The principle of moving horizontal under horizontal force on an isosceles triangle top remains, when the upward and downward ground deflection of the two foot places is equal. In the tower design of **Figure 4**, the foots of the perpendicular upward triangles are apart from the foots of the triangles, which carry the wind force. Under each pair of foot places of parallel triangles is a concrete block. So, four concrete blocks, which are under the foot places with the numbers in **Figure 4**: 1 and 3; 2 and 4 for the upward triangles in North-South direction 5 and 7; 6 and 8 for the upward triangles in East-West direction. The top surfaces of the four concrete blocks are visible on the photo at the bottom of **Figure 11**. Backside is North, frontside is South, right side is East and left side West. The four blocks do not influence each other if they lower slightly or rise slightly, when the load changes. The parallel shift of the platform is maintained even with some deformation of the ground under the loads of the feet.

The blocks are 2-m deep and are of 25 cubic meter concrete each, necessary because of the possible extreme storms, with closed dome, giving large forces to the tower top and from there to the tower foots. The concrete blocks are in loose lava sand. So, the weight of the blocks prevents fall over of the tower in extreme storms. During the design of the tower, we asked advice of a colleague engineer in the USA about the wind velocities of storms, which can be expected on islands in the ocean. As result, the design was based on a wind velocity of 70m/s (252 km/hour) with in addition a safety factor for the forces of 1.4. During the construction of the tower and telescope in the Netherlands, there was some criticism that we were exaggerating the solidity of the construction. Later with the DOT in operation on the La Palma observatory, storm Delta passed the Canary Islands in the night of 28 to 29 November 2005. Maximum measured wind velocity was 245 km/hour (68 m/s). The DOT survived this storm without any problems, whereas other telescope installations at the observatory had damages. So, it was wise to make the construction with this storm stability. In the lava sand are inclined basalt plates of very irregular shape not suitable for support of the tower foundation. On the contrary, it was a huge amount of work to break away the basalt slabs with a large special machine before the concrete blocks could be made. The work with this machine took 10 full working days.



Figure 11. Vibrations caused by wind, known as Vortex Oscillations and explained in **Table 1**, are reliably prevented with dampers between the tubes. **Figure 2** left side shows, that, for all tubes, two tubes pass closely to each other at half tower height. There, dampers are placed between the tubes. **Top left:** The dampers seen from the base of the tower. The damper on the right is near the ladder. **Top right:** Damper in close up seen from the ladder. Two flexible rubber plates connect the tubes. The drawing in **Figure 11a** shows the parts of the damper construction with dimensions. **Bottom:** From each pair of tubes with damper in between, the free length of one tube is shortened with additional small tubes perpendicular to the upward tube at a height of 2.34m, bringing the resonance frequency from 5.8Hz (see **Figure 8**) to about 7 Hz. Consequently, the two upward tubes with damper in between can not vibrate together, giving reliable prevention of vibrations. The small perpendicular tubes do not disturb the compensation principle for parallel motion of the platform.

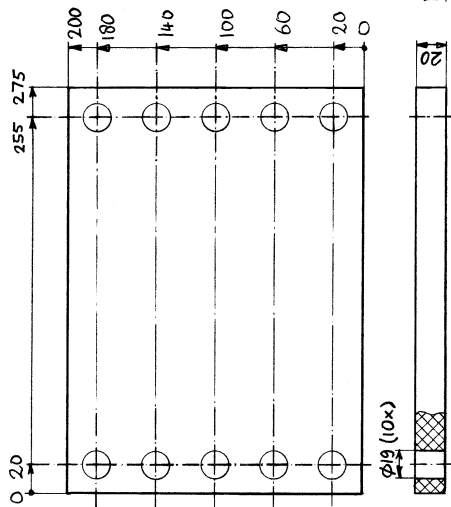


Clamp Strip
4p/damper

Pos 354 Klemstrip voor rubber platen. Aantal: 16 Mat.: Al 50 ST strip 40x15
Toevoeging van afrondingen R=3
Schaal 1:2.5

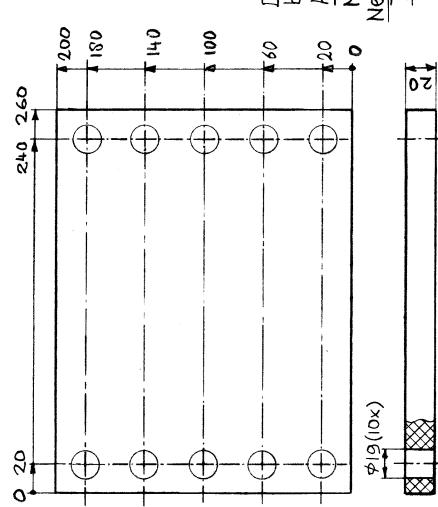
Rubber Plate
Longer
lower side

Pos 353 A
Dempingsplaat
onderzijde van klem
Aantal: 4
Materiaal:
Neoprene rubber
70° Shore A



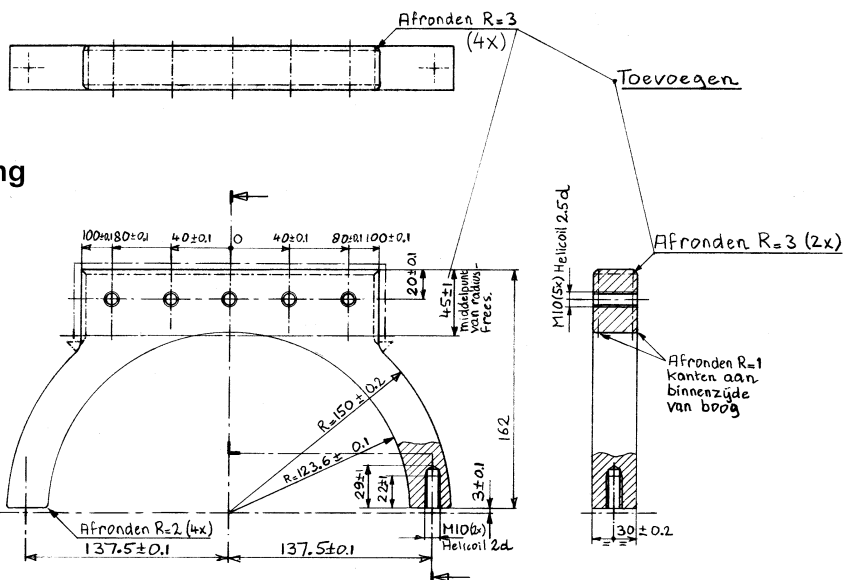
Rubber Plate
Shorter
Upper side

Pos 353 B
Dempingsplaat
bovenzijde van klem
Aantal: 4
Materiaal:
Neoprene rubber
70° Shore A



Spacer ring
20p/damper

Pos 358 Afronding voor dempers
Aantal: 80 Schaal: 1:1
Mat.: Al 51 ST steel #20 Blank werkstuk



Clamp Ring

Pos 352 Klemhelmft met bevestigingsvlakken voor rubber platen. Aantal: 8 Mat.: Al 51 ST
Toevoeging van afrondingen R=3, daarna opnieuw blank anodiseren. Schaal 1:2.5

Damper parts Free length of rubber plate between clamps:
Upper rubber plate 180 mm, Lower rubber plate 195 mm
Distance tube center - free rubber 165 mm

Figure 11a. The parts of the damper construction. A damper consists of two flexible rubber plates clamped to rings around the two nearby upward tubes, see **Figure 11** right top. More information in **ref. 2a DOTtowerInfo**. The black UV stable rubber is painted white with a silicone paint, which does not damage the rubber and remains cool in sunshine.

2. The completely open-foldable dome

Telescope protection is essential against the extreme weather situations, which sometimes can occur at the observatory with much snow and also ice formation, when the observatory is in an supercooled cloud. **Figure 13** shows such an extreme situation. Also, the closed dome has to be stable to the extreme storms like storm Delta as already mentioned in the required stability of the tower foundation on page13, penultimate paragraph.



Figure 13. *Extreme weather situation to which the completely open-foldable is able to protect the telescope. Intense ice growth has taken place during the stay in a supercooled cloud. However practically no ice sticks on the textile membranes, whereas there are huge amounts of ice on all metal parts, like the bows, which are strong enough to withstand the heavy ice load.*

The textile membranes are curved to the inside of the dome from bow to bow, see **Figure 14 and 15**, and curved to the outside going from bow ends to bow ends over the whole dome. Consequently, the textile membranes have a saddle shape at each local point. The curvature inward gives stability against the pressure forces of wind. The curvature to the outside gives stability against the sucking forces of wind, which can go along the surface of the membrane between two bows.

The used textile is based on strong polyester fabric. On both sides is a PVC layer, which facilitates the welding of pieces together with an overlap, the welds, as visible in **Figure 14**. Above the PVC layers, outside top layers of PVDF provide stability to the ultra-violet light of the sun, present on the high locations of telescopes, for the DOT 2350m above sea level. In addition, snow and ice glides downward over the PVDF top layer, no ice formation on the textile, see **Figure 13**. And when no ice and snow, the PVDF layer prevents algae formation on the textile. The textile used for the DOT membranes is of a special fabrication type of the layers, which provides stability against frequent folding and tensioning.

The overall dome structure is visible on **Figure 15** with a photo made during the test assembly of the DOT dome in the workshop at Delft University of Technology. Open-bow support arms on the outside of the in between bows lie on small pillars outside the ground bow, when the dome is open. In this way, the textile of the membranes has no sharp folds, when the dome is open.



Figure 14. The textile membranes seen from the inside of the closed dome. The membranes are curved to the inside of the dome from bow to bow, and curved to the outside going from one dome side with downward bow ends to the other side of the dome with downward bow ends. This two sided curvature in opposite direction is similar to the shape of a saddle, so this membrane shape is called saddle shape. Consequently, the membranes are not flat pieces of textile. If one tries to put a membrane on a flat floor, then the rims are longer than the centerline along the membrane, and hence, the rims lie in waves.

Such a not flat membrane is made by textile strips, which are welded together to reach this special shape. The welds are darker in this image, because less light comes through the double layer of textile of the weld. The welds show clearly the curvature to the inside going from bow to bow.

Each side of the dome consists of three membranes and two in-between bows as shown **Figure 15**.

A top bow is called main bow. This bow is driven by two strong actuators, one at each bow end. The main bow is a strong framework construction, because it has to bring the lifting force of the actuators to the upper membrane. From there the lifting force goes to the lower bows and membranes. Single tube bows are strong enough for the in-between bows bringing the force from membrane to membrane on the both sides of the tube.

The membranes have to be tensioned high enough for storm stability of the closed dome. One of the main bows carries on its top a clamp actuator moving a pin, which engages in a hook fixed to the other main bow. The clamp actuator brings the membranes to the required tension for storm stability. In addition, the clamp actuator provides the force for pressing together the rubber sealing tubes. This rubber is stable against the ultraviolet light of the sun like the membrane textile.



Figure 15. Test assembly of the DOT dome in the workshop of Delft University of Technology.

The dome consists of two halves, each half going from floor of dome upward to the dome top with three membranes and two in-between bows, so from floor to top:

Ground bow very strong connected to the outer platform, see drawing and explanation in **Figure 12**.

Lower membrane from ground bow to lower in-between bow.

Lower in-between bow.

Middle membrane from lower in-between bow to upper in-between bow.

Upper in-between bow.

Upper membrane from upper in-between bow to the top bow.

The dome is partly open, the slit between the two main bows is visible. The in-between bows have enough weight that the middle and upper membrane are still tensioned. This facilitates opening and closing with wind, essential for the sharp high resolution movies, see the explanation in **Figure 17**.

We have observing experiences till wind speed 20m/sec. Above this windspeed, we had never clear sky suitable for observations. Highest wind speed of closing the dome was 25m/sec and there were no problems. The calculations for strength of partly open dome and size of the actuators were based on a windspeed of 30m/sec. The calculations for strength of closed dome were based on a wind speed of 70m/sec like for the tower construction and its foundation as mentioned in the description of the tower structure, page13, penultimate paragraph.

The open-bow support arms on the outside of the in between bows are visible. These small arms have round rubber blocks, which rest on short pillars outside the ground bow, when the dome is open. These pillars were not present, when this photo was made during the test assembly.

Workshop employee Piet Hoogendoorn is on the right side of the dome. He explains the operation of the dome to solar physicist Rob Rutten standing on a ladder, because the dome is on the also test-assembled tower platform, see **Figure 15a**. Piet Hoogendoorn has made many essential contributions to the construction of the DOT. Rob Rutten has continued to support the DOT after the death of Kees Zwaan, who is the founder of the open telescope principle with his site test measurements. Rob Rutten was the initiator of the tomography of the solar atmosphere with the DOT observations, see **section 8**.



Figure 15a. In the workshop of Delft University of Technology the test assembly of the open platform for the DOT with the open foldable dome, closed in the top image and open in the bottom image.

The bows are in a very low position, when the dome is open, as is visible in **Figure 2** on the left, in **Figure 15a** bottom photo and in **Figure 17**. As explained in **Figure 12**, very open is advantageous for only small moments to the tower top by the desired wind during the observation. The downward main bow framework fits inside the in-between bows to reach this very open dome.

The tensioned textile membranes have a damping effect on the steel construction. We have never seen any vibrations of the construction in the sometimes very gusty wind. We made simultaneously measurements of wind and dome bow deformations of the closed dome, see **Figure 16**.

