Mem. S.A.It. Vol. 89, 540

Memorie della

Guido Horn d'Arturo: selected papers

1. Introduction

In order to maintain and underline the authorship of Guido Horn d'Arturo of the innovative idea to build a tessellated mirror with all the well-known advantages, it is needed a -late- effort by the Italian astronomical community to give an international wide-ranging diffusion to the scientific legacy of the Italian astronomer.

Starting in the early 1930s, foreseeing the great difficulties that the construction of the mirror for the large 5-meter telescope for the Palomar Observatory would have encounter, Guido Horn d'Arturo had the ingenious idea of replacing the large surface of a monolithic mirror with the optimal assembly of a mosaic of many small ones, so having evident huge advantages in terms of construction, cost and maintenance.

This idea actually preceded what is now called the "active optics", the technology that -thanks also to the enormous technological developments in the following 90 years- allows nowadays to optimize the performance of the telescope itself by adjusting a system of actuators underlying the individual mirrors, according to the observational conditions. In perspective this technical active approach is the precursor of what is now commonly called "adaptive optics", the correction of the image quality by reconstructing the incident light wavefront.

Only in the Seventies, thanks to the new generation of large multi-mirrors telescopes, the huge technological and scientific impact of the glorious idea of Guido Horn d'Arturo -but rarely its authorship- has been definitively recognized.

The translation in English of a collection of the most significant scientific articles by Guido Horn d'Arturo, most of them written in Italian and for that often ignored by the international astronomical community, is an attempt to recall to memory his work and his name to an international framework.

The collection of the following articles has been selected by Marina Zuccoli e Fabrizio Bonoli in "Guido Horn d'Arturo e lo specchio a tasselli" (CLUEB Bologna, 1999), from now accessible to the whole astronomical community.

A not easy selection of the large numbers of Horn's papers let us understand the development of his work, starting from the first papers published in 1932 on Coelum, the monthly magazine devoted to spread the astronomical culture to professionals and amateurs. The selection of articles was published, beyond Coelum, in Memorie della Società Astronomica Italiana, and in Pubblicazioni of the University Astronomical Observatory of Bologna.

Send offprint requests to: R. Spiga

Rossella Spiga
INAF Osservatorio Astrofisico di Arcetri Largo E. Fermi 5, 50125 Firenze - Italy

Translation of Horn's papers by Giuliana Giobbi
INAF- Osservatorio Astronomico di Roma Via Frascati, 33, 00078, Monte Porzio Catone (Roma) - Italy

Astronomy Instruments and Advancements
(Coelum, 2, 1932, pp.25-27)

In another section of this issue, we are talking of the giant 5mt-aperture telescope which is being built in California for the Mount Wilson Observatory: here we are going to make a few general comments on the same topic. When scientist can observe for the first time with that instrument, many years will have passed from the start of its construction, and a sum of money will have been spent, which will make even Americans smile. Its power will *virtually* enable scientists only to observe up to a distance of 300 millions light-years, rather then to the limits of the Universe which, according to relativists, should be a few billions light-years from us. I'm underlying the term “virtually”, since there are a few obstacles to a full exploitation of the reflecting area. First of all – indeed - the mirror undergoes distortion with varying temperature during long photographic poses. According to Ritchey, a well-known giant-mirror grinder and finisher of huge mirrors, the disk edges are more affected by variations of ambience temperature than its centre, so that the glass mass, a poor conductor of heat, never has the same temperature in all its points, so that expansion is not homogeneous. It is therefore necessary to cover the border area with a opaque screen – a specular loop, thus excluded from reflection, is a few centimetres thick in the 1mt-aperture mirrors, and a few decimetres in the 2,50mt-mirror, and has already been used in the Mount Wilson Observatory. Just imagine the useless edge of a 5-mt mirror!

Ritchey tried to overcome the drawback of distortion by replacing the mirror's compact mass (whose minimum depth is usually one-seventh of the diameter) with a 1 or 2cm-thick glass reflecting disk, supported by a glass rear frame, soldered to the disc with a very strong resin. With this *cellular* system, the disc weight decreases, and it is easier to merge large masses. Moreover, a crystal thermal balance is quickly established, thanks to the air which circulates (sometimes artificially) down to the innermost sections of the frame, thus remarkably reducing the harmful effects of inhomogeneous dilation. However, as far as I know, nobody has ever built large-dimension mirrors with this system, and for a while now nobody has talked about it.

