EXCURSION: TOWER, PARKING LOT, GEOSTATIONARY ORBIT

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ABSTRACT

A tower, which consists of an open framework of steel, is built for the support of a solar telescope. Interferometric measurements showed the stability of the tower in wind. The interferometric measurements also showed that the seeing improves with wind and that the seeing bubbles near the ground have diameters of several meters. This makes it understandable that for smaller instruments the seeing is good from a parking lot. Some variants of the tower construction and of the interferometers are discussed. One of these interferometers is used for the measurement of the vibrations of a 25 m radio telescope in wind. The interferometers may provide interesting applications in space too. Some speculations about stellar Michelson interferometers in geostationary orbits are given. The achievable resolution of 10^{-6} arc sec is of interest for the study of solar-like stars.

1. THE TOWER

The ground is heated by the sun. A layer of forced convection develops near the ground. The temperature varies in this layer, which would deteriorate the image quality. The tower should elevate the telescope above this layer. A wind breeze mixes the air and keeps the layer of forced convection thin. In this situation the tower platform will reach air with homogeneous temperature. Temperature measurements and also the interferometric measurements, which will be treated later in this paper, show that wind speeds above 5 m/s give sufficient mixing.

The tower itself should not disturb the air mass around the telescope. An open framework meets this requirement. The question is whether a framework tower is stiff enough, because the rotational vibrations of the tower platform excited by the wind should be smaller than the resolution limit of the telescope. A classical solution is a double tower where the inner tower supports the telescope and the outer tower encloses the inner tower without touching it. In this construction the separation of the foundations of the two towers requires extreme care in order to prevent that the vibrations of the outer tower reach the inner tower through the foundations. In addition, the instrument on top of the inner tower may catch some wind. These problems are avoided if it is possible to construct a single tower, which is stiff enough against rotational vibrations of the platform. We searched for such a construction to be applied in a removable tower with a height of 15 m. This tower should support a 45 cm telescope with a resolution of 0.25 arc sec and so the rotational vibrations of the platform should not exceed this value for wind speeds up to 10 m/sec.

We first calculated a tower in classical framework as indicated in figure 1a. 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 1b. 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 (Serrurier, 1938) shown in figure 1c is 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^{o} 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. 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 3 shows the tower, which is temporarily mounted on the site of the radio telescope at Westerbork in The Netherlands. Some information about the dimensions of the parts used in the tower can be found in Hammerschlag (1973), some photographs of the assembly in Hammerschlag and Zwaan (1975).

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 tri-

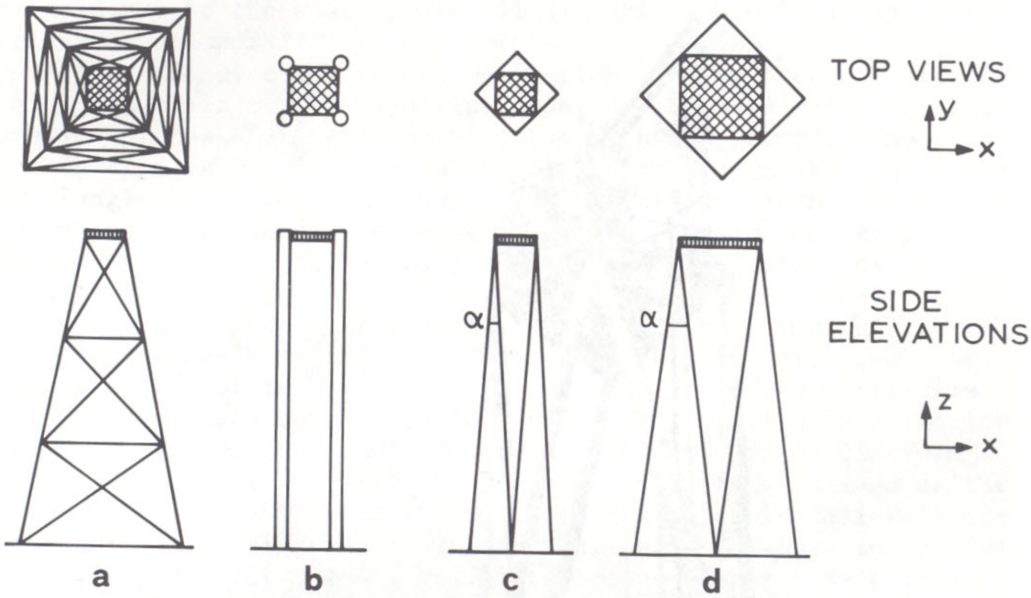

FIG. 1.— Various tower constructions
a. classical framework
b. platform on posts
c. 4 triangle truss with small platform and small base
d. 4 triangle truss with large base and large platform

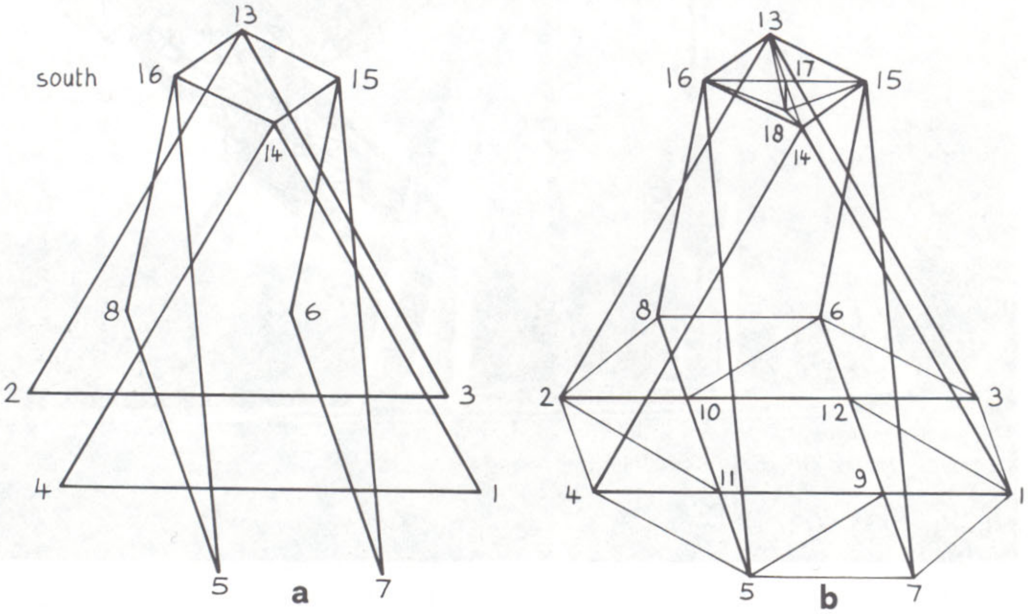

FIG. 2.— Tower construction with large base and small platform
a. principle of the construction
b. the complete framework