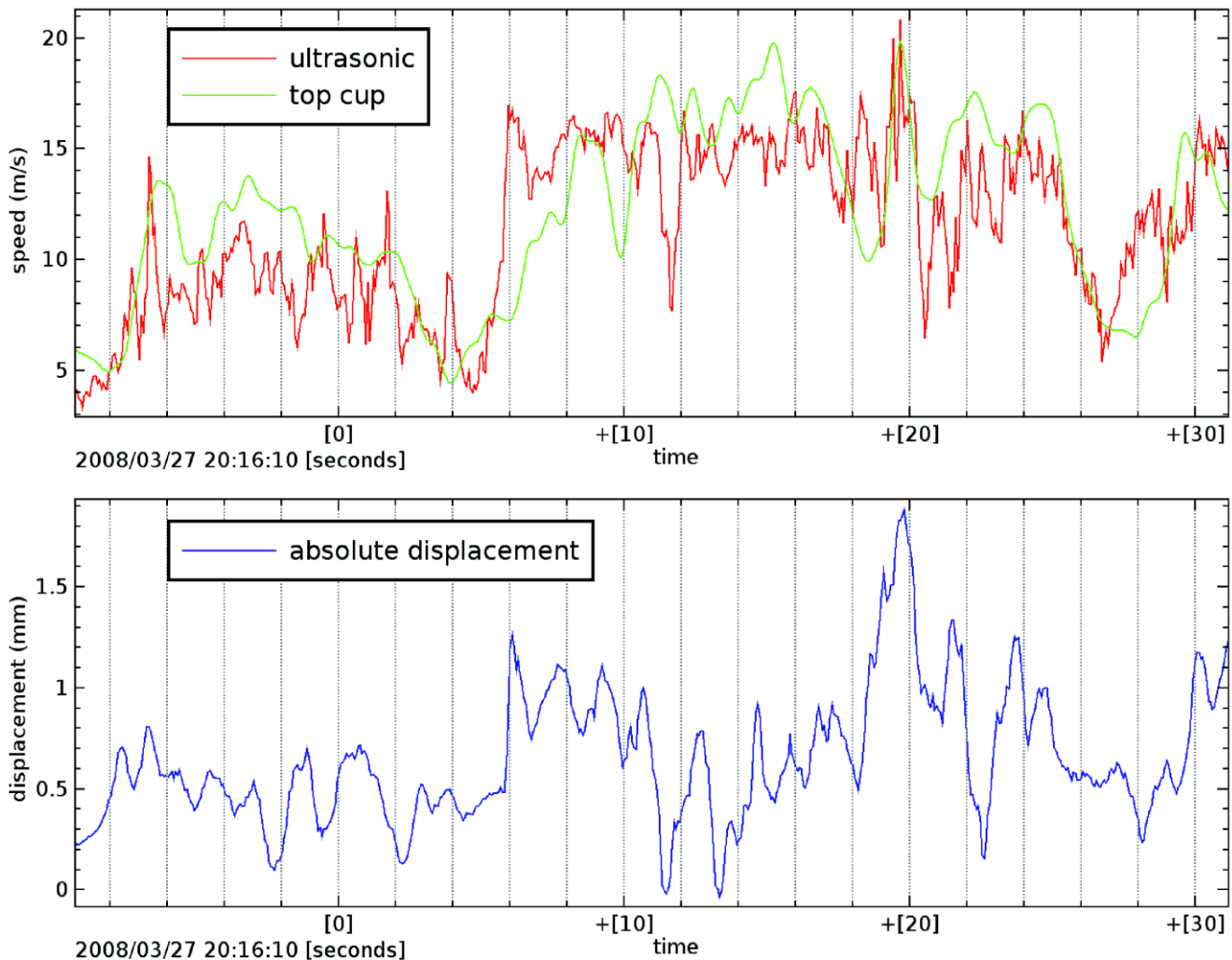


Figure 16. Simultaneous wind and bow-deformation measurements of closed dome.

Top: wind measurements. The ultrasonic anemometer has a much faster response than the cup anemometer. The cup anemometer is on the top bow, the ultrasonic is on a pillar beside the dome.

Bottom: displacement of bow point measured by a 3DD3 unit, special developed optical instrument to measure from the dome floor the deformations of a place on the dome in 3 perpendicular directions, see **ref. 7 and 8** for explanation how these instruments work. The fast wind fluctuations by the ultrasonic anemometer are clearly correlated to equal fast deformations in the bows, which proves that these fast fluctuations are real. Of course, the bow load does not correspond one to one to the wind velocity at the point of the ultrasonic anemometer. The degree of correlation strongly depends on the wind direction. However, the fast gusts are clearly visible in the displacement curve and it is clear that no eigenfrequency vibrations are present in the bows.

We were asked to realize the dome for the GREGOR telescope after successful operation of the DOT dome. The GREGOR dome is somewhat larger, 9m diameter instead of the 7m of the DOT dome. Subsequently we designed a much larger dome of 28m diameter for a planned European Solar Telescope (EST). More information about the properties of the GREGOR dome and the design of the EST dome are in the **ref. 9, 10, 11 and 12**.

3. The open telescope construction

The essential principle for the telescope is: so open that the air in the primary beam cannot take over different temperature from the telescope structure. **Figure 17** explains this principle. With the successful realization of this principle, the DOT is the first solar telescope, which realizes high-resolution images without vacuum for the primary telescope beam.

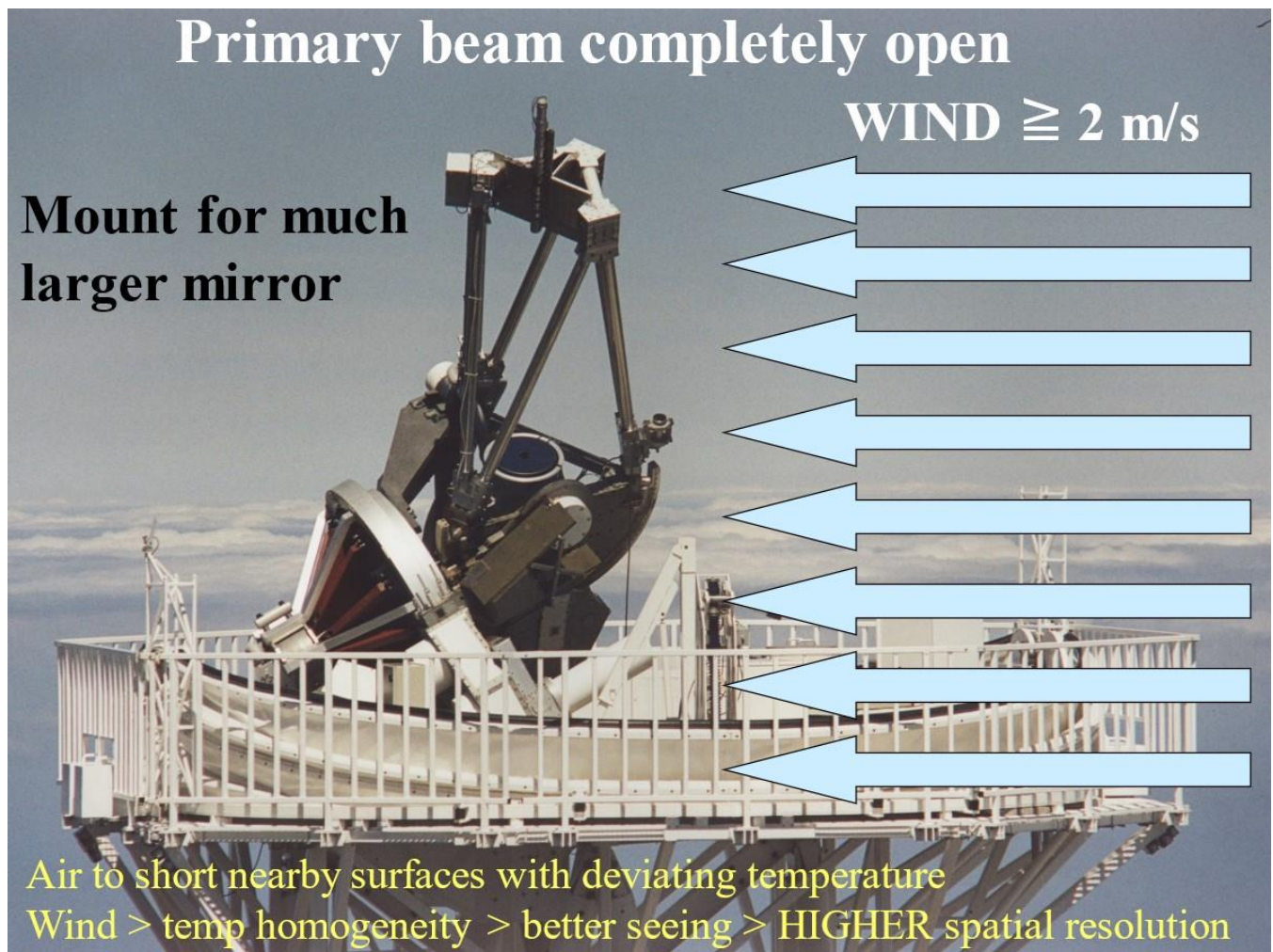


Figure 17. Open telescope principle for sharpest images with explanation how it works.

The index of refraction of air depends on the temperature. Temperature differences of 0.1°C within an imaging beam already start to reduce image sharpness. Large diameter beams can easier have such temperature differences of the air within the beam. The incoming air can be very homogeneous in temperature at the location of the DOT in the case of wind in the directions around the North direction from East to West. Without wind during the day with sun shining, the warm air bubbles from the ground dominate and sharp images are not possible. However, already wind from 1.5m/sec (5 km/h), more sure from 2m/sec (7km/h), improves the situation if the telescope is on an open tower, which prevents warm air bubbles coming upward from the ground and the walls of a building.

The favorable situation can occur with changing temperature during the day. Measurements showed that even with temperature changes of the incoming wind air of 3°C in 15 minutes, the required homogeneity of the air remains, see **Figure 18**. With 2m/sec wind, 1800m air passes in 15 minutes ($15 \times 60 \times 2 = 1800$). For a temperature change of 0.1°C , there passes 60m air ($1800/30 = 60$). However, the telescope structure can not follow such temperature changes and will have a temperature deviating from the temperature of the incoming air. The air is to short nearby surfaces with deviating temperature, when the air can move with the wind through the primary beam free enough.

Experiences showed that 80 percent open works. The low thermal conductivity of air is an advantage. However, it remains essential that the telescope structure has no places where stagnant air remains longer time and can take over the temperature of the structure surface.

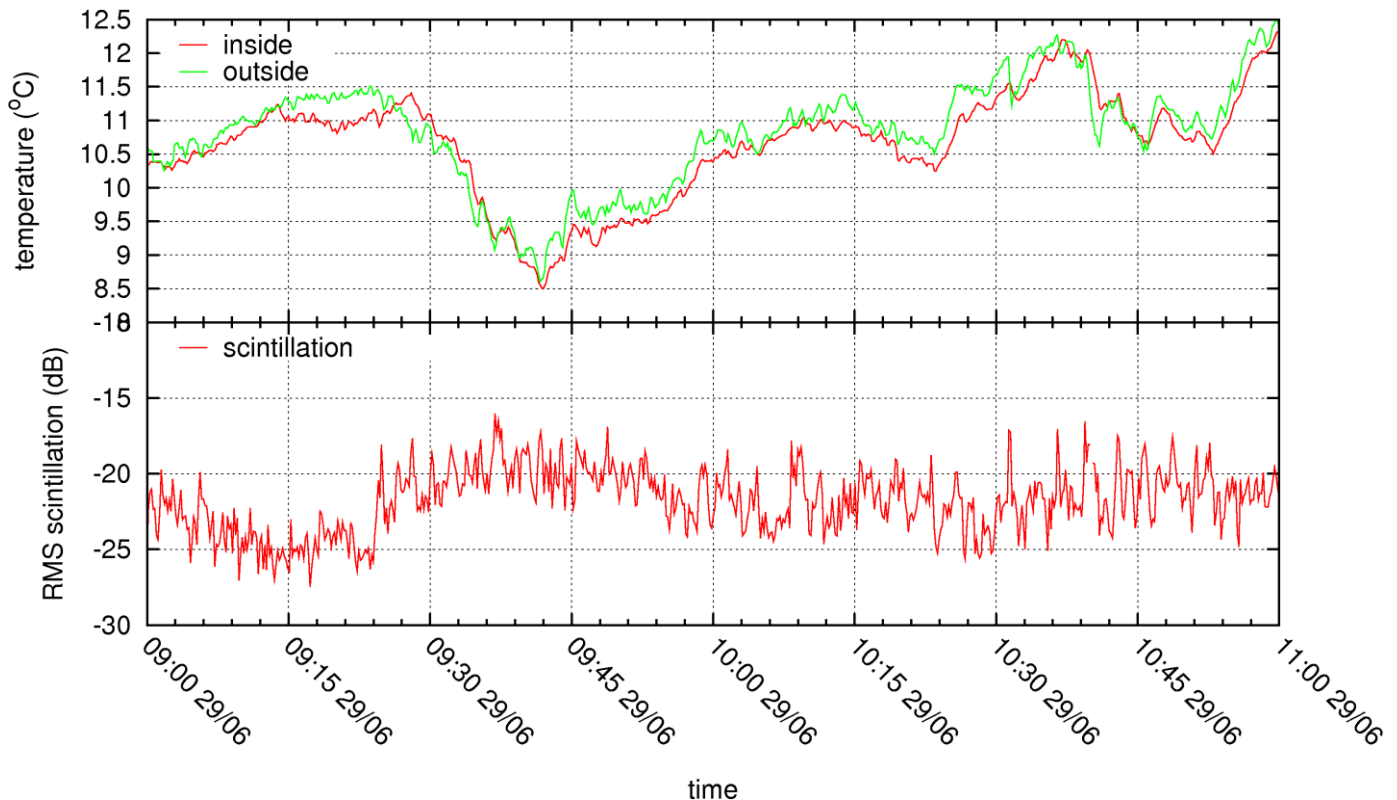


Figure 18. Temperature and scintillation at the DOT during June 29th, 2009 when the dome was opened for observations. This plot shows a period of two hours. We see the variations in temperature during daytime measured by sensors outside and inside the completely open dome. A steep drop of 3°C in 15 minutes was observed between 9:27 UT and 9:42 UT.