If you add to the distortion problem also the difficulty of making a huge mirror move regularly like a clock, since it is attached to the end of a really heavy tube, you must admit that the *current* telescope industry is near to its ultimate test, if it has not already reached it.

Since the Astronomer, unlike other scientists, has an object of study which is practically unreachable, and only one of his senses, sight, is useful to his research, unless his sight is further helped and sharpened, he won't be supplied with new material, and no further advancement will be possible. I am not saying that we have already observed *everything* current telescoped might help us observe. However, if the instrument progress has stopped, future observations will be useful for the completion of current knowledge, rather than for the discovery of new truths.

Just imagine what Astronomy would be like without the invention of telescope: the Solar System would end with the Saturn orbit. Without seeing Jupiter's satellites, the Copernican System itself would have never been established. The stellar world would be reduced to the stars of the first-order of magnitude, and to the impenetrable veil of the Milky Way. We could not have had the stars' precise positions, so as to draw their proper motions. If the spectroscope had not been added to the telescope, nowadays we would know nothing about the very weak lights which the human eye cannot grasp, whereas they leave their trace upon a sensitive plate, thanks to a prolonged exposure.

The lack of new observational material implies an ethical consequence, since it pushes researchers to *imagine* where they cannot *see*; now, imagination is fruitful until a researcher interprets certain facts. However, without the support of facts, imagination is a source of scientific aberration. In my opinion, we can find examples of this adverse effect in the history of any Science, and of Astronomy in particular. Indeed, for instance, when the Greeks completed their knowledge of all the objects which could be seen by the human eye, any substantial progress was deferred to the age of Galileo. However, Humankind did not stop fantasizing with *astrology*, which was carried on as a false science, namely not based upon the strict observation of facts, but rather upon prejudice and superstition. We should not believe, moreover, that Astrology was only practiced by quacks, since even University lecturers and scientists were interested in it. Only the triumph of the Copernican system showed the vanity of *celestial houses*, which suddenly missed the basis of a still Earth, and messed up the millennial patterns of astrologers, which did no longer correspond to the real planetary hierarchy.

Getting back to our case, we can say that the progress of both Optics and Mechanics, which has gone on for about three centuries, appears to be grinding to a halt. This cannot leave astronomers indifferent, since there are fewer objects for observations, and there is no chance to increase their knowledge and discover further secrets of Nature. There is certainly no fear of a comeback to Astrology, but we have to admit that in recent literature (of both Astronomy and other Sciences), we may note a few supernatural concepts, which actually appeared banned from the scientific language forever. Natural scientists are not repulsed by metaphysical problems, but history teaches us that everytime Metaphysics intervened into Science, it rerouted researchers, rather than helping them in their efforts.

We are all convinced that the main problem is *knowledge*. Until the lucky day comes, when someone finally tells us where our eyes make mistakes in looking at the world, and what portion of a supposedly real phenomenon is actually subjective, we had better forget this problem, and keep studying Nature with our senses, trying to sharpen them with more and more powerful and precise instruments.

Telescopes of the Future
Coelum 3, (1932), pp.49-52

In order to illustrate the reasoning we made in the February issue, we reproduce in Fig.1 the large equatorial telescope, mounted fifteen years ago at the Mount Wilson Observatory in California; at the lower end of the tube of the steel trellis, a parabolic mirror of silver glass[1] is attached, which has a diameter of 2,54 mt and a minimum thickness of 30 cm. The shapeless glass mass came out of the *St. Gobain* furnace in 1908, and it took three years for the reflecting surface to reach the required shape and smoothness. Only in 1917 could the telescope be completed. We should take into account the fact that the mobile portion of the instrument alone, which is given a uniform speed within 24 hours, has a total weight of about 100 tons. On the other hand, the revolving dome has a diameter of 18 metres.

Although – as we mentioned above – they are now facing the challenge of building a mounting which may be appropriate to the 5mt aperture, we doubt one can continue in this direction in the future. Perhaps, the moment will come when we must give up building mobile instruments, and settle for the use of huge mirrors in their horizontal stillness, while observing only that reduced strip of sky passing during the night across the *zenith* of the astronomical station.