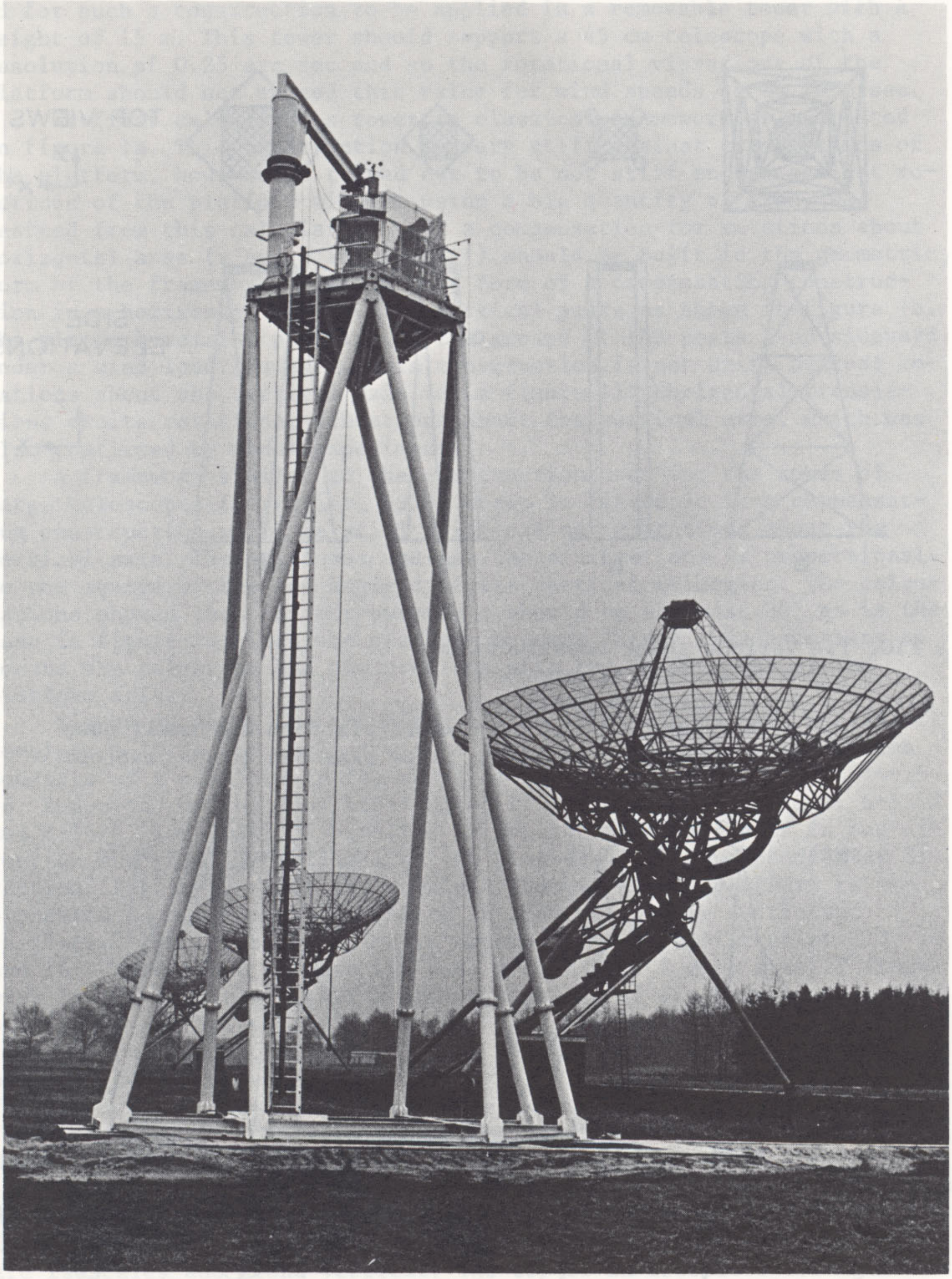

FIG. 3.— The tower temporarily mounted on the site of the radio telescope at Westerbork

angle. 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 4 shows one of the variations. This tower consists of three vertical isosceles triangles ABD, BCE and CAF, which bear the platform DEF. We put the telescope (Hammerschlag, 1980) 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.

The tower was originally designed for erection on dune sand. The four triangle tower with 8 base points possesses a compensating effect which eliminates largely the rotation of the platform about horizontal axes caused by elastic impression of the ground under the fundaments of the base points. A separate concrete block is under each base point. It measures 1.5 m square and has a depth of 1.1 m. Suppose that the wind comes from the south in figure 2a and produces a horizontal force on the platform. The triangles 1-4-14 and 3-2-13 bring this force down to the base points. The base points 1 and 3 will go downwards and the points 4 and 2 will go upwards with the same amount, if the ground stiffness is homogeneous over the area of the base points. Consequently the platform points 14 and 13 will remain at the same height. The triangles 5-8-16 and 7-6-15 hold the platform parallel. The functions of the pairs of triangles are interchanged for wind forces from the perpendicular direction and a force in arbitrary horizontal direction can be resolved in the two perpendicular directions.

The tower with three base points in figure 4 will possibly rotate too much in wind, if it stands on only three small concrete blocks in sand. The information about the stiffness of sand ground in the domain of μm deformations, which I could get from experts on soil mechanics, was very uncertain. They suspect large differences, which depend on the history of the ground. An expensive concrete block with an area equal or larger than that of the base triangle ABC may be necessary. A thin concrete plate will bend too much.