The scintillation signal of a single photocell was recorded at the same time, and is plotted in a logarithmic scale in the lower part of the graph. This scintillation measurement is mainly sensitive to fluctuations of the index of refraction of the lower atmosphere, the first 100m above the ground, because the Sun is an extended source. The value of 20 dB during the 15 minutes between 9:27 and 9:42 is sufficient good to use the recorded images for speckle reconstruction, which provides images with diffraction limited spatial resolution 0.2 arcsec for the 45 cm DOT mirror and the 400 nm wavelength region. A value of 25 dB can be qualified as very good seeing. More information in **ref. 9**.

The DOT has made sharp high resolution images of the sun in wind velocities from 1.5m/sec (5 km/h) till 20m/s (70 km/h). Above 20m/s, there were never situations with clear sky suitable for observations.

Figure 19 shows the primary beam region from first mirror to image. As indicated in **Figure 17**, the telescope mount of the DOT is suitable for a much larger mirror. The tower and telescope are constructed in the university workshops of Delft and Utrecht. All large parts like the tower and mount are constructed in the Delft University workshop. For high resolution images, the primary mirror has to be of high quality concerning the shape. The mirror had to be made by an external optical company. The financial resources for this were very limited. The 45 cm diameter is large enough to make the very interesting high-resolution images of the sun in the wavelength range of the visible light. The plan was to move to larger mirror after the 45cm mirror had proven that an open primary beam is indeed possible. Designs are made for 140cm and 250cm diameter primary mirror, which still fit to the large mount. Only the telescope top structure needs to be adjusted for this.

The DOT not only makes sharp high-resolution images. The consequent open construction of tower and telescope facilitates continuous good seeing over longer times up to several hours. This is the key to the sharp high-resolution movies and mosaics over very large fields in which the DOT observations are unique. Sharp movies and mosaics are also made in the violet Ca-H line with the the short wavelength of 396.8nm. The shorter the light wavelength, the more it is difficult to get good enough seeing for sharp images. The diffraction limit of 0.2 arcsec resolution related to the 45cm mirror and 396.8nm wavelength is really reached by the DOT in the movies and over the mosaics.



Figure 19. Observing DOT in the later afternoon. Left the primary mirror of 45cm diameter and 1997mm focal length. The primary image of the sun with diameter of 18mm diameter is visible as a very bright spot on the diaphragm plate, which selects a small part of the solar image, which goes through a hole in the diaphragm plate to the secondary optics.

The diaphragm plate is a mirror, which reflects most of the light away between the telescope structure beams, which carry the secondary optics. Despite the high reflection of the diaphragm surface in a direction away, the primary solar image looks very bright. The diaphragm plate is supported from the backside by a copper body with hollow channels, through which 6 liters of water flow per minute. The water comes from a tank of 300l on the ground 30 meter away from the open telescope tower. So, the water is pumped around in 50 minutes. This is enough to cool the diaphragm, on which falls about 200Watt. An antifreeze fluid has been added to the water for winter operation with frost on the height of 2350m above sea level.

In addition to the water cooling, the air is sucked away around the primary image. The ring of the air suction system is visible around the diaphragm mirror plate. Air suction is also around the electronics of the image cameras. The sucked air goes through a flexible hose to the telescope base and from there downward to the ground, where the air goes through a plastic pipe to the suction fan at the same place as the water pump 30m from the base of the tower. We have chosen air suction and not air blowing, because the air temperature increases somewhat by the air compression of a fan (known as adiabatic compression). And we put the air suction fan far away from the telescope.

The multi-channel system with 7 cameras that observe in 7 different wavelengths, described in **section 7**, is located below the primary beam during observations and therefore has no negative influence on the primary beam.

So the DOT has unique capabilities already with the 45cm diameter primary mirror. The use of the large telescope mount has demonstrated that the open principle of primary beam completely open as shown in **Figure 17 and 19** will work also for a large mirror.

The DOT has the unique capability to make sharp high resolution movies also in the later afternoon. This is due to the open tower, hence no warm building walls nearby the open telescope. An example of a film in the later afternoon is the movie of the solar rim in the violet Ca-H line with the short wavelength of 396.8nm, which is the first movie link indicated with M1 in the manual:

“Manual for viewing DOT solar movies and papers with examples”, link to the manual is in **ref. 18**.

This movie shows together the unique capabilities for movies of the DOT:

1. Short wavelength 396.8nm of the used spectral line Ca-H for the images, possible because of minimal disturbance of the air in the primary beam
2. Solar rim: the fibrils sticking outward the rim and the solar surface are together visible due to the very low straylight in the optical system design. Only a single mirror with large diameter in the primary beam is one of the properties in favor of low straylight. Further measures to ensure little stray light are pupil diaphragms on the right places in the secondary optics and low straylight coatings. See also the **section 6** “The optics for the open telescope” with **Figures 30 and 31**.
3. Movie made in the later afternoon possible because of open telescope on open tower as explained here above.

No image rotation is present during the observations because of the equatorial mount. This facilitates the make of large mosaics in an efficient way without optical de-rotator. So minimum optical components, which has to be of very high shape precision to reach the high spatial resolution in the images. The capabilities concerning mosaic images because of the unique design are shown in the paper: “Advanced capabilities of the Dutch Open Telescope”, link is in **ref. 19**.

A mosaic from the sun’s North pole till the South pole is in this paper shown in parts. The complete mosaic is in the file:

20040913-sunstrip-gb.png (16 MB) or more compact 20040913-sunstrip-gb.jpg (5 MB), **see ref.19**.

The make of mosaics has been automated and mosaic movies are made, **see ref. 20**.

The design of the telescope mount has some special mechanical structural properties.

1. The mount base is incorporated in the inner platform structure. The double CNP22 beams in the inner platform are partly replaced by very sturdy steel-box constructions, which bring the wind forces on the telescope structure in a very stiff way to three of the four outside corner points of the inner platform, being also the top corner points of three of the four upward isosceles triangles of the tower. **Figure 20** shows the adapted construction of the inner platform.
2. An equatorial mount instead of the nowadays usual alt-azimuth mount. This equatorial mount differs from the in former days usual equatorial mount, where the declination axis and hour axis intersect. The declination axis and the hour axis pass each other at a distance in the DOT design. The declination axis is deep under the hour axis in parked position. The telescope is compactly folded together and the completely open-foldable dome can be closed over the telescope, **see Figure 1 and Figure 2** both on the right side. The telescope is moved upward with the hour axis for the observations, whereby the declination axis moves upward, **see Figure 1 and Figure 2** on the left side and **Figure 17**. In this way, the primary mirror with the incoming beam comes high above the platform free in the wind in favour of getting sharp images.
3. The declination axis next to the incoming primary beam is usual for the classical equatorial mounts. And also, the elevation axis is next to the primary beam in the nowadays common alt-azimuth mounts. In the DOT construction, the declination axis is under the primary mirror, therefore not next to the incoming primary beam. Consequently, the primary beam is more open and for the wind to blow more freely through. The more open construction with declination axis underneath the primary mirror is visible in the photos of **Figure 2** left side, **Figure 17** and **Figure 19**.

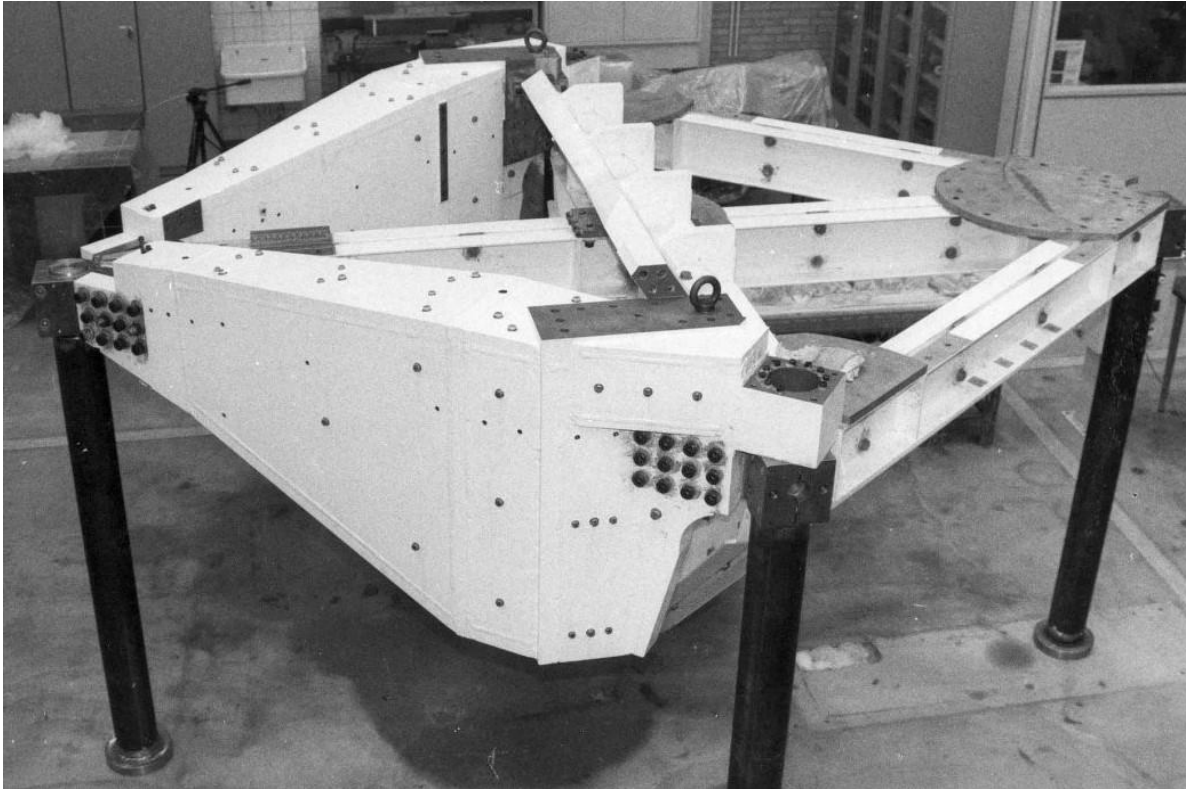


Figure 20. In the workshop of Delft University of Technology, the inner platform transformed into part of the telescope mount. The double CNP22 beams have been replaced by very sturdy steel box constructions from the South corner on the left to: the East corner at the front and the West corner at the back. An additional sturdy construction is placed on the double CNP22 beams from the East corner at the front to the West corner at the back. The frame, which carries the large hour angle-wheel with bearings and drives, is attached to the two grey surfaces near the East and West corner, and to the South corner with an in height adjustable connection for adjusting to the pole height of the telescope location. The pole height can be changed from 0° for the equator to about 55° with the backside hour-wheel bearing resting on the South corner.

Concerning the moment to the tower top by wind force: The wind forces on the surfaces of the steel-box constructions underneath the platform level work compensating for the wind forces on the telescope-construction parts above the platform level.

For the assembly of the transformed platform in the workshop, four pillars are placed underneath the corners, where the upward isosceles triangles of the tower end.

4. Gears of unique stiffness for telescope observations in wind

A new type of gears has been developed, which solves several unusual properties of the open telescope construction. The telescope part in front of the declination axis is much longer than the part behind the declination axis due to this unusual location of the declination axis. Balancing around the declination axis would require a very large counterweight behind the declination axis. Or the structure part behind the declination had to be much longer. Both solutions would result to a less compact, stiff telescope construction. Not balanced situation is also for the hour axis because of the distance between declination and hour axis for moving upward the primary mirror high above the platform for the observations. The developed drives have a very large speed reduction factor between motor and declination, respectively hour axis, still low friction and stiff.

The entire size of the telescope mount is used for the large first gear wheels, for both declination angle and hour angle for the right ascension. The construction of the hour-angle wheel is shown in **Figure 21**. The large gear wheels are driven by self-aligning pinions as explained in **Figure 22**. This construction provides sure line contact between the teeth of the large gearwheel and the pinion with the relative low forces of the telescope drive. The line contact serves high stiffness for keeping precise pointing in wind gusts and for avoiding stick-slip effects. In normal use of gears, the size of

the drive is determined by the required force, which then produces line contact between the teeth of the much smaller gears. More information about these things is in **ref. 13**.

Using the right lubricants is also important. The right lubricant prevents the friction coefficient from dropping sharply when transitioning from standstill to moving, also important for avoiding stick-slip effects. More information about lubrication and stick-slip in **ref. 14**.

Start with accurate manufacturing of the teeth is also essential for line contact. We developed a simple instrument to measure the deviations in the teeth distant and straightness of the teeth, shown and explained in the **Figures 23, 24 and 25**.

A special stiff shape of the gear teeth was developed with short teeth and positive profile displacement. A positive profile displacement increases the strength and stiffness due to a smaller local elastic deformation. In machine engineering it is normal practice to use a positive profile displacement only for the pinion, because it is not necessary for the strength of the teeth of the large wheel. As a consequence, the contact region along the line of action shifts to one side of the rolling or pitch point. Only in the pitch point a pure rolling without sliding takes place. The sliding and, with it, the friction increase by the shift of the contact region. For normal gears, which transform power from high speed to low speed, this is not important, but for the telescope gears it is. In the following we will give an explanation.

The telescope has on each large gear wheel two pinions with separate motors which are tensioned against each other to eliminate the backlash. This is absolutely necessary because of changing temperature differences between the large gear wheel and the bearing house. One of the motors is the driver and the other is the driven one. The gears of the driver motor are used in the normal way, i.e. from high speed to low speed. However, the gears of the driven motor are used from low speed to high speed and have more problems with friction.

The solution for this problem is the addition of a large positive profile shift to the teeth of the large gear wheel. This shifts the contact region back to its symmetric position around the rolling point without reducing the positive effect of the increase of the curvature radius of the used involute tooth surface part for the pinion. The fabrication of the large positive profile shift is not a problem for a gearwheel with many teeth, more than 100, like the declination and hour-angle wheels.