The first step in this direction was made with *solar towers* and *horizontal camera mounts*, where the parabolic mirror, or the objective, stay motionless. However, in order to channel the light coming from any sky area upon these tools, you need an auxiliary mobile mirror (i.e. a *coelostat*). Therefore, the difficulty is bypassed rather than solved. Moreover, by increasing the dimensions of the motionless mirror, the mobile one grows out of all proportions. Thus the builder comes up against obstacles comparable to the ones linked to large equatorial mirrors.

---

[1] For the astronomical use, the mirror is silver-plated on its front surface rather than on its back, as is happens in ordinary mirror.

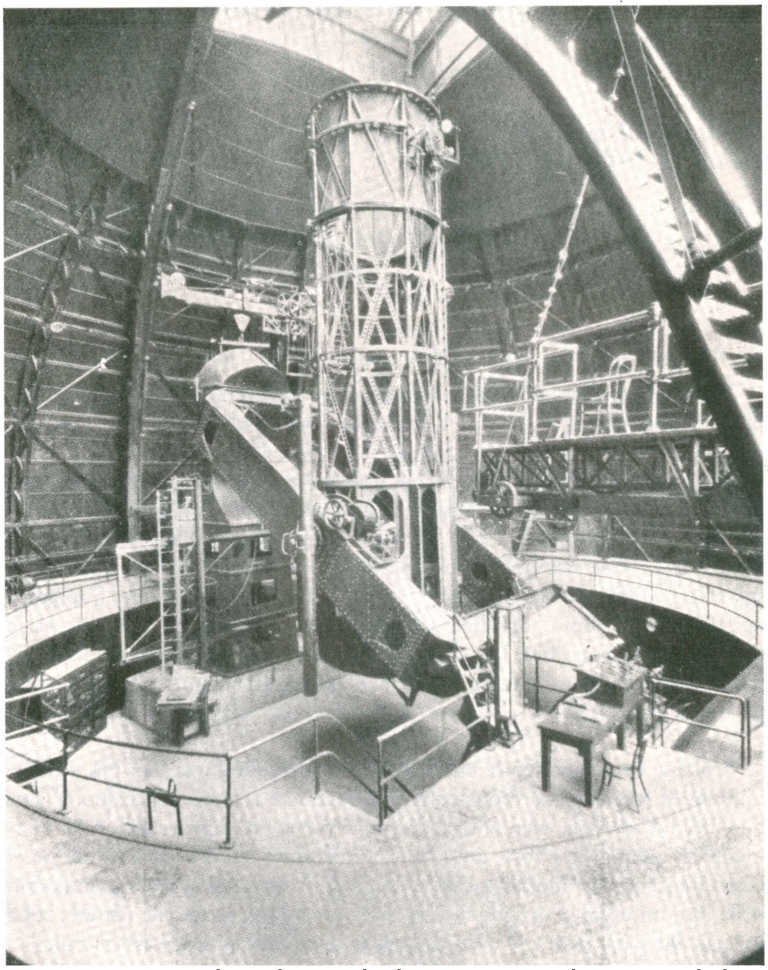

Figure 1 - Hooker Telescope, the largest astronomical instrument built sofar. The mirror diameter is 2,54 metres.

In the second half of the last century, the illusion ruled that large parabolic mirrors could be obtained quite easily, for horizontal usage. More than one builder thought of recurring to *mercury*, taking advantage of the fluids' property to assume a parabolic shape as their free surface rotates with a uniform speed. As far as anyone knows, the first attempt of this kind was made in 1870 by the English scientist C. Carrington, in his Observatory at *Red Hill*, where he spent most of his short life studying the varying speed of the Sun's fluid zones. However, his decisive experiment unfortunately showed, not the impossibility, but rather the obstacles challenging this genial idea. On the other hand, in 1909, the physicist R. W. Wood, of the University of Baltimora, published the results of his successful test. Figure 2 shows his device for the rotation of the metal plate containing mercury, through an electrical engine, whereas Figure 3 shows the concave surface of the fluid, which reflects the observer's image. The impossibility of obtaining an absolutely uniform angular velocity makes the focal distance of the fluid paraboloid change all the time, so that the observer is never sure of having either a sensitive plate – or rather his eyepiece - on the mirror's focus. Moreover, the unavoidable jolts of the engine provoke ripples on the fluid's surface, and a sort of tidal wave is produced by the imperfect verticality of the rotation axis. That is why the experiment by Todd and McAfee failed: they wanted to take a picture of Mars' *channels* with one such rotating fluid 15-mt mirrors, with a focal distance of 200 metres. The experiment should have been done 2500 mt high, from a pit, in the gold mines of Chanarol, Chile, since Mars passed its zenith there in the evening of August 24, 1924.