To achieve the compensation effect for the deformation of the ground with a three triangle tower one has to change the three base points construction into one with six base points. For example, we can

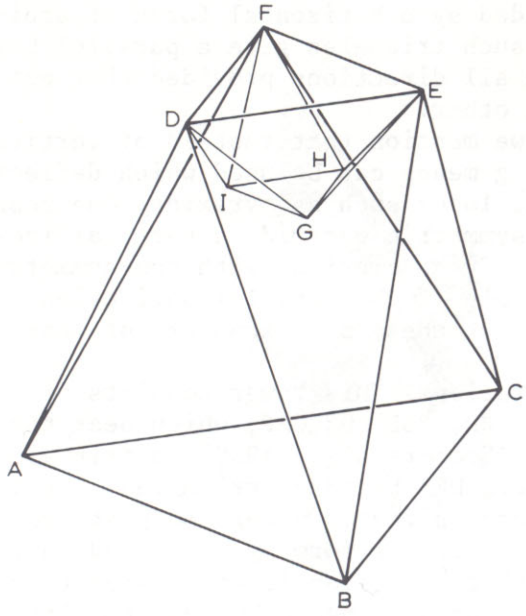

FIG. 4.— Three triangle tower

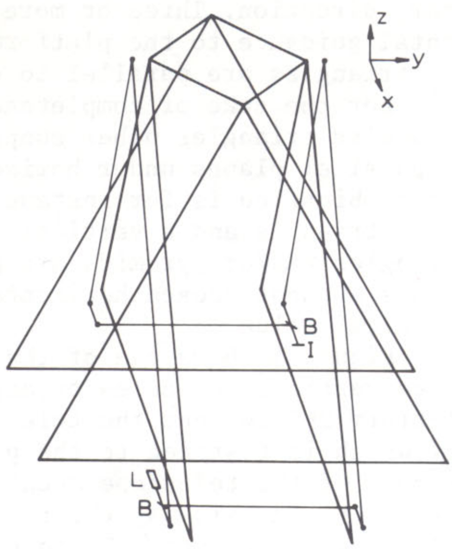

FIG. 5.— Interferometer for measuring the rotations of the platform about the horizontal x axis

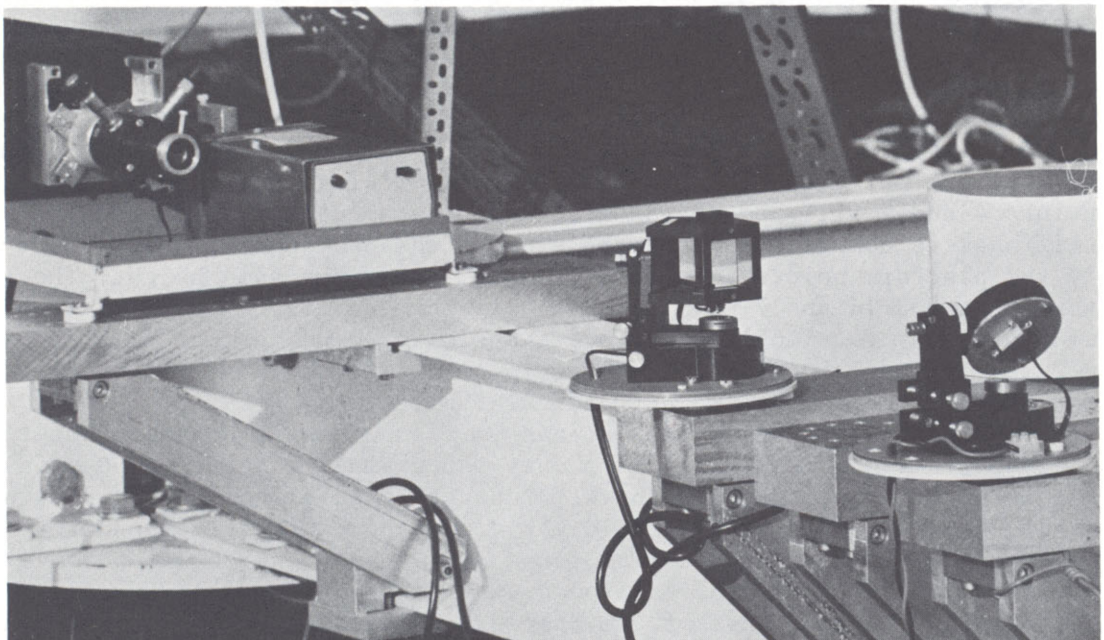

FIG. 6.— Beam expander on laser, beam splitter and deflection mirror

rotate the vertical triangles in figure 4 about vertical axes through their tops. In this way, the three base points become six base points. However, the stiffness of the platform against rotations about the vertical axis decreases. The vertical components of the forces on the base points caused by a torque about the vertical axis on the platform neutralize each other in the case of three base points. This neutralization is lost by splitting each combined base point of two vertical triangles into two separate base points. The same neutralization effect is present in the tower principle of figure 1d. Therefore, the tower of figure 2 is less stable than the one of figure 1d for platform rotations about the vertical axis. The described rotation of the triangles in the three triangle tower of figure 4 gives an additional decrease of the stiffness against platform rotations about the vertical axis because the planes of the vertical triangles come nearer to the center of the platform and the triangles are less able to bear a torque about the vertical axis.

Solid rock does not require any compensation effect for the deformation of the ground. The tower of figure 4 is suitable for sites on this type of ground.

2. INTERFEROMETERS

2.1. Interferometric measurements at the open tower

Figure 5 shows schematically an interferometer for measuring the rotations of the platform about the horizontal x axis. The tower construction is indicated with the principal framework of figure 2a. The light beams of the interferometer are drawn with thinner lines. The symbol L indicates a laser, B a beam splitter, I the interference pattern and the dots indicate deflection mirrors. The laser beam is split into two beams, which are reflected to two 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 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. 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 rotation.