We gave the teeth a small tip relief at the top of the teeth, both large wheel and pinion, for smooth transitions from tooth to tooth. The relief is much smaller and less deep than the relief for compensation of the tooth bending in fast running turbine gears.

Very low energy consumption of the motors is reached with the developed low friction drives. The strong servomotors consume only 20Watt when following the sun. This is good for not disturbing the temperature homogeneity of the air in the primary beam.

After the success of the DOT drives, we were asked to develop the drives for the Swedish Solar Telescope (SST), in which we used the developed special teeth shape. A publication about the drives is in **ref. 15** with more information. Production of the special teeth shape was no problem with the classical method of grinding gear teeth with a rolling process used for the DOT gears. A more modern method with the teeth shape made in the grinding stone is used for the SST gears.

The SST is a vacuum telescope with an alt-azimuth mount, entrance lens of 97cm aperture followed by 2 large flat mirrors under 45° to reflect downward the primary beam, followed by a more complex image correction system called Schupmann corrector, see **ref.15**. The alt-azimuth mount causes image rotation when tracking the sun. A controlled optical de-rotator can solve this. However, this results in a more complex optical system. The equatorial mount of the DOT does not cause image rotation. The DOT can thus efficiently produce mosaics over large fields using straightforward optic. This optic of the DOT with only 1 large mirror in the primary beam contributes to very low stray light, making the DOT very suitable for taking images with the rim of the sun in it, as explained on **page 25** and in **section 6** "The optics for the open telescope" with **Figure 30 and 31**.

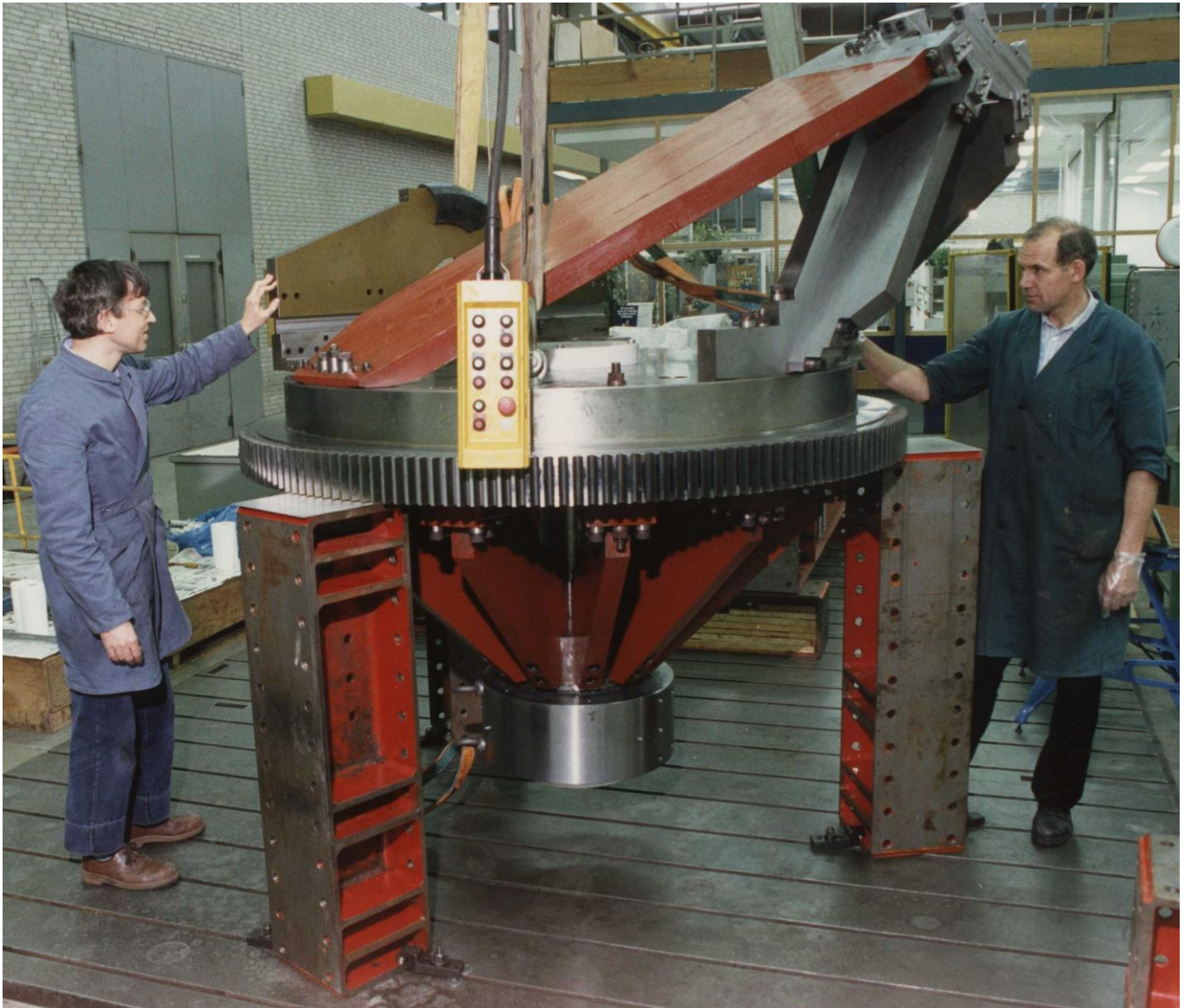


Figure 21. In the workshop of Delft University of Technology, the hour-angle wheel in construction. The circle of teeth of the first gear wheel is over the full 1.90m diameter of the hour-angle wheel. A large reduction factor is from the first pinion to this gear wheel serving high stiffness. A roller raceway is above the gear teeth. The roller raceway rests on two rollers in the base frame on the inner platform underneath the hour wheel. The fork to carry the declination wheel is mounted on top of the roller raceway. The backside construction of the hour-angle wheel is in this photo downward. This construction is visible in **Figure 17** on the left side of the telescope. The gear teeth and roller raceway are protected by a cap of aluminum, which is blank anodized, remaining cool in sunshine because of very good reflection of the solar light from green to near infrared and radiating in the longer wavelength infrared to the cold open blue sky.

A large double-row spherical roller bearing is at the backside of the hour-angle wheel with a framework between gear and the bearing inner ring. The bearing is of the type with large center hole, so relative to the hole a slender bearing. A light beam is possible through this center hole. Also the declination axis has such a bearing with large hole for light beam passage. These bearings permit an optional Coudé focus and a beam downward the tower to an optical lab. There are several possibilities for optical realization of the downward imaging over long distance within a small diameter tube. Probably, a vacuum tube downward the tower is advisable because of the long length of the beam. The diameter of this tube can be small compared to the incoming primary beam. So the vacuum tube realization with entrance and exit window will give no technical problems. The tube will not disturb the open tower principle because of the small diameter of the tube.

Left Rob Hammerschlag, right Piet Hoogendoorn, involved in design and construction from start.

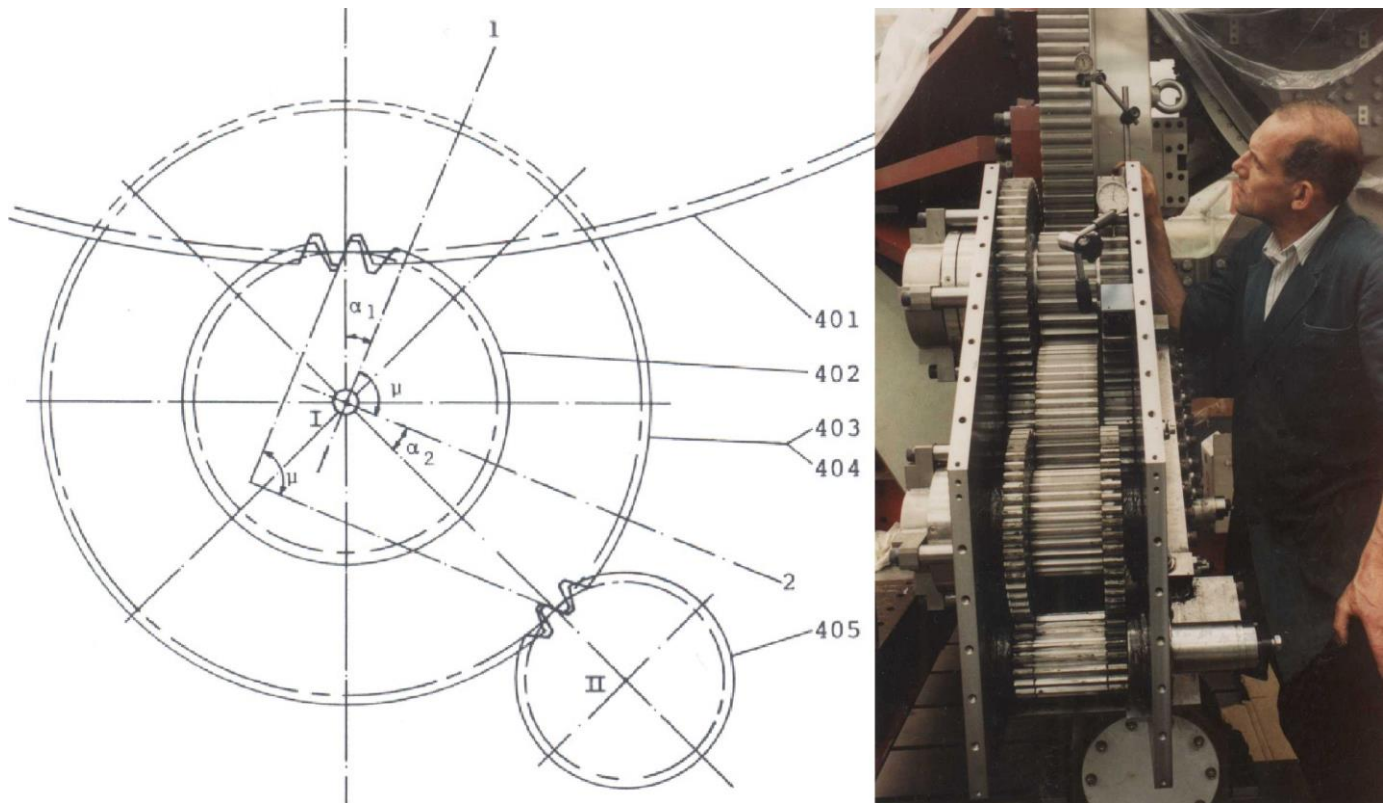


Figure 22. Left: The principle of self-aligning pinion. On both sides of a pinion is a gear of the next stage. This pair of gears is fixed with a ring of screws to the pinion. It forms a single block, which is supported in its center by a single double-row spherical roller bearing. This bearing permits rotation around three axes: the normal rotation around axis I perpendicular to the drawing plane, and two perpendicular axes 1 and 2 in the plane of the drawing. Rotations of the block around axis 1 provide line contact of the pinion with the large gear wheel whereas rotation around axis 2 provides line contact between the gears of the next stage (pinion II). The two half parts of the next gear, mounted on the pinion, were ground together for optimum matching. More with drawings is in **ref.13**.

Right: One of the two hour-angle gears. All gears have self-aligning pinions. This special design achieves line contact between the meshing teeth over the whole tooth width even under the relatively small loads used here. The gauges are used to measure the backlash of the gears.



Figure 23. A relative simple instrument to measure with μm precision the pitch deviations of the teeth is developed. Piet Hoogendoorn uses here this instrument to control the pitch of the teeth of the outside gears screwed to the self-aligning pinion. Explanation of the instrument in **Figure 24**.



Figure 24. Side view showing how the pitch measuring instrument works. A small block is pressed against a tooth – the height is adjustable with a second small block behind the tooth. The instrument is so-to-say lying on a tooth. The gauge pin is behind the second block and hits the next tooth. The red plastic handle is moved up and down and the maximum push-in of the gauge corresponds to the minimum distance, i.e. the pitch. The person moving up and down the handle can read the μm gauge as **Figure 25** is showing.

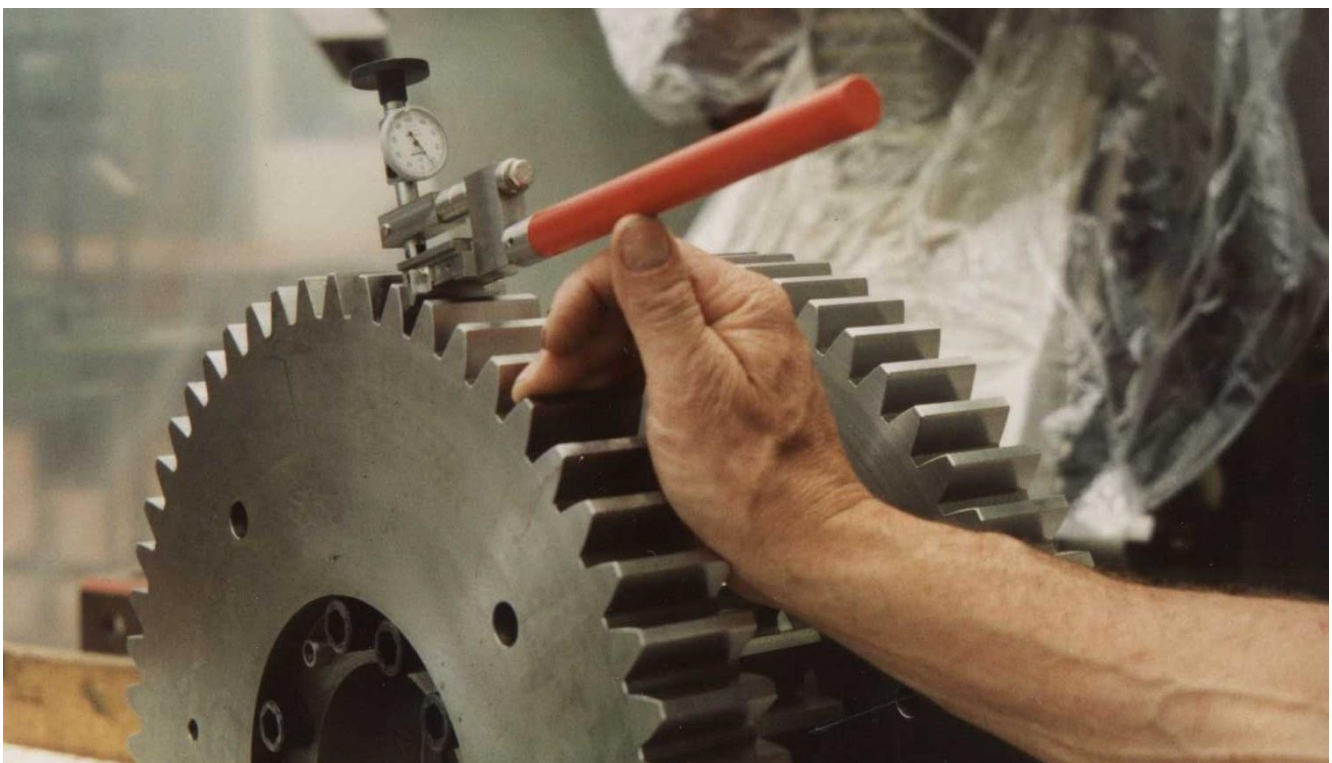


Figure 25. Front view with the dial of the gauge visible to the measuring person while moving up and down the red plastic handle. Only access from the head-side of the gear teeth is needed. As a consequence, with this instrument developed by us, gears can be reached at difficult places. If desired, the pinion can be measured even after it is mounted between the two gears.