In order to recall all the attempts to increase the diameter of our instruments, let us quote the one made by E.H. Synge, who, two years ago, suggested an idea, which had been essentially already put into practice (by A. Michelson, for his interferometer, with a less complicated device). This test consists in replacing a huge, virtually impracticable lens with many small parabolic mirrors, which collect the light and transmit it to an ordinary lens after a series of reflections and refractions, as shown in figure 4 for one of these light collectors.

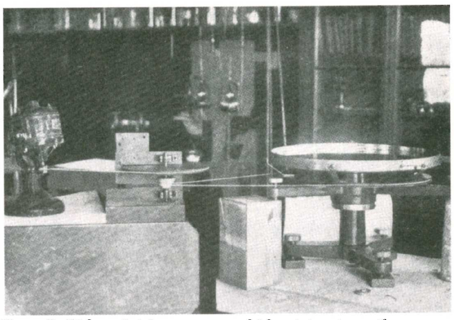

Figure 2 - Dish containing mercury, which rotates at a uniform pace thanks to an electrical engine.

Figure 3 – Observer's reflection onto the parabolic surface of rotating mercury

We have to imagine the whole circular area, which we see projected in its diameter PQ, filled by many mirrors *a*, each one with its linked convex and flat mirrors and collimating lenses, destined to collect all the light falling upon the larger *PQ* area onto the smaller *oo* area. Through the *oo* objective, the rays finally reach the photographic plate, the objective and the observer's eye. In this way, the quantity of collected light is not measured from the the restricted *oo* area, but rather from the *PQ*, which can be enlarged as much as we want, by multiplying the number of mirrors *a* and their sequel.

Although – in theory – there should be no objections to this system, apparently it is not so easy to put it into practice. Indeed, as far as we know, no one has ever tested it. However, anyone may realize that such an astronomical machine will never be used easily, unless it is motionless, namely, always pointing at the same area of the sky.

In fact, we do believe it is necessary to obtain immobility, if we somehow manage to build better instruments in comparison with current parabolic mirrors. Let us see in detail the consequences of this limitation.

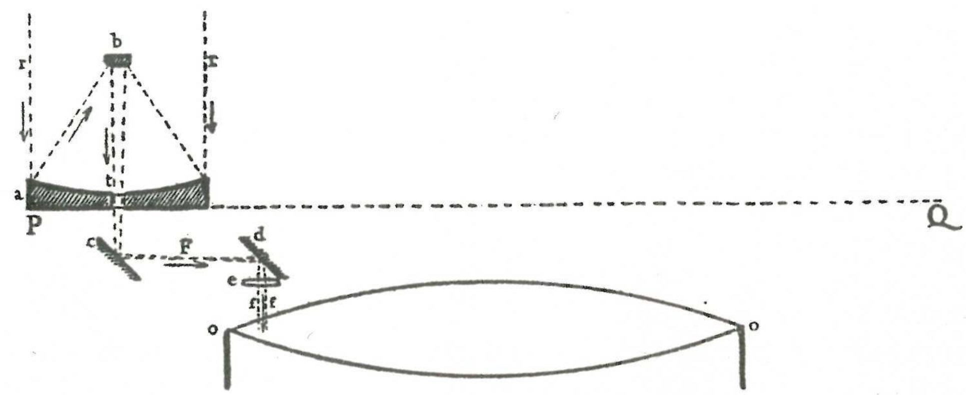

Figure 4
a) parabolic mirror with a hole t, collecting directly from the star a bundle of parallel rays rr
b) convex mirror reflecting upon c the light received from a
c) flat mirror reflecting the light upon d
d) flat mirror reflecting the light upon the collimating lens e
ff) bundle of parallel rays coming out of e oo) objective
F) focus of the ab system and collimating lens e

With a mirror which is constantly pointing at the zenith, an astronomer can only observer what is there in his vertical line at the moment, but the rotation of the sky brings on the same vertical adjacent sections of the sky little by little. Within 24 hours, a whole area will have passed upon his head in the place where he is observing. Needless to say, the remaining portion of the sky will never be observed by this astronomer, but rather by others, placed elsewhere in latitude, and endowed with similar mirrors. In order to clarify our point, let's say that these parabolic mirrors have a focal distance which has been chosen so as to include a 3-degree field (three degrees correspond to about six aligned full moons). If we placed three mirrors at intervals of 333 km, measured in latitude, for instance one in Bologna, the second one in Foggia and the last one on the island of Lipari, with them we would be able to observe the whole sky over Italy in the course of one year. Thus each country would take care of its own zenithal sky.