The photos in figures 6 and 7 show the kind of material used for the interferometers. The beam expander on the laser, the first beam splitter and the back of one of the deflection mirrors are visible in figure 6. Notice the stiff supports under the beam splitter and the deflection mirror. The supports of the deflection mirrors in the ground plane rest on the concrete blocks of the base points of the tower. Hence the interferometer measures only the deformation of the steel construction and not the deformation of the ground. Inclusion of the ground deformation would require separate foundations for the mirrors in the ground plane. An electrical heating resistor is visible behind the mirror. A few watts dissipation prevents condensation of

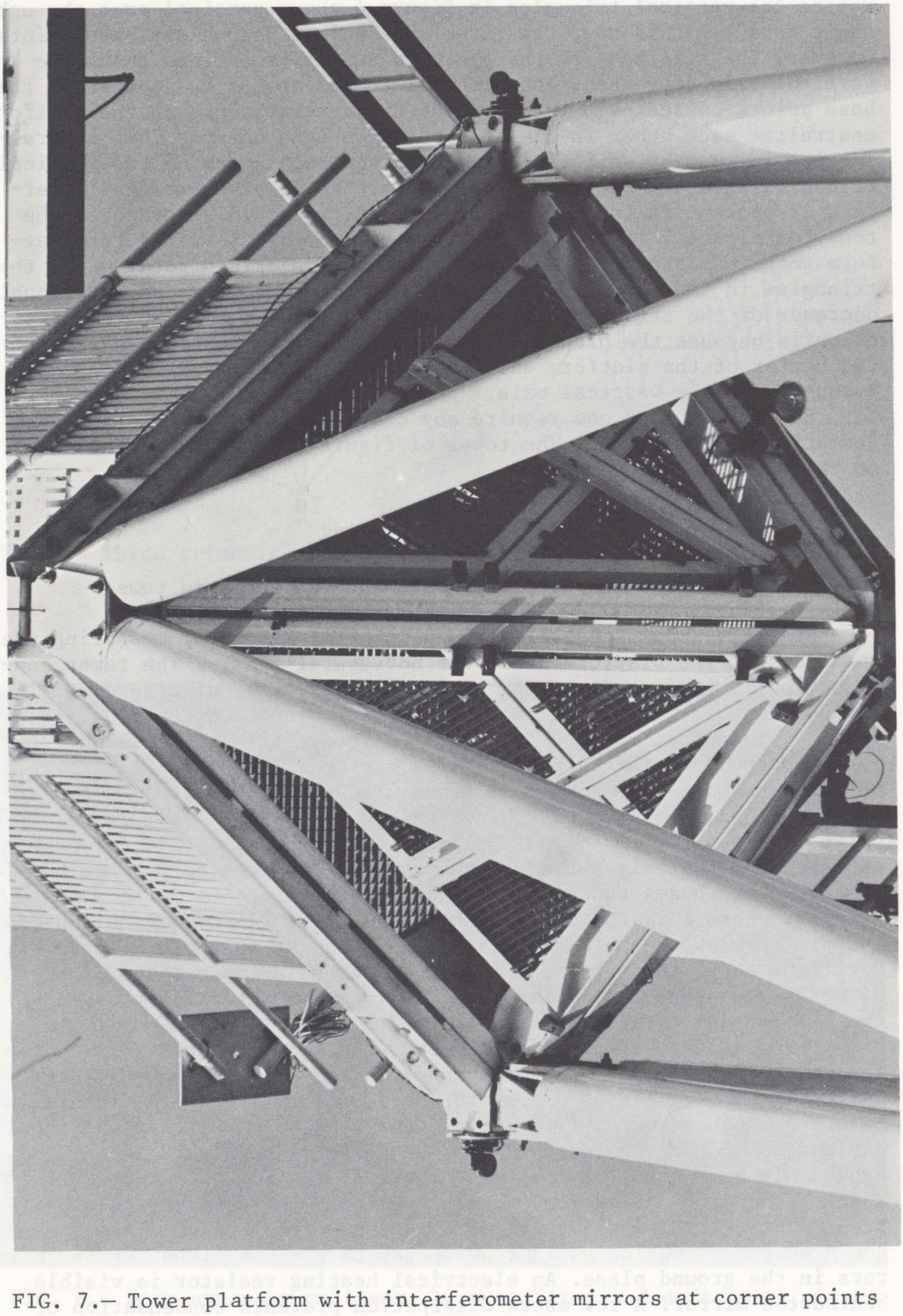

FIG. 7.— Tower platform with interferometer mirrors at corner points

water on the optical components during night measurements. Our experience is, that this small amount of heating does not disturb the interference pattern. Figure 7 shows the platform with the interferometer mirrors on two opposite corner points. An optoelectronic scanning system in the interference pattern counts the number of shifted fringes (Hammerschlag, 1975). The digital signal is converted to an analog signal and registrated on a recorder.

Figure 8 shows registrations of the interferometer. Not only rotations of the platform but also seeing effects do change the optical paths in the interferometer arms. These unwanted seeing effects are strongest on sunny days with wind speeds lower than a few meters per second. Figure 8a shows the largest seeing bubble which was registrated. No wind means a wind speed lower than 1.5 m/s. The bar 5 µm seeing on the registration indicates 5 µm path difference between the two interferometer arms, the bar 5 µm vibration stands for 5 µm height difference between two opposite corner points of the platform and the bar 0.5" stands for 0.5" rotation of the platform calculated from the height difference divided by the distance between the two corner points. The peak to valley distance in the registration corresponds to an average temperature difference of $0.5^{o}C$ between both interferometer arms with a length of 33 m. The drift of a bubble of a temperature difference of several degrees and a diameter of several meters through one arm and a few seconds later through the second arm is a plausible explanation of the registration. As soon as the wind speed is higher than a few meters per second these bubbles disappear from the registrations. Figure 8b shows the registration with a wind gust of 9 m/s. No significant vibrations are visible.

As mentioned earlier, figure 8a shows the largest bubble on the registrations. But the time scale of this largest bubble is typical: smaller perturbations occur on the same time scale. This means, that most of the large seeing bubbles near the ground have probably a diameter of some meters. During this meeting, there was doubt whether wind will improve the seeing, because there was experience of excellent seeing from the ground of a parking lot (Title, 1980). The occurrence of seeing bubbles of several meters diameter near the ground makes it plausible, that the seeing will be qualified as good with telescopes of smaller diameter. The deterioration of the image caused by the bubbles will increase with increasing telescope diameter. Hence it may still be meaningful to put a larger telescope on a tower in the wind above the layer of forced convection.