The functioning of the DOT drives was tested in the workshop of Delft University of Technology during the construction of the telescope. The test setup is shown in **Figure 26**. The telescope was moved slowly, while the top of the telescope in horizontal position pressed downward a gauge with electrical output. Registrations are shown in **Figure 27**. The movements are gradual without jerks even at extremely low speeds. The motor velocities can be regulated from very low speed, as shown in the registrations of **Figure 27**, till high speeds to move the telescope from compact parked position to the position high above the tower platform for observations, which needs some minutes.

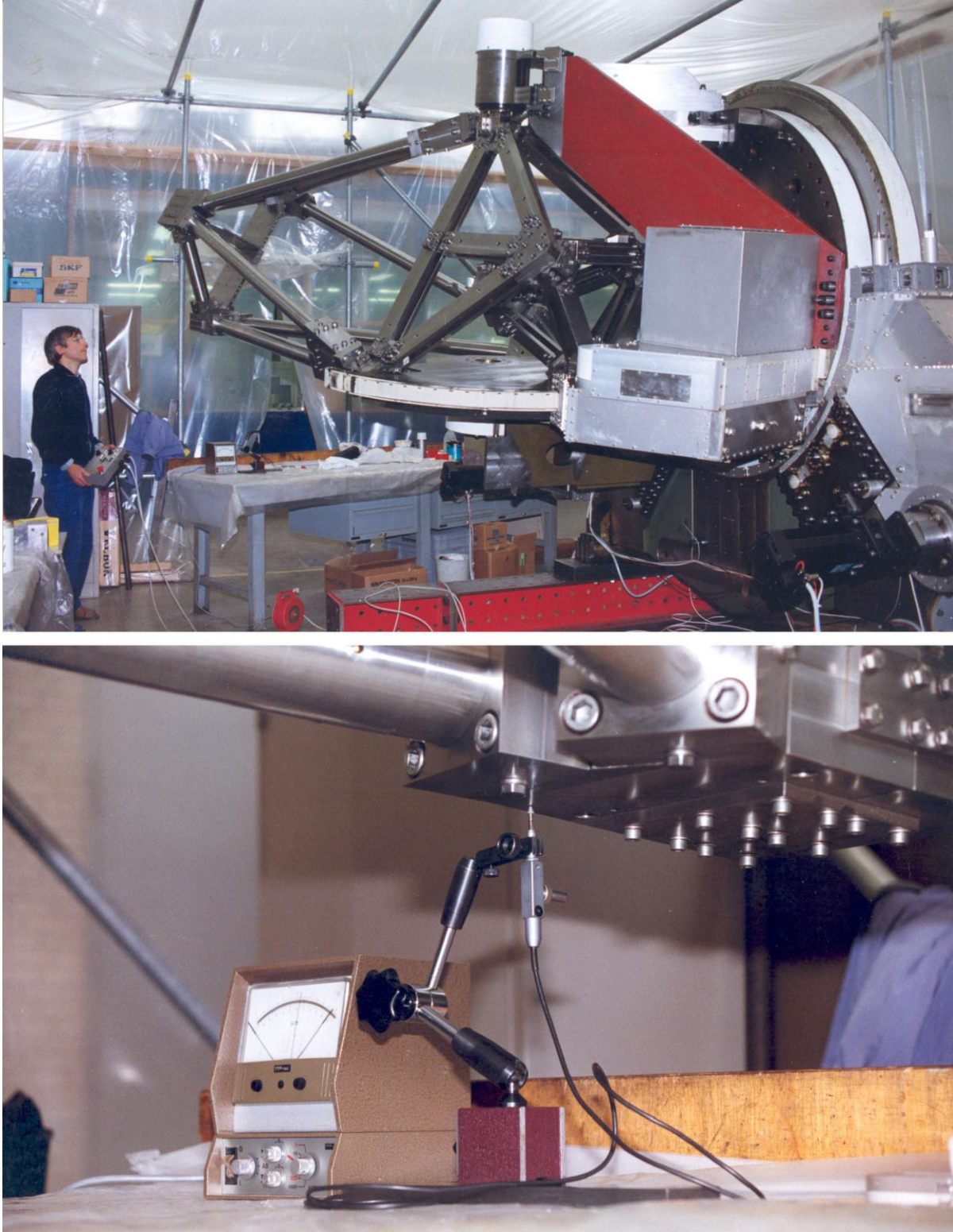


Figure 26. Test setup for the drives in the workshop of Delft University of Technology.

Top: The telescope was moved slowly downward to a horizontal position, where the top of the telescope will press downward a gauge with electrical output standing on the table left side.

Bottom: The telescope top presses downward the gauge connected to an electrical measuring device and a plotter, not visible on the photos. Registrations with the plotter are shown in **Figure 27**.

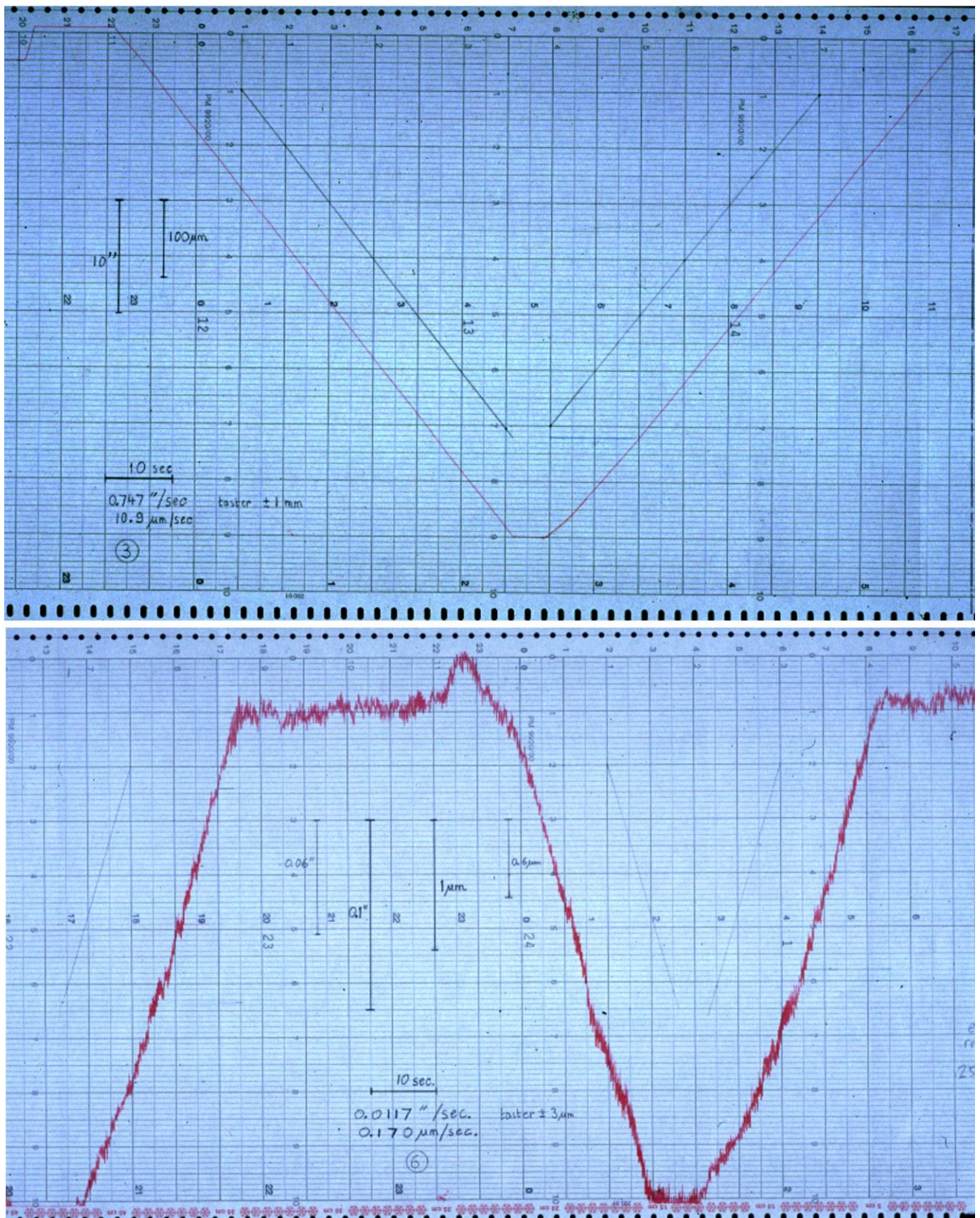


Figure 27. Results of drive tests with the setup in **Figure 26**. Registrations of the movement of the telescope top by hour-angle rotation, the vertical axis, as function of the time, the horizontal axis. **Top:** Rotation velocity 0.747 arcsec/sec, slow to go over the sun with diameter of about 1900 arcsec. The red line is the registration, the blue line is drawn with the expected velocity from the speed setting on the controller. Comparison of red and blue line shows the correctness of the velocity. **Bottom:** Extreme low velocity with high position sensitivity shows the electronic noise in the registration and the movement without jerks with this extreme slow motion of 0.0117 arcsec/sec.

5. Overview of the telescope construction

The drawing of **Figure 28** shows an overview of the telescope construction. The different telescope parts are indicated. A photo of the observing telescope taken from the tower platform is in **Figure 29**. Many parts of the construction indicated in **Figure 28** are visible on this photo.

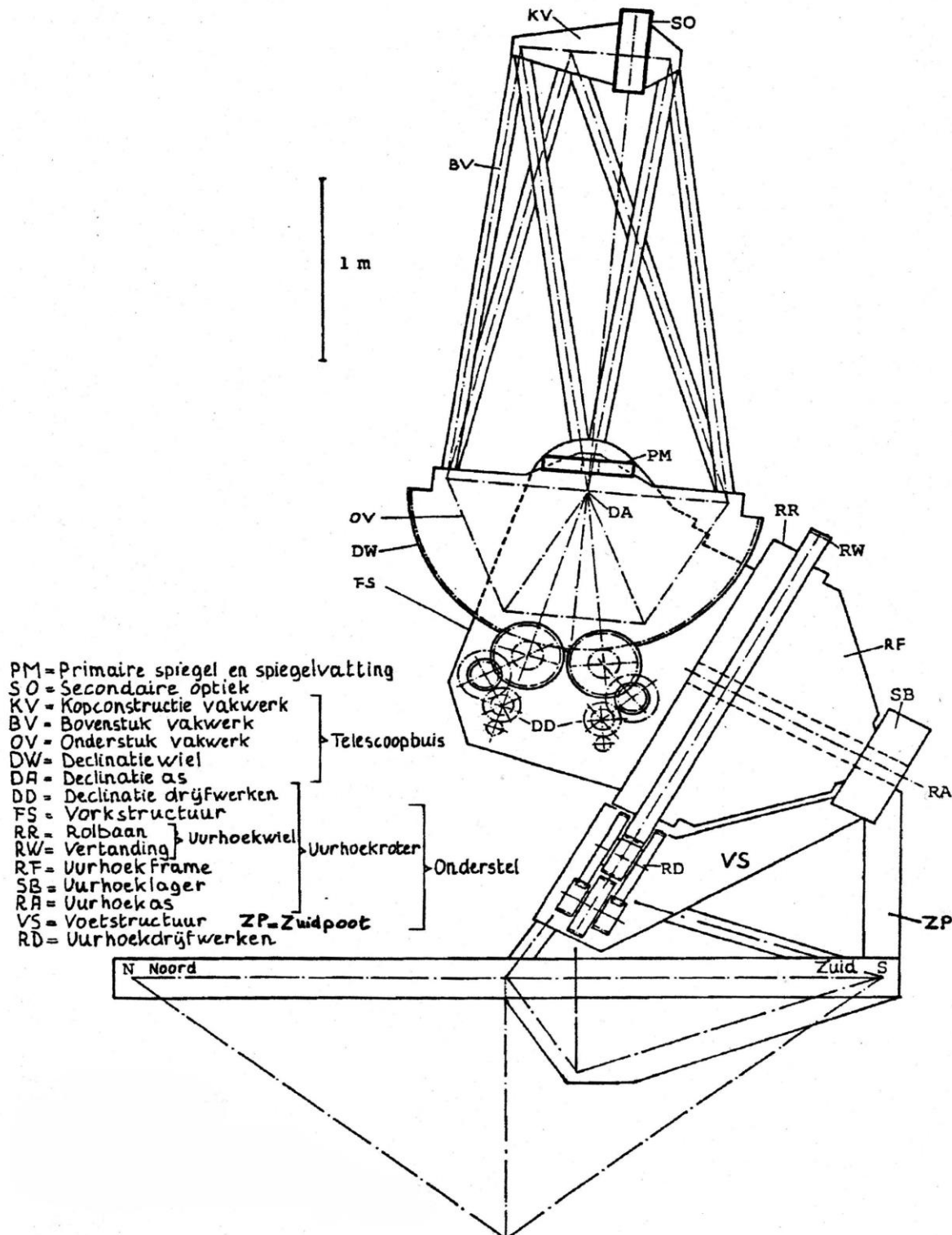


Figure 28. Overview of the telescope construction.