The most serious constraint astronomer should impose upon themselves actually lies in the shortness, even the immediacy of the pose, since the motionless instrument would no more follow the designed region in its ceaseless motion, but would only catch it in its transit, which is the quicker, the nearer that region is to the Equator. However, this drawback would be compensated by the higher quantity of light collected by the mirror, since we are talking of mirror which are much larger than the ordinary ones.

If we want to give a concrete example, in the International effort of the photographic star atlas, we decided to use mobile equatorials with a 33cm-aperture objective: with such instruments, we followed the designed region, by exposing the plate for 5 minutes, and found star of the 11th magnitude and beyond. On the other hand, when using a motionless 5mt-aperture mirror, we would obtain the same effect with a reduced 1,3 sec pose, or even a 1 sec one, if we take into account both absorption and inevitable objective aberrations, which are absent from a well-refined parabolic mirror. Not by chance did we choose the title *Telescopes of the Future* – since building mirrors with an aperture higher than 1 metre still is nowadays a long and difficult enterprise. We can only hope that, in the near future, we shall find suitable materials and systems for larger mirrors, as well as the way to speed up the sensitivity of photographic plates. We wish the time is near, in which the giant California 5-mt aperture mirror will be considered small.

Telescopes of the Future and Segmented Mirrors

Coelum, 6 (1932), pp. 121-125

In the February and March issues we had already entertained the readers on the future of the instruments used by astronomers, and we reached the conclusion that the ordinary kind of equatorial telescope had by now reached the size limits of both Mechanics and Optics. We also said that mechanical difficulties will be overcome in future by placing both objective and mirror in a fixed, horizontal position, and limiting the observation to the zenith sky, whereas the obstacles to the construction of optical instruments with a diameter larger than the current ones still appear insurmountable. As a proof of this, we described a few recent attempts to enlarge the diameter of the optical instrument, which should collect as much light from the stars as possible: these attempts were quite ingenious, but unpractical.

Today we want to talk about another system, which is being tested at the Observatory of Bologna (see Fig. 1) and consists in *replacing the whole mirror surface with a series of "tiles" which make up the surface, just like a mosaic.*

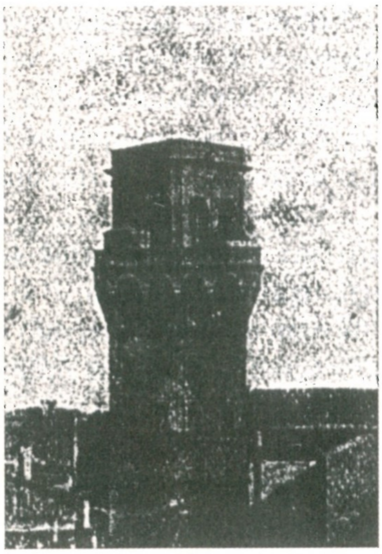

Fig. 1

Just to get an idea of this system, have a look at the figure, reproducing the Bologna mirror in a ratio of 1 to 9. In the upper part of the page, the 80 tiles can be seen in front, whereas in the lower part of the page, they can be seen on the side. Underneath the tiles, you can see a supporting marble table, with holes for three screw-pegs on which each tile is placed. The peg device, with slides for lateral movements, is attached to the marble table. Thus, if we move the latter with our hands, we make any lateral or vertical movement of both pegs and tiles possible. The polished surfaces of the tiles follow a spherical curvature, and their radius – the same for all of them – is 20 mt. Thus the focal distance of each tile, as well as of the total spherical surface they compose, is 10 mt. The pegs are useful for the adjustment of tiles, which lie so that an infinitely remoted light source may converge its parallel rays upon them, and give one pin-point image, which is actually the sum of 80 images. The adjustment is made with an artificial source (a collimator) which can light up two nearby tiles with its beam of parallel rays. Starting from the picture reflected by the first tile, the one reflected by the second neighbour one is pointed back to the first one: both tiles are struck by the same beam of parallel rays. By moving the beam, so that the rays may fall no longer upon the first and second tile, but rather upon the second and the third one, the reflected picture of the third is made to coincide with the one reflected by the second one, and so on, until the 80th tile.