The steps of the author, walking to-and-fro between the two corner points of the platform, are registrated in figure 8c. The measured platform rotations agree with the calculated stiffness of the tower and the weight of the author. This registration was often repeated between other registrations and we always found the same rotation, which proved that the interferometer worked properly. The individual footsteps are visible on the registration in figure 8c. Sometimes the author stamped across the platform. The result is shown in figure 8d, where the resonance frequency of the legs of the tower appears. Figure 8e shows the registration of a slap on a leg with a rubber hammer. This registration with 5 times higher paper speed shows, that the res-

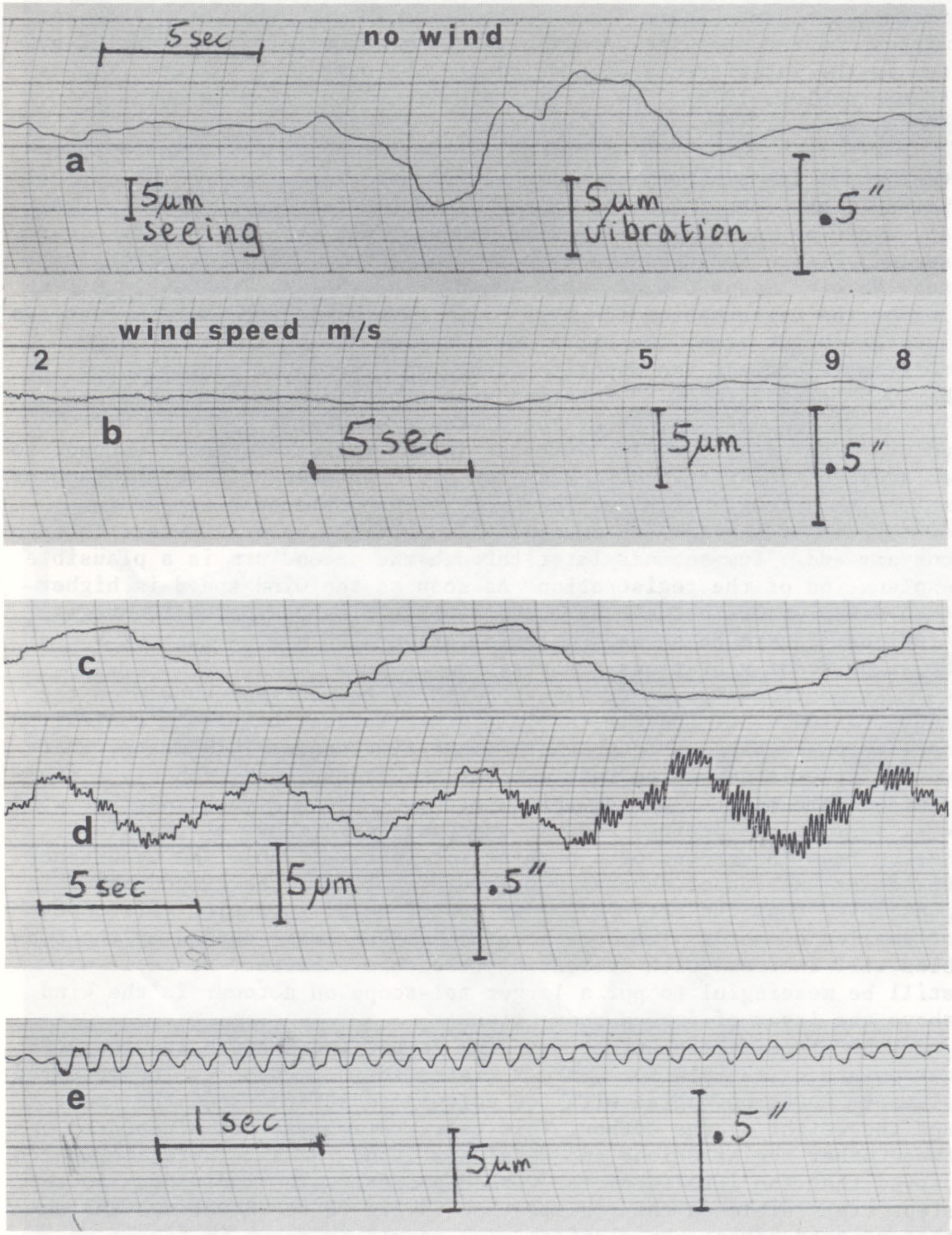

FIG. 8.— Registrations from interferometer of figure 5
a. Seeing bubble
b. Wind gust of 9 m/s
c. Walking across the platform
d. Stamping across the platform
e. Slap on leg

onance frequency is about 6 Hz.

We see from the registration in figure 8d, that the legs come easily in resonance because of the low internal damping of metal. Wind can also cause resonance vibrations. The site at Westerbork is flat. The wind velocity increases with the height. The wind load on the lower part of the legs is small. On top of a mountain like on La Palma, the wind velocity will be high as far as the ground and also the middle and lower parts of the legs will catch the full wind load. The risk of resonance vibrations induced by wind will increase. If necessary, we will install dampers between the tubes similar to the method described for the telescope tubes, see figure 3 and the appendix in Hammerschlag (1980).