PM = Primary mirror. SO = Secondary optics. KV = Top construction framework.

BV = Upper part framework. OV = Lower part framework.

DA = Declination axis. DW = Declination wheel DD = Declination drives. FS = Fork structure.

RR = Roller raceway. RW = Hour-angle teeth. RF = Hour-angle frame. SB = Spherical roller bearing.

RA = Hour-angle axis. VS = Foot structure. ZP = South pillar. RD = Hour-angle drives.

Other word for Hour angle is Right ascension, the origin of the letter R in the abbreviations.

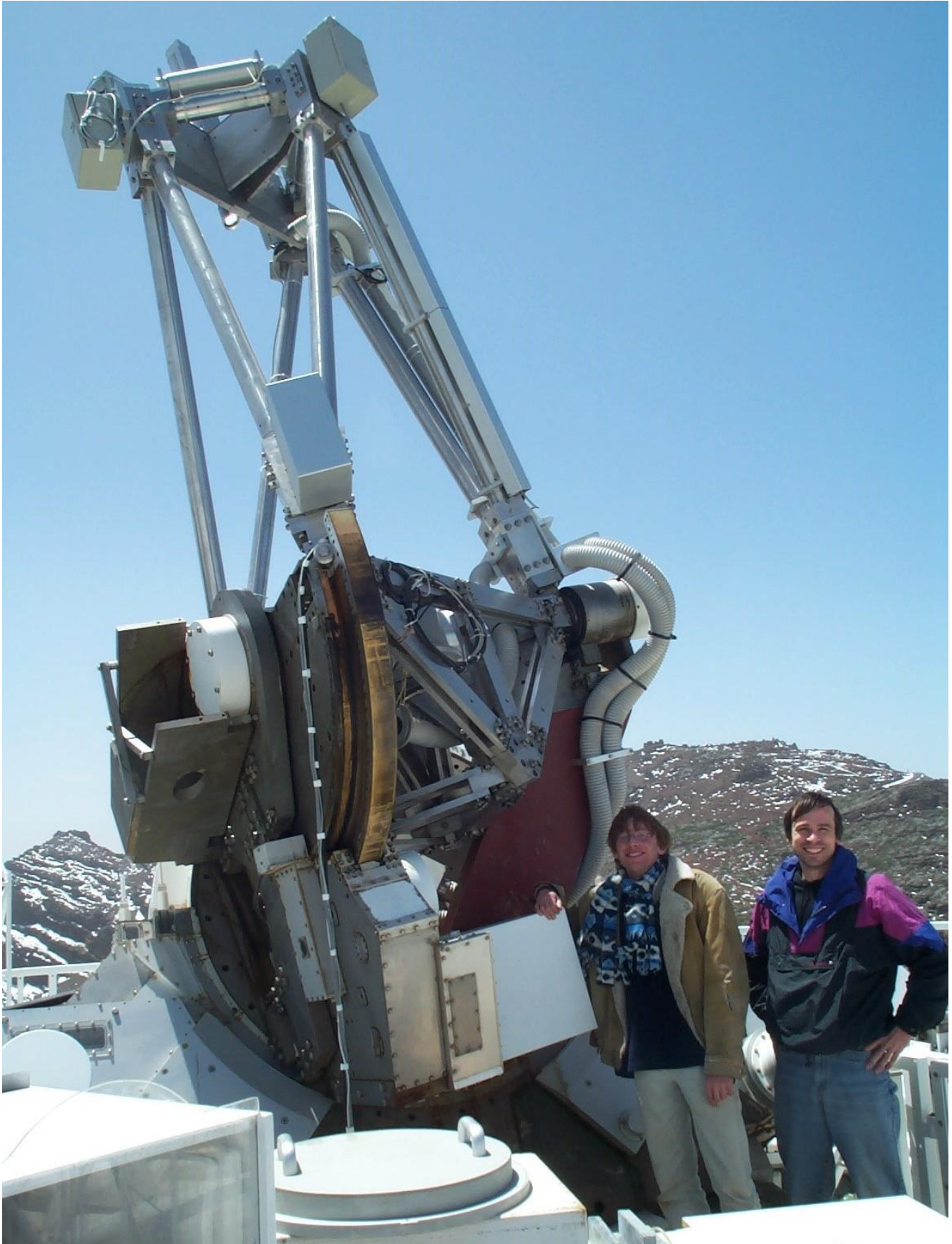


Figure 29. Telescope construction seen from the backside during observations. The parts of the telescope construction can be recognized with the overview in **Figure 28**. Left Felix Bettonvil, right Pit Sütterlin, essential persons for the development and use of the multi-channel system integrated in the open telescope construction. The observations with the multi-channel system showed the advanced capabilities for the production of high-resolution solar movies and mosaics over very large fields with stable, sharp images over long periods of time due to the unique open constructions of tower and telescope.

6. The optics for the open telescope

The optics consists of a primary mirror with parabolic shape forming the primary image on a water-cooled diaphragm, see **Figure 19**. The caption of this figure describes the structure of the diaphragm. A lens system consisting of two doublets forms a 10 times enlarged image of the transmitted solar-image part behind the diaphragm. All the optical beams behind the water-cooled diaphragm have a diameter of only a few cm. As a result, these beams are much less sensitive for small temperature fluctuations in the air. These beams can go through closed tubes and boxes with color filters, forming what is called the secondary optical system.

A parabolic mirror produces an image, which is only completely sharp in a very small area, almost only a point. The line from the center of the parabola to the sharp point is the center line of the optical system, the optical axis. The two doublet lenses compensate for the ray deviations, resulting in image sharpness also further away from the point on the optical axis. The two doublets reach complete sharpness over a field of 4 arcminutes on the sun, corresponding with an image diameter of 2.4mm at the place of the diaphragm, 24mm at the place of the image behind the doublets. The diaphragm hole has at the moment a diameter of 1.6mm, which is sufficient for the cameras in use with field 113x113 arcseconds. Exchange of diaphragm is possible to achieve a larger field.

The full sharpness, limited by the diffraction limit, is achieved over the entire spectrum from the short-wave violet light of calcium line Ca II H of 396.8nm wavelength, diffraction limit 0.18 arcsec, to the red light of the hydrogen line H-alpha of 656.3nm wavelength, diffraction limit 0.30 arcsec.

The first doublet lens behind the diaphragm is the imaging lens for the 10 times enlarged image. The second doublet lens corrects the aberrations outside the optical axis of the parabolic mirror. This lens is a self-made design and is made specially for the DOT.

The first doublet lens forms an image of the primary mirror near the second doublet lens. A diaphragm is placed in the image of the primary mirror. This diaphragm allows light to pass from the inner 438mm of the primary mirror with 450mm diameter and is called the pupil diaphragm. The 438mm is called the effective entrance pupil. This diaphragm is one of the measures for very low stray light, which facilitates sharp images of the solar rim as described on **page 25**. **Figure 30** shows a large mosaic in which active regions with sunspots, including the rim of the sun where the outward flowing gas can be seen as protruding hairs, called fibrils, more in active regions, less in quiet regions. The observations have greater resolution than can be shown here in the presentation image with combined pixels. A section of the rim with fibrils in full resolution can be seen in **Figure 31**. This image is from a movie of the solar rim. Further information is in the figure caption and in **ref.16**, where also the multichannel imaging system is described.

The primary optical system of the DOT has no reflections to other directions, only reflection back along the optical axis. The polarization properties of the incident light are well preserved. Light in specific spectral lines can be polarized because of magnetic fields on the sun, which can be observed with tunable small-band spectral (color) filters.

7. Multi channel system for tomography of the solar atmosphere

The solar light comes from the solar atmosphere, the outside layer being thin relative to the solar diameter. In this layer, the gas density decreases rapidly from the density in the solar sphere to the very low density in the solar corona. We see the most deep part of the solar atmosphere in the continuum light, which is the light with wavelengths outside the solar spectral absorption lines. This deepest layer of the solar atmosphere is called photosphere, from the word photo for light. Most solar light comes from the photosphere.

The lower density layer above the photosphere is called chromosphere from the word chromo for color, visible during total solar eclipse. The thicknesses can not said precisely, because these thicknesses depend on the variable intensity of the magnetic activity of the sun at a place, thicker when more activity. In terms of order of magnitude, the photosphere is several 100 km thick and the chromosphere several 1000 km.

A certain substance in the solar atmosphere causes absorption of light in specific narrow wavelength areas, the spectral lines associated with this substance. Hence, the light in the spectral lines come from a higher layer in the solar atmosphere. How deep in the solar atmosphere depends on which spectral line. The solar atmosphere on several heights can be observed with images made simultaneously in several spectral lines. The behaviour of the solar atmosphere can be visualized three-dimensionally in this way, which is called tomography.

Special beam-splitter cubes split the light coming from the second lens after the primary image into different spectral regions corresponding to the spectral lines to be observed, see **ref. 16**. The light from only a spectral line itself is selected with a filter of very narrow bandwidth, a narrow bandpass filter. The DOT has 7 channels, which can make simultaneously images. In some channels, the narrow bandpass filter can be exchanged, so you can choose from different filters. The following table shows the filter combination most commonly used for the DOT observations.

Wavelength	Width	Name and description
396.85nm	0.13nm	Ca II H line, imaging lower Chromosphere, tunable by tilt.
430.5nm	1.0nm	G band consisting of some CH lines, imaging lower Photosphere with the small magnetic tubes well visible as explained in Figure 32a .
431.9nm	0.6nm	Continuum light nearby G band, imaging lowest Photosphere, the solar surface. The small magnetic tubes are much less visible than in G band.
450.5nm	0.54nm	Continuum light nearby Ba II line for speckle image reconstruction with Ba II line.
455.4nm	0.008nm	Ba II line, Lyot filter with birefringent crystal plates, motoric fast tunable ± 0.2 nm, imaging higher Photosphere
655.05nm	0.24nm	Continuum light nearby H-alpha line for speckle image reconstruction with H-alpha line.
656.28nm	0.025nm	H-alpha line, Lyot filter with birefringent crystal plates, motoric fast tunable ± 8 nm, imaging high Chromosphere.

For the narrow bandpass filters, the optical beam path is designed in such a way that the image of the entrance pupil lies at infinity. Then from each point of the solar image, the beam goes to the pupil image at infinity with same angles through the filter for all points on the solar image. As a result, the filter effect is the same for all points of the solar image, i.e. the spectral transmission is the same for every image point. This beam path is called telecentric. **Reference 17** provides further description of this telecentric multichannel system including the motorized fast-tunable H-alpha filter.

Figure 19 shows the multi-channel system with cameras underneath the primary beam.

Light beam through the bearings and downward the tower to an optical laboratory on the ground would be possible as described in the caption of **Figure 21**. Due to limited financial resources, this option with multi-channel system hanging on the telescope was chosen without an optical laboratory on the ground. Advantage of the chosen system is a less complex optical system with less optical components, which have to be of very high shape quality to reach the diffraction limited sharpness of the images. If desired, an optical laboratory can be added in the future.

8. Solar tomography observations with the DOT

The **Figure 32a, 32b and 32c** show an example of 3 mosaics made simultaneously of an magnetic active region in several spectral lines showing the solar atmosphere in different heights.

Figure 32a: 430.5nm, G band, lower Photosphere near the solar surface.

Figure 32b: 396.8nm, Ca II H line, low Chromosphere at height of about 400km above solar surface.

Figure 32c: 656.28nm, H-alpha line, high Chromosphere at height of 2000km above solar surface.

Much more explanations are in the captions of the figures.

These 3 images are used for the comparison of the structures in different height at same moment, as shown by shifting a line over the combined images in <https://dutchopentelescope.nl/images/>

The 3 combinations are: G band and Ca II H line; Ca II H line and H-alpha; G band and H-alpha

Figure 32d is the **Figure 32c** colored in to make the structures of the magnetic field currents more clearly visible.

Many scientific papers are published in which are used the DOT tomography observations, see in the website part <https://dutchopentlescope.nl/publications/>

Seven publications use as part of the publication name: *DOT Tomography of the Solar Atmosphere*. These publications are listed here in the **references 21 to 27**. The initiator of the tomography of the solar atmosphere with DOT observations was Rob Rutten, see **Figure 15**.