The mirror is placed horizontally in the highest room of the Observatory (fig. 1 and 3), 50 cm from the floor. It receives the light from a circular opening *aa*, with a diameter of 1,20 mt, in the centre of the terrace above. In coincidence with the focal plane *FF*, we find the sensitive plate *L*, supported by a specific structure. Since the room is about 10 mt high, the mirror's focus slightly exceeds the terrace level.

The experiment, which has just started, will show whether the system can be put into practice, namely whether the concentration of the rays will take place as in the whole mirror, and the effects of diffraction caused by the intervals between tiles will be negligible. These intervals can be minimized, whereas in figure 2 they are shown as far too large. On the other hand, we should not forget that the effects of diffraction cannot be cancelled even in current instruments, whose star images are – at best – nothing but diffraction rings, as large as the instrument aperture[1].

[1] I do not want to aggrieve the reader by entering into the complexities of the problem. For further details, see the next isseu of the *Pubblicazioni dell'Osservatorio di Bologna*. There you will also see that, by conveniently moving the tiles from the position they should occupy in order to compose the continuous surface of a sphere, one can correct spherical aberration as well, which could not be discarded i the whole mirror; that is why snigle-piece mirrors were long ago banned from astronomical use, and replaced by parabolic mirrors, which are more difficult to polish.

The reader will ask why we want to compose the mirror with tiles, when you can have a whole one. I will answer that beyond a certain diameter (2,50mt is sofar the largest size reached by mirrors with proven experience), the melting and grinding of such large blocks of glass exceed human force. On the other hand, making tiles which are 1cm thick and have an area of about one square dm. is a rather easy task for a fully-equipped workshop. A whole 1,10 mt surface requires the work of many people for over a year, whereas the construction of 80 tiles – making up a mirror with the same aperture – takes a few weeks only. Needless to say, the expense is in a ration of one to one-thousand.

One might expect that, if the experiment with a 1,10 mt. diameter succeeds, we might reach a larger surface without much difficulty.

However, a further advantage of a fractioned area consists in cancelling the harmful effect of deflection, which huge blocks of glass suffer with varying temperature. In a fractioned surface, each tile dilates only a little bit, independently from its neighbour, so that the effects of deflection do not sum up, as in the single block, on whose edge they reach unacceptable values, so much so that a good portion of the edge must be framed and excluded from reflection.

Once we have completed the test, we shall come back to this topic.