Calculations show that already the static wind load gives too much rotation to the platform, if we assume that the full area of all 8 legs gets the full wind pressure and that the platform including the connections with the legs is completely stiff. The reason is, that in this case the legs of the tower bring too much torque to the platform. Tension and compression forces in the legs bring the torque to the ground. The platform rotates by the elongation and shortening of the legs. The calculated torque brought by the legs to the platform is substantially larger than the torque from the telescope. The calculation gives an upper limit for the torque on the platform. The real torque will be smaller, but it is difficult to give a precise estimate. It also depends on the wind direction. If it turns out to be necessary, we can select out of 4 methods, which reduce the torque on the platform:

1. Installation of hinges in both directions between legs and platform. Legs pin connected to the platform can not transport a torque to the platform. The resonance frequency of the legs is multiplied with 0.7, which can be a disadvantage. The installation of the hinges gives less problems in a three triangle tower than in a four triangle tower, because the former is statically determinate. Internal stresses, which load the hinges, can not occur in a statically determinate construction.
2. Installation of tubes around the existing tubes of the legs. These outer tubes rest loosely against the platform or top of the inner tubes and do not touch the inner tubes between base and top. There is no high stiffness requirement on the outer tubes, but damping will be advisable.
3. Installation of bars or tubes from the ground to the center part of the legs. The center parts of the legs make a relatively large excursion before a troublesome torque is transmitted to the platform. Connections to the ground with relatively small cross section area will satisfy. But resonance vibrations of the connections itself should be avoided by sufficient moment of inertia of the cross section.
4. A semi transparent wind shield (Hammerschlag and Zwaan, 1973a,b) around the lower and middle part of the tower.

The walls of the tubes of the legs of the existing tower have 10 mm thickness, the diameter of the tubes is 244.5 mm. A larger thickness of the walls increases the stiffness of the platform against rotations. The resonance frequency does not decrease significantly with increasing wall thickness. Hence also an increase of the wall thickness solves a possible problem with the rotation of the platform by torque from the legs.

2.2. Other configurations for interferometers

A method for the measurement of the rotation of the platform about the vertical axis was described by Hammerschlag (1975). It combines the measurements of two interferometers. However, the rotation about the vertical axis can be measured with a single interferometer. Figure 9 shows two versions of an interferometer only sensitive to rotations about the vertical z axis. The principle is the same as in the interferometer of figure 5: the difference between the two separated light paths from the first beam splitter B to the second beam splitter B is measured. Rotations about horizontal axes and translations of the platform do not change the path difference between the two interferometer beams. In figure 9a the beams go over the platform. If equipment on the platform prevents this, then the interferometer in figure 9b can be used. The paths in the interferometer of figure 9b are longer, which makes the interferometer more sensitive to seeing and the alignment more difficult.

Figure 10 shows an interferometer, which is only sensitive to translations perpendicular to the direction BQ. Figure 10a gives an outline of the components. L is the laser, B1 and B2 the beam splitters, R the fringe counter in the interference pattern and M1, M2, M4

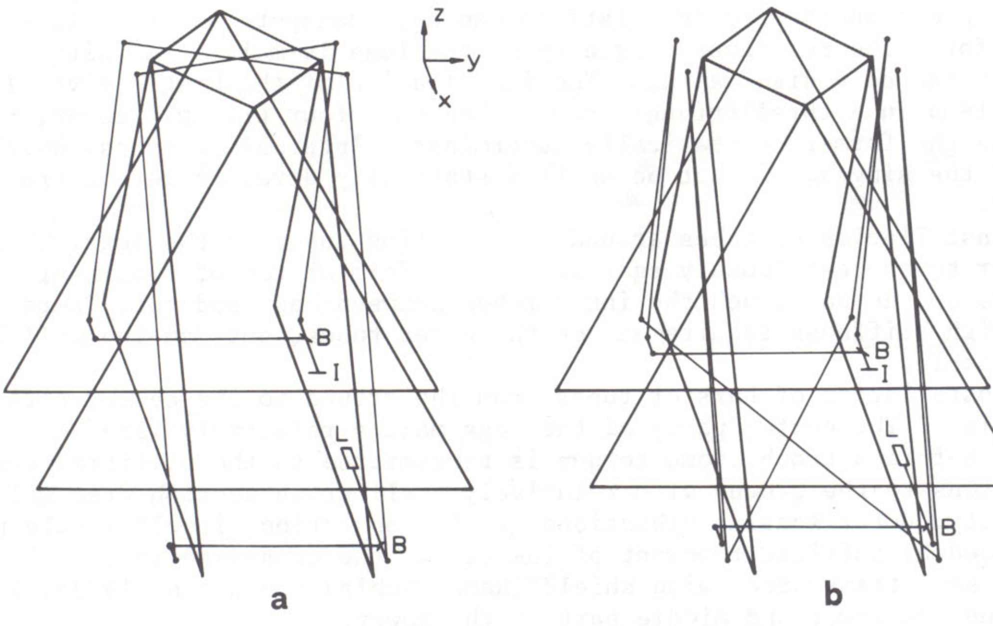

FIG. 9.— Interferometers for measuring the rotations of the platform about the vertical z axis
a. light beams over platform
b. without light beams over platform

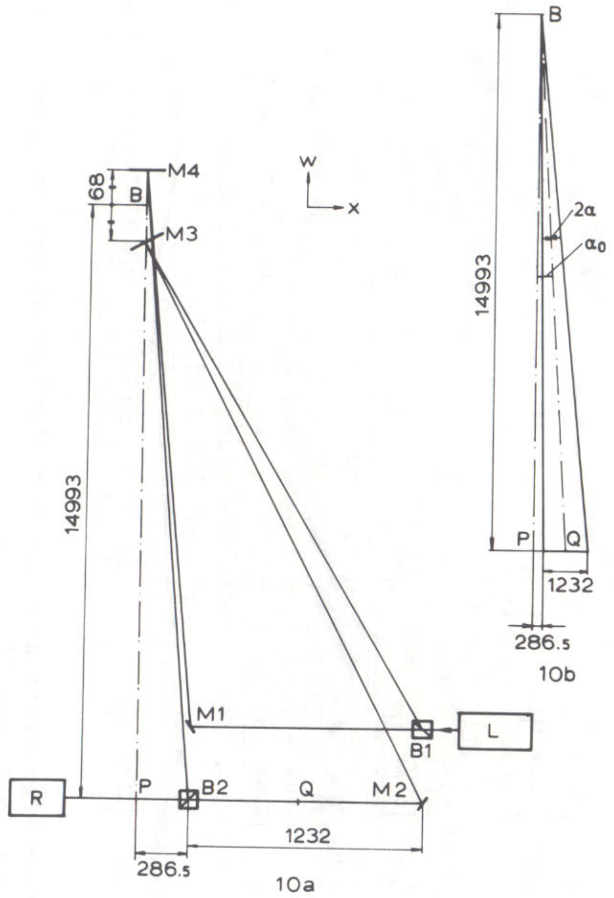

FIG. 10.– Interferometer for measuring translations
a. outline of the components
b. outline on scale, all dimensions in mm