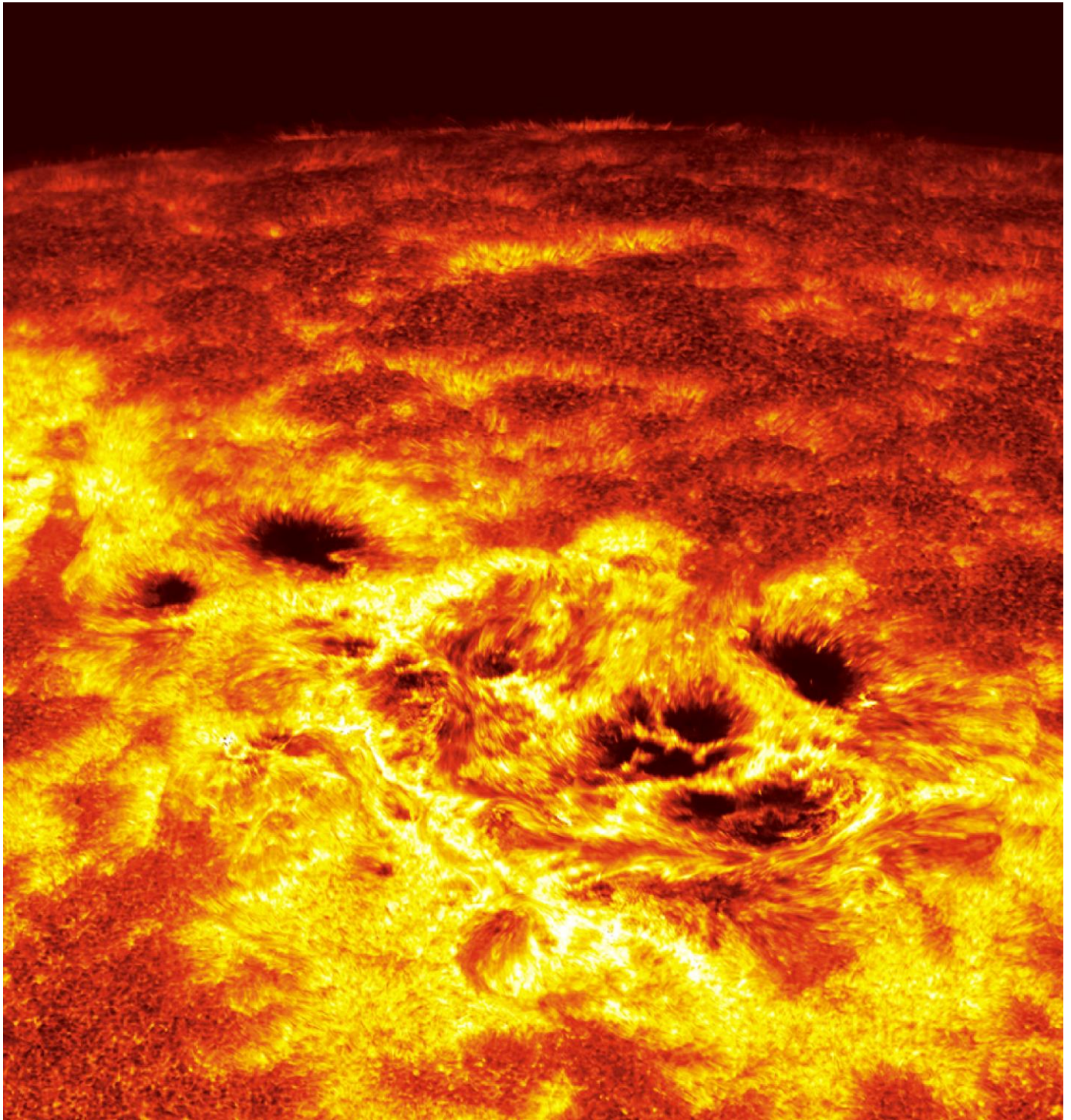


Figure 30. Mosaic of active regions with sunspots with the sun's rim with the spectral filter at 396.8nm width 0.1nm in the Ca II H line, imaging the lower Chromosphere. The images were recorded with a black-and-white camera with a wide range of brightness between darker and lighter image details. The image is afterwards colored from red to yellow to white, dark to bright, making the bright areas more clearly visible. At the rim, the outward flowing gas can be seen as protruding hairs, called fibrils, more in active regions, less in quiet regions. The observations have greater resolution than can be shown here in the presentation image with combined pixels. A section of the rim with fibrils in full resolution can be seen in **Figure 31**. Combination of this Ca II H line with the same region at the time in the G-band is in <https://dutchopentlescope.nl/images/> in the 2003 part, the first image combination.

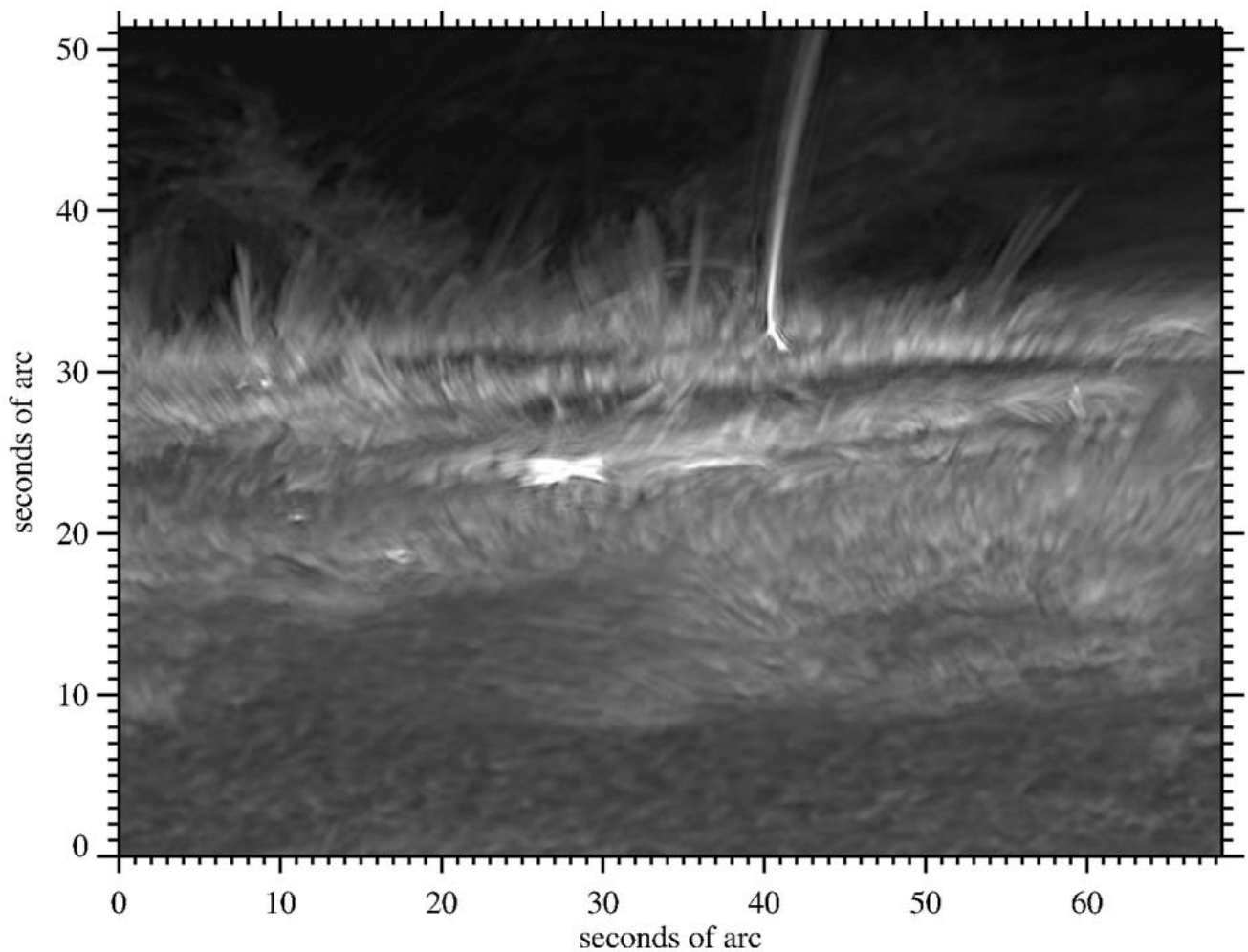


Figure 31. Image from a movie of the solar rim in Ca II H line at the short violet wavelength of 396.8nm, which is difficult concerning seeing. The unique open construction of tower and telescope can handle this perfectly even in the later afternoon, when this movie was made. The open tower prevents upward warm air from building walls and ground.

The low straylight due to only a single large mirror followed by secondary optics with diaphragms in the pupil locations provides that the outgoing gas streams at the rim, the fine fibrils in the chromosphere, and the bright solar surface are visible simultaneously.

The sunspots appear as flat dark pancakes amidst the bushes of Chromosphere fibrils.

The large upward gas stream is called a surge, which was visible during a few hours. It may have resulted from magnetic reconnection, explanation in **ref. 25**

This image is from the movie, which is indicated with the link M1 in the manual:

"Manual for viewing DOT solar movies and papers with examples",

DOT-MoviesSun-SciencePapers.pdf (1.8 MB), see **ref. 18** with a link.

Information is also in the paper:

"Advanced capabilities of the Dutch Open Telescope"

DOT-AdvancedCapabilities.pdf (8.6 MB), see **ref. 19** with a link.

Further Information is in <https://dutchopentelescope.nl/future/>

with there the image in **Figure 3** and the movie, which is also directly reachable in:

<https://dutchopentelescope.nl/wp-content/uploads/2024/06/2003-11-04-AR10486-ca-limb.mp4>

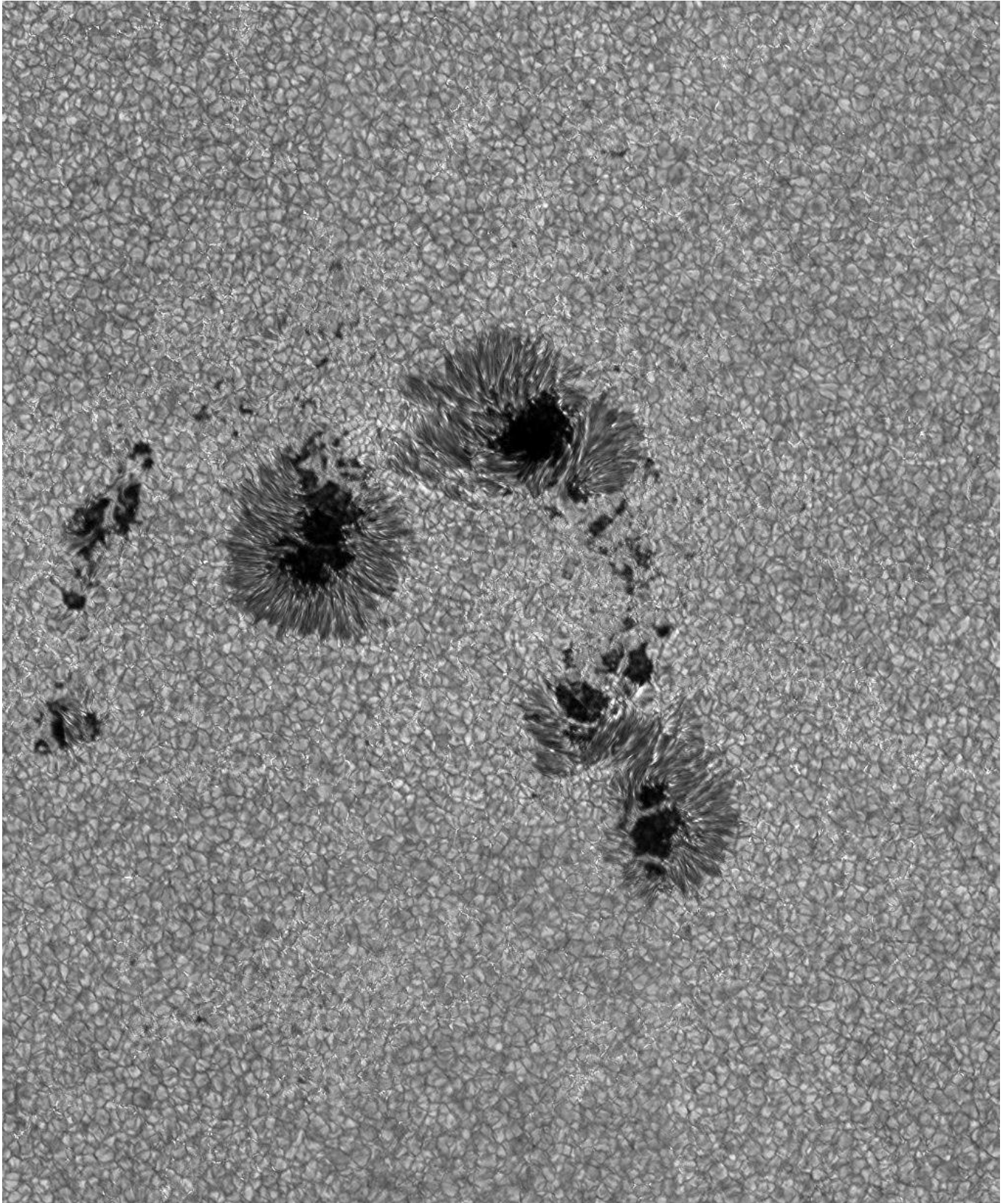


Figure 32a. G band 430.5nm, filter width 1.0nm. Multitude of CH spectral lines shows the solar photosphere, the "surface" where the visible light with continuous spectrum escapes. Outside the active regions, the G band shows granulation, the pattern of greyish blobs surrounded by dark inter-granular lanes. This granulation is the solar surface manifestation of the convection by which the sun transports energy through its outer part. The G band also shows, with special emphasis, magnetic elements appearing as tiny bright structures, known as "Bright Points". They cluster in the inter-granular lanes, being swept into these by the convective motions. They consist of slender, near-vertical magnetic "flux tubes" with magnetic field strength of about 1200-1500 Gauss. It takes a sharp telescope as the DOT to properly image these flux tubes. They brighten especially in the G band because the CH molecules dissociate within the flux tubes, making these more transparent viewing pipes into the hotter solar sub-surface gas. The image can be enlarged on the screen for better visibility of the tiny bright structures. See also **ref. 28** for study of the motions of the bright points. The images in **Figures 32 a to d** are compared with each other in the website part <https://dutchopentelelescope.nl/images/> There, the images are displayed 90° rotated to the left.