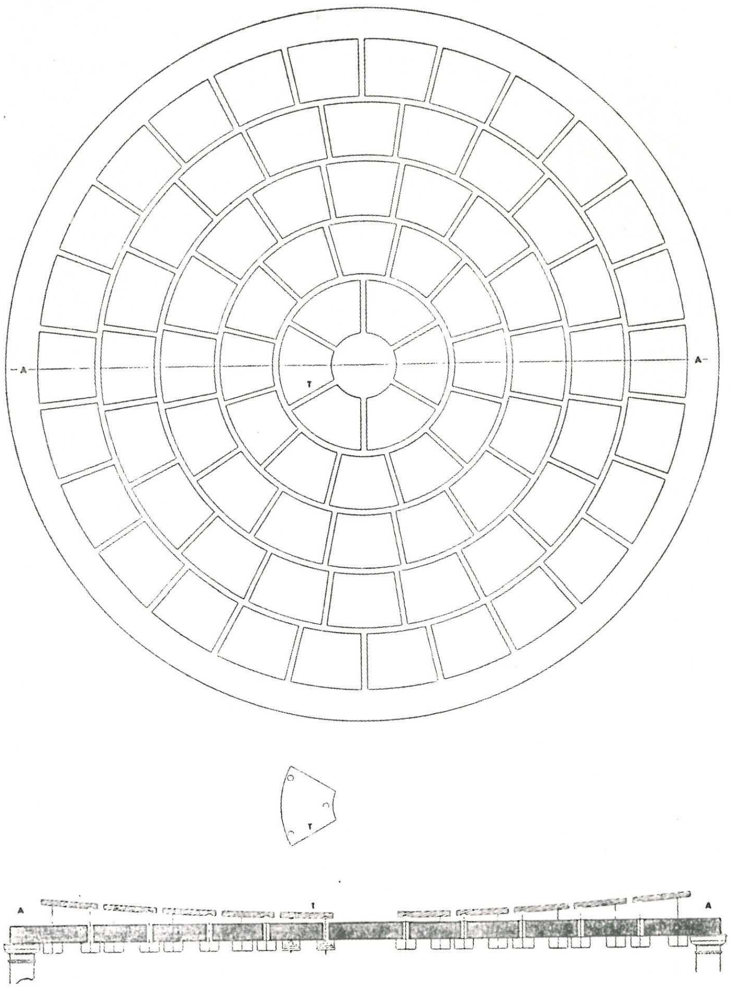

Fig. 2: Above: the mirror seen in front. Underneath: a cross section AA: the dotted lines are the tiles' sections, whereas the straight line is the section of the perforated marble table supporting the tiles through the pegs; the tile T is represented also in the rear, and shows the three holes in which the pegs' heads are placed. Here the mirror section is represented as more curved than in the original, so that you can see the curvature better. With the real size of the curvature, the tile layer would indeed appear almost flat.

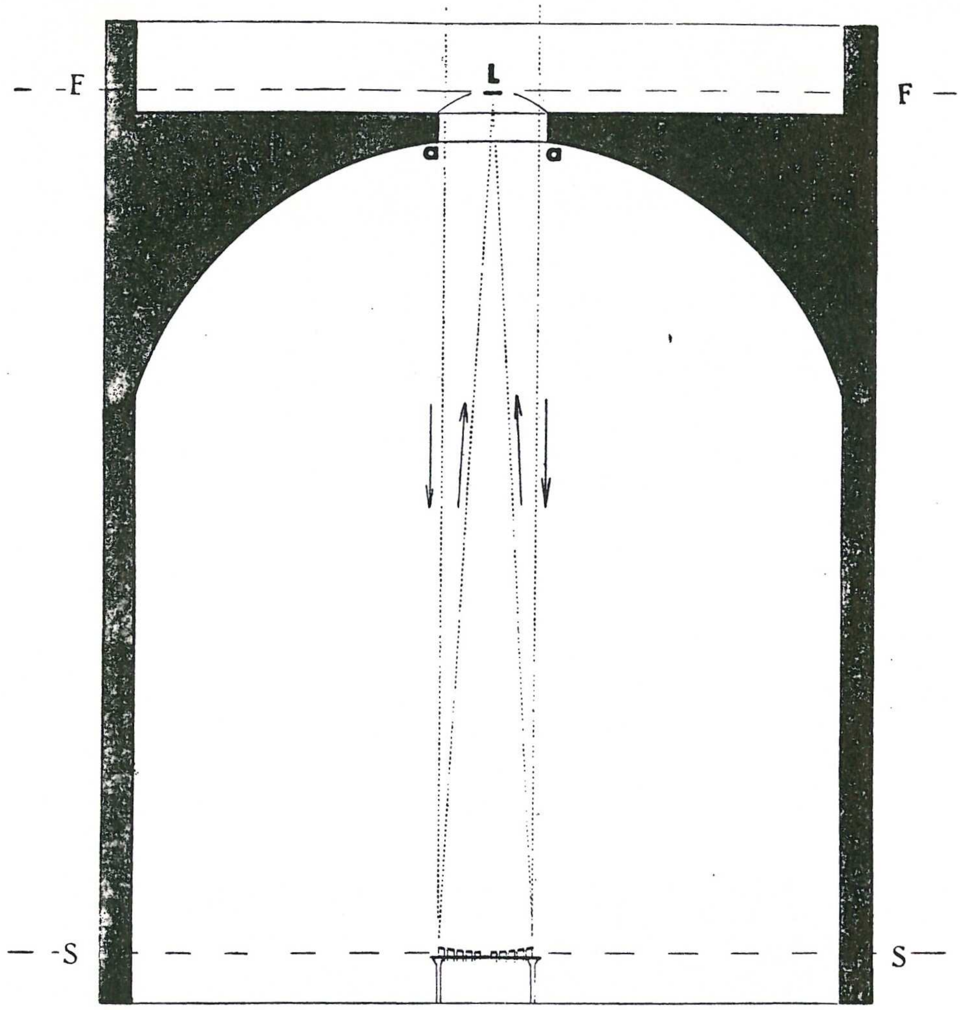

Fig. 3: Cross-section of the room containing, at the SS level, the segmented mirror; at the FF level, we find the sensitive plate, which intercepts, to a small extent, the light destined to the mirror, as it unavoidably happens in reflecting telescopes. The height of the room, as the focal distance of the mirror shows, is 10 metres.