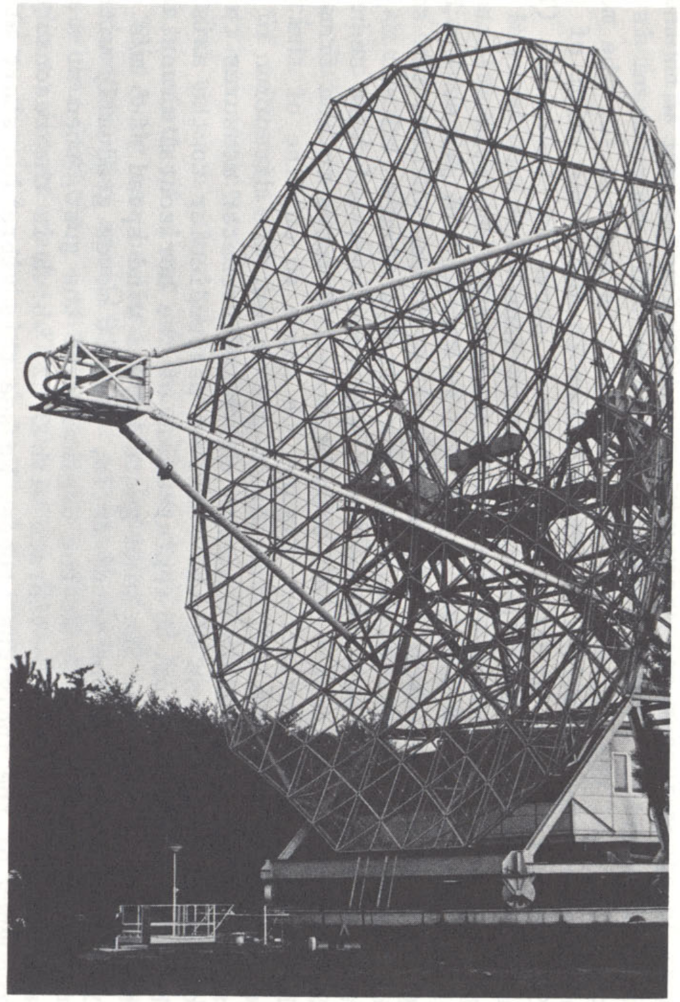

FIG. 11.– 25 m radio telescope at Dwingeloo

are mirrors. M3 is a semi transparent mirror, which transmits 2/3 of the light and reflects 1/3. The position of the mirrors M3 and M4 above each other removes the rotation sensitivity present with the mirrors M3 and M4 side by side. The price for this improvement is the loss of 2/3 of the light. The interferometer is applied for the measurement of the vibrations of the receiver in the focus point of the 25 m radio telescope at Dwingeloo, which is shown in figure 11. (This radio telescope was used for solar observations with a 60 channel spectrograph.) The laser L, the fringe counter R, the beam splitters B1 and B2 and the mirrors M1 and M2 are in the ground plane. The beam splitter B1 and the mirror M2 are very close to each other, the same for the beam splitter B2 and the mirror M1. The mirrors M3 and M4 are at the place of the receiver antenna. The receiver, which is seen on the left side of figure 11, is connected with 4 tubes to the frame of the 25 m parabolic reflector. Figure 10b shows an outline of the interferometer on scale. All dimensions are in mm. The direction of BQ is nearly vertical and in practice the interferometer measures the horizontal translations of the receiver perpendicular to the axis of the parabolic reflector. A registration of the horizontal translations is shown in figure 12. The wind gusts have a wind speed of 5 m/s. The typical behaviour of the receiver is, that it moves gradually with the increasing wind velocity at the beginning of the gust, then at a certain moment it starts to vibrate with 3 Hz, which is the resonance frequency of the individual tubes. We see this vibration start at second 230 and at second 295. After the end of the wind gust the 3 Hz vibration maintains tens of seconds because of the low internal damping. The measured vibrations are much larger than those of the tower and the seeing does not give a noticeable contribution in this registra-

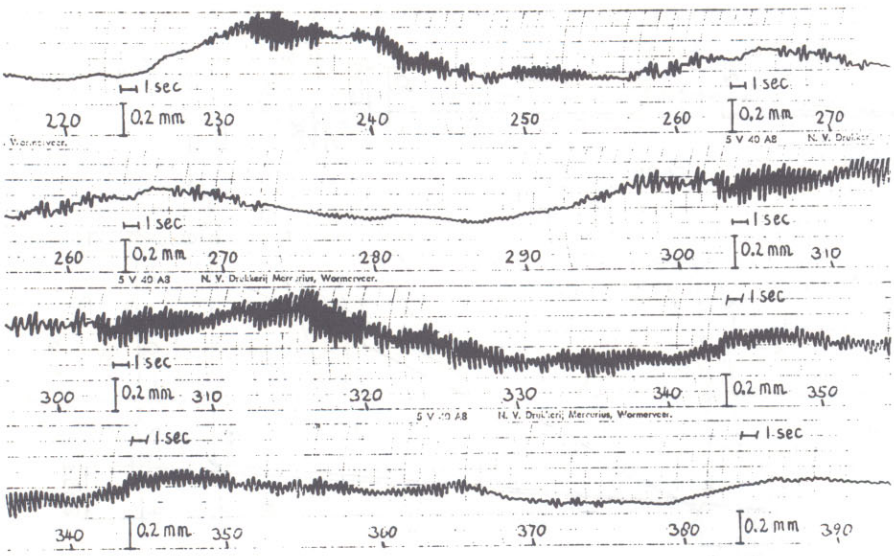

FIG. 12.— Registration of the translations of the receiver of the telescope in figure 11

tion. However, the amount of seeing is important for the amount of light necessary for the measurements: more seeing requires more light. More details about the interferometric vibration measurements of the 25 m radio telescope can be found in Hammerschlag (1979).