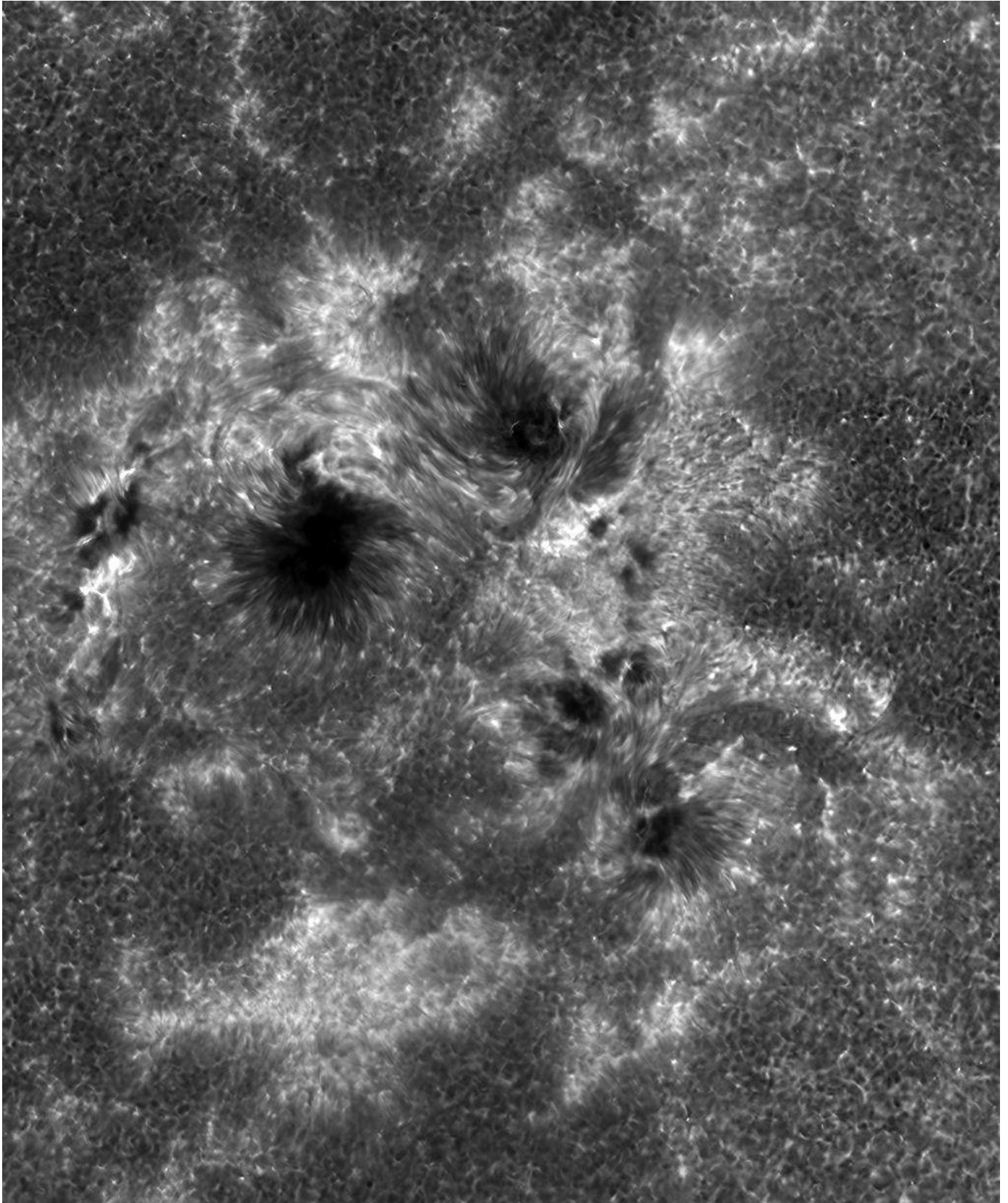


Figure 32b. Ca II H line 396.85nm, filter width 0.13nm. Same solar area as G band in Figure 32a at exactly same moment. The Ca II H line is formed a few hundred kilometers above the solar "surface" as seen in white light and G band. This is the low chromosphere at height of about 400km, precise height depends on the degree of activity. This line is due to once-ionized calcium and is one of the two strongest in the visible-light part of the solar spectrum. The other is its companion, the Ca II K line at 393.37nm. They are wide adjacent absorption lines in the violet part of the spectrum. At this height, the magnetic regions, where large numbers of magnetic elements cluster together, known as "plages", are very bright. The dark areas contain "reversed granulation" with a partial contrast reversal of the granulation seen in the corresponding G band image in **Figure 32a**. Some isolated small bright features in the dark areas are due to shocks in the solar atmosphere, made by low-frequency sound waves that travel upward and steepen into shocks where the gas density decreases at larger height. See also **ref. 24** for the study of the plages. The images in **Figures 32 a to d** are shown and compared with each other in the website part <https://dutchopentlescope.nl/images/> There, the images are displayed 90° rotated to the left.

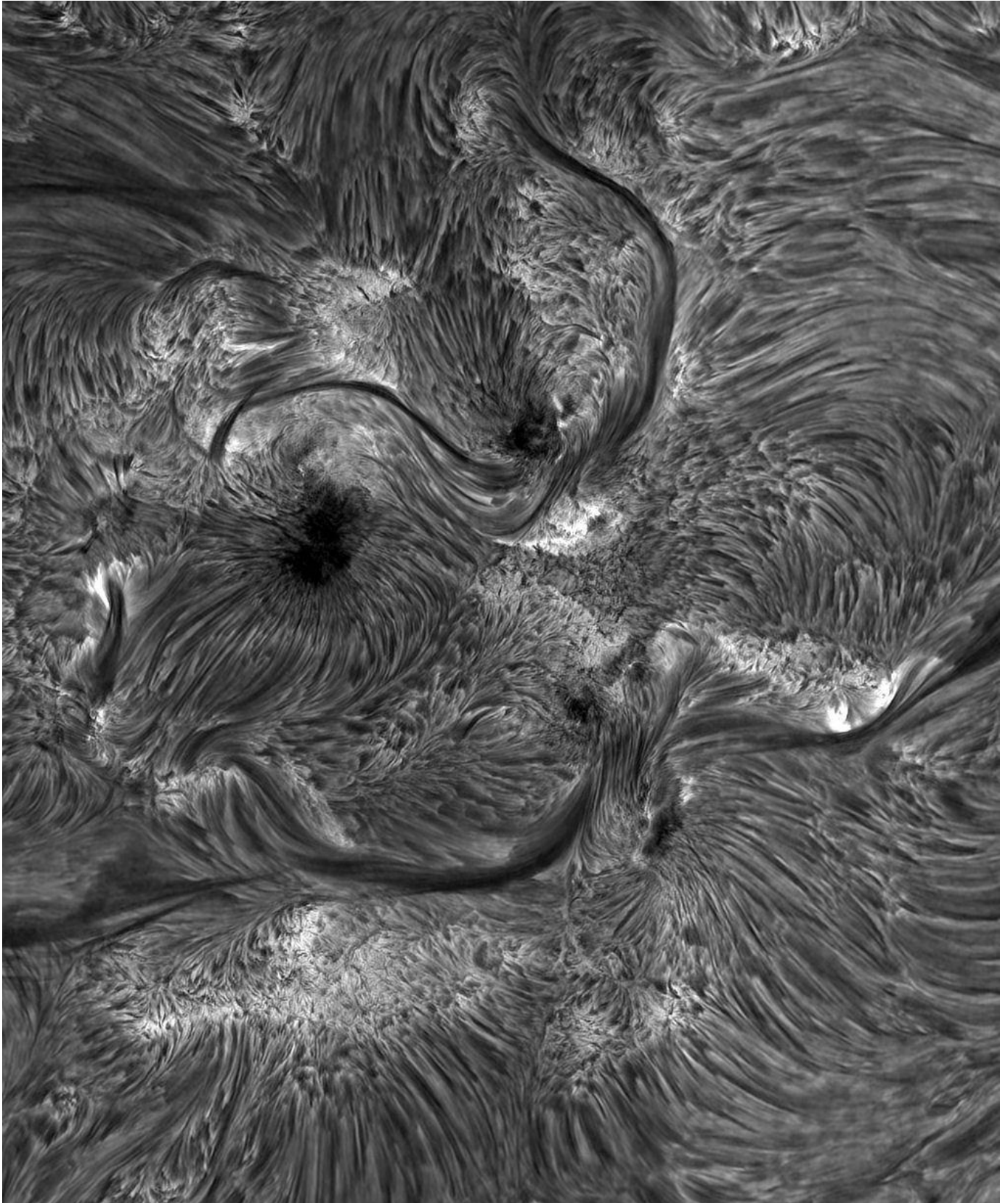


Figure 32c. H-alpha line 656.28nm, filter width 0.025nm. Same solar area as G band and Ca II H in **Figure 32a and 32b** at exactly same moment. Hydrogen H is about 80% of the solar gas and the H-alpha line is formed in the high Chromosphere about 2000km above the solar "surface", again precise height depends on the degree of activity. The sunspot center parts, the umbrae remain dark in H-alpha. Many so-called fibrils emanate away from the sunspots. They outline magnetic connections between different areas, like iron filings around a bar magnet show the magnetic field structure. The many fibrils show how complex solar magnetism is arranged within the solar atmosphere. The whitish areas surrounding the sunspots are plage, where large numbers of magnetic elements cluster together. The long slender dark structures are active region filaments. They end in bipolar regions where both positive and negative magnetic fields emerge through the solar surface. More, including instrument, see **ref. 17**. The images in **Figures 32 a to d** are shown and compared with each other in the website part <https://dutchopentlescope.nl/images/> There, the images are displayed 90° rotated to the left.

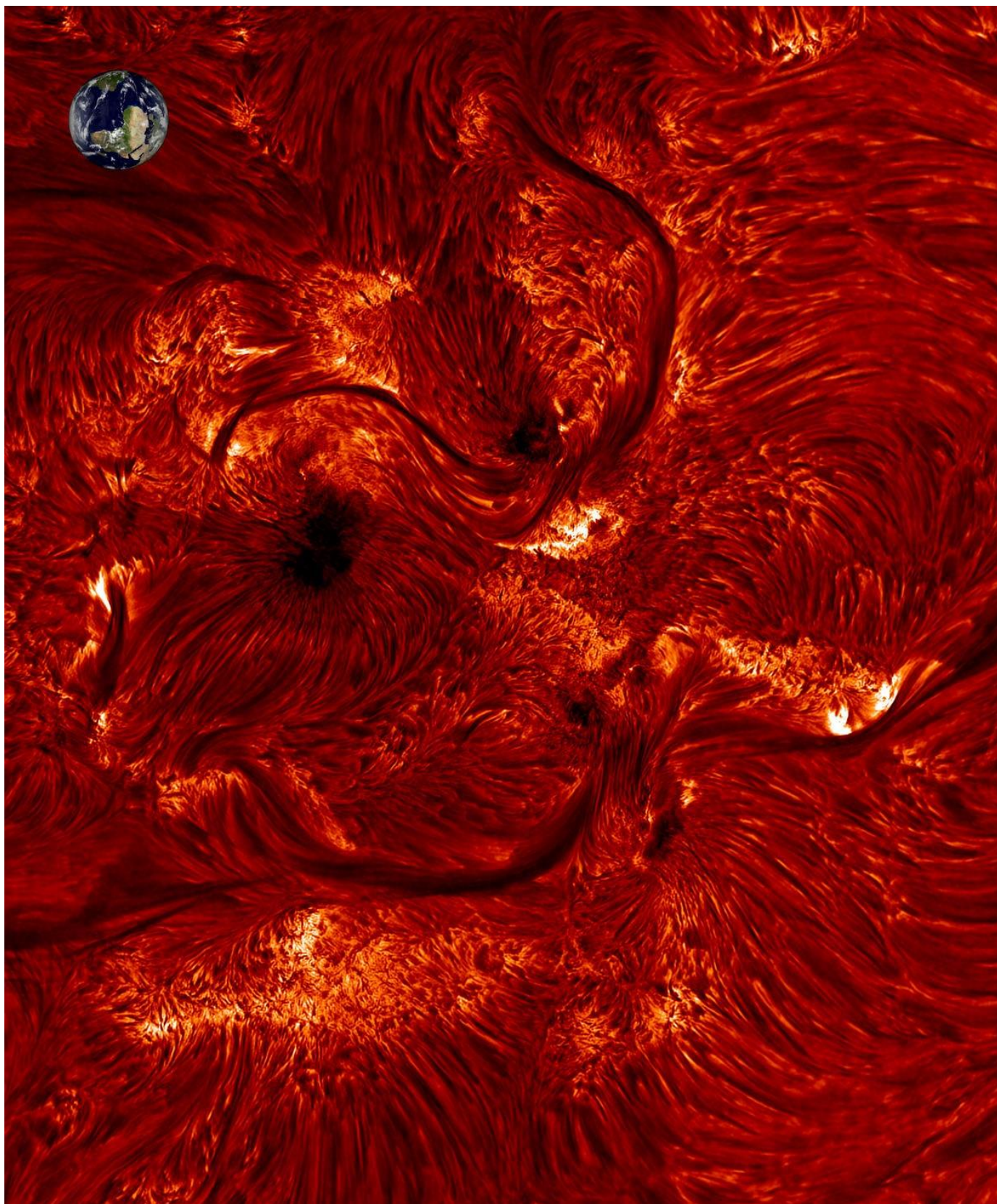


Figure 32d. H-alpha line 656.28nm, filter width 0.025nm. Image of **Figure 32c** with added colouring for more noticeable visibility of the structures. The inserted Earth photograph from space indicates the scale. The whole sun has a diameter of 109 times the earth. The images in Figures 32 a to d are shown and compared with each other in the website part <https://dutchopentelescope.nl/images/> There, the images are displayed 90° rotated to the left., the images are shown 90° rotated to the left..

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A mosaic from the sun’s North pole till the South pole is in this paper shown in parts.

The complete mosaic is in the file:

20040913-sunstrip-gb.png (16 MB) in

https://drive.google.com/file/d/15PFP2-h-av3JaJedBMn2INuLv_hnYSnz/view?usp=sharing

or more compact 20040913-sunstrip-gb.jpg (5 MB) in

https://drive.google.com/file/d/1uoBoCBPdSBV8GlcrcnPMhjiPKH7D_SlX/view?usp=sharing

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