2.3. Interferometers in space

We used the interferometers to measure the deformations of structures, which are constructed as stiff as possible. On the other hand, one can use the interferometric measurements for feeding a system, which corrects the position of the structure elements (active system). Even structures which have not any mechanical connection can be positioned to each other. This may give interesting applications in space. To conclude this excursion, let us speculate a bit about these possibilities.

If telescopes of 1 m diameter are used for expanding the laser beams then structures on distances up to 100 km can be positioned relative to each other with μm precision. A kind of body can be built, which consists of a set of satellites coupled by interferometers.

This body can be used for the location of a Michelson stellar interferometer. Two satellites are equipped with mirrors which reflect the stellar light to a third satellite, where the two beams are brought to interference. The light paths from the star to the third satellite should be made equal as good as possible. This increases the usable spectral bandwidth. A broader bandwidth increases the signal. Figures 13a and b show two satellite configurations. Geostationary orbits are chosen, because they offer the possibility of real time control from a single groundstation, which is an advantage for a complex system like an interferometer. We suppose, that the star is somewhere near the equator.

The configuration in figure 13a has an interferometer baseline in the equator plane. The plane of the drawing is the equator plane. A and B are the two satellites, which reflect the stellar light to the third satellite C. The distance from A to B is exaggerated in the figure for the sake of clearness. The interferometric distance is DA, which goes from 0 for $\alpha = 0$ to the maximum value AB for $\alpha = \pi/2$ and goes back to 0 for $\alpha = \pi$. On the traject of α from π to 2π the same cycle is completed with A and B interchanged. The requirement of equal paths gives: DB + BC = CA. It follows that C has to be near A for $\alpha = 0$ and has to move from A to B when α goes from 0 to π. For $\alpha = \pi/2$ satellite C has to be in the point M just in the middle of A and B. Satellite C has to go back from B to A when α goes from π to 2π. Suppose A and B are in circular orbits. The satellite C will make the motion between A and B, if it has a slightly elliptical orbit with the lower part of the orbit from $\alpha = 0$ to π and the higher part from $\alpha = \pi$ to 2π.

Figure 13b shows a configuration with the interferometer baseline A'B' perpendicular to the equator plane. The equator plane is perpendicular to the plane of the drawing. Now the satellites A' and B' reflect the stellar light to the satellite C'. The satellite C' is in an exact equatorial orbit. The orbits of the satellites A' and B' have a small inclination with respect to the equator. The inclinations have

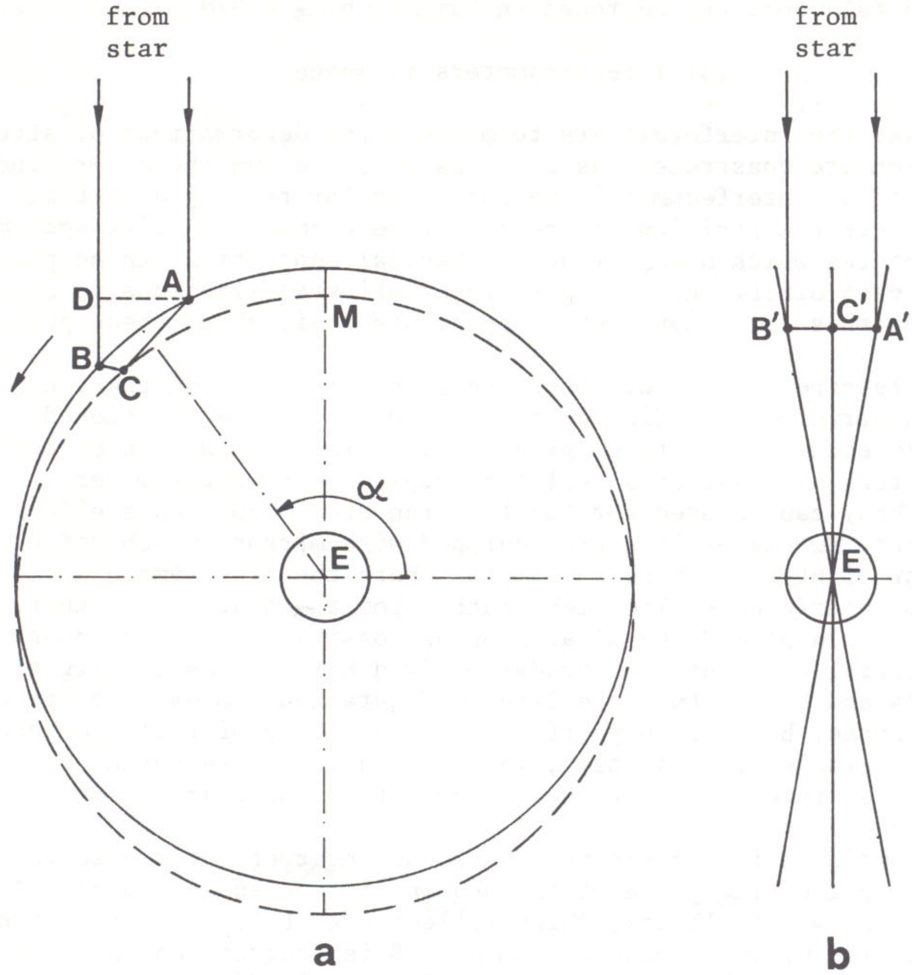

FIG. 13.— Satellite configurations for stellar interferometer
a. interferometer baseline AB in equator plane
b. interferometer baseline A'B' perpendicular to equator plane
E = earth; A, B and C satellites in configuration a;
A', B' and C' satellites in configuration b

equal magnitude and contrary directions. Consequently, A'C' is always equal to C'B' and the light paths from the star to satellite C' are equal. The inclination of the orbits of the satellites A' and B' is drawn exaggerated for the sake of clearness.

Measurements with the described laser interferometers of the positions of the satellites can feed an active system, which improves the equality of the star light paths. In addition, sufficient precise measurements of the positions can help to get the phase of the stellar interferometer fringes. In this way it would be possible to reconstruct star images. A maximum interferometer distance of 100 km means a resolution of 10^{-6} arc sec in visible light. Of course, there are many interesting objects, which can be studied with this kind of resolution. Among them are solar-like stars.

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