First experiments with the segmented mirror

Memorie della Società Astronomica Italiana, vol. IX, 2 (1935), pp. 133-146

ABSTRACT: The author reports the experiments made at the Observatory of Bologna with a concave mirror composed of ten tiles: the reflecting surface, though only looking at the zenith, gave point-like pictures of the stars, since the plate was moved upon the focal plane at a suitable speed, in order to follow the diurnal rotation. A copy, printed on photo paper, shows the outcome of the experiment. The method used for adjusting the tiles is described in detail.

HISTORY. In 1932, considering the difficulty of building huge mirrors, I had thought of the possibility of replacing the monolithic block with a series of mirroring tiles which, once conveniently adjusted, could compose the reflecting surface we were looking for. A historical precedent of such a solution was the idea of Lord Rosse who, while pursuing a different goal, planned the construction of metal mirrors in two pieces, with a spherical curvature. He wanted to correct the spherical aberration. Indeed *S* (fig.1) is a spherical surface, F^1 , the average focus of the cap *BC*, and *F* the average focus of the spherical ring *AB, CD* for rays parallel to the *L* axis. If the surface *S* were composed of two pieces (i.e. cap and ring), by keeping the cap still, one could move the ring, bringing it to A^1B^1 , C^1D^1, so that the average focus of the *F* ring coincides with the F^1 focus of the cap, approximately avoiding the formation of caustics; the aberration would be corrected so much better if there were more rings, which would end up emulating the paraboloid, if their number were infinite, and their focus coincided in one single point. There is no record of Rosse's ever experimenting his idea in practice. Incidentally, if applied to mirrors with a large diameter, it would increase difficulties for its construction. On the other hand, melting the crystal and grinding the reflecting surface would be made easier, if the latter be divided up into rings, and, in turn in small tiles (for instance, a square decimetre, see fig.2). Thus the tile's thickness would be reduced to a couple of centimetres and, as a consequence, the thickness of the whole segmented mirror, though huge, would not exceed this measure. On the other hand, in monolithic mirrors, thickness is about one sixth of the diameter, so that the weight of huge mirrors goes up to tons. Moreover, grinding small tiles would be much easier, as we shall explain further on, since they all have the same strictly spherical curvature.

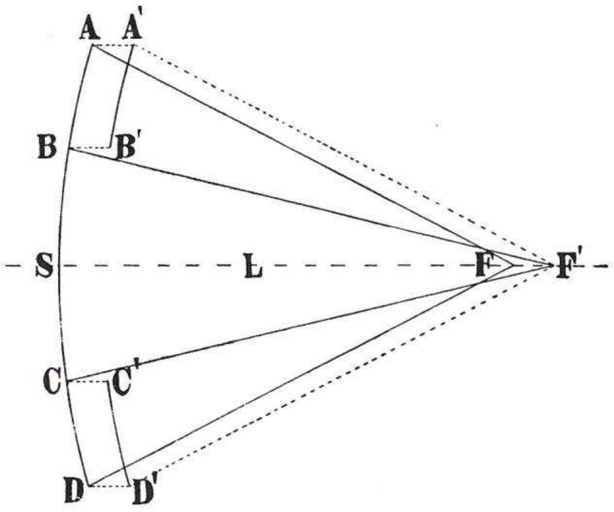

Fig.1 ***Correction of the spherical aberration****. The light rays coming from the right are parallel to L.*

NON-CONTINUITY OF THE REFLECTING SURFACE. Let us consider an intact surface, with a faultless curvature, like the one of our telescopes. Let us suppose to cover it all with a sheet of paper, cutting it so as to let the light pass through trapezoidal areas (fig.2), and be captured by the networked composed of the intervals between the cut-out area. Clearly, this framed area will reflected less light, but it will produce unique pictures of each object, as long as the photographic plate lies on the focal plane. If we blur it, we would have not so much blurred pictures, as multiple pictures. For instance, we would get as many point-like pictures of a fixed star, as the number of reflecting areas, according to the so-called Scheiner phenomenon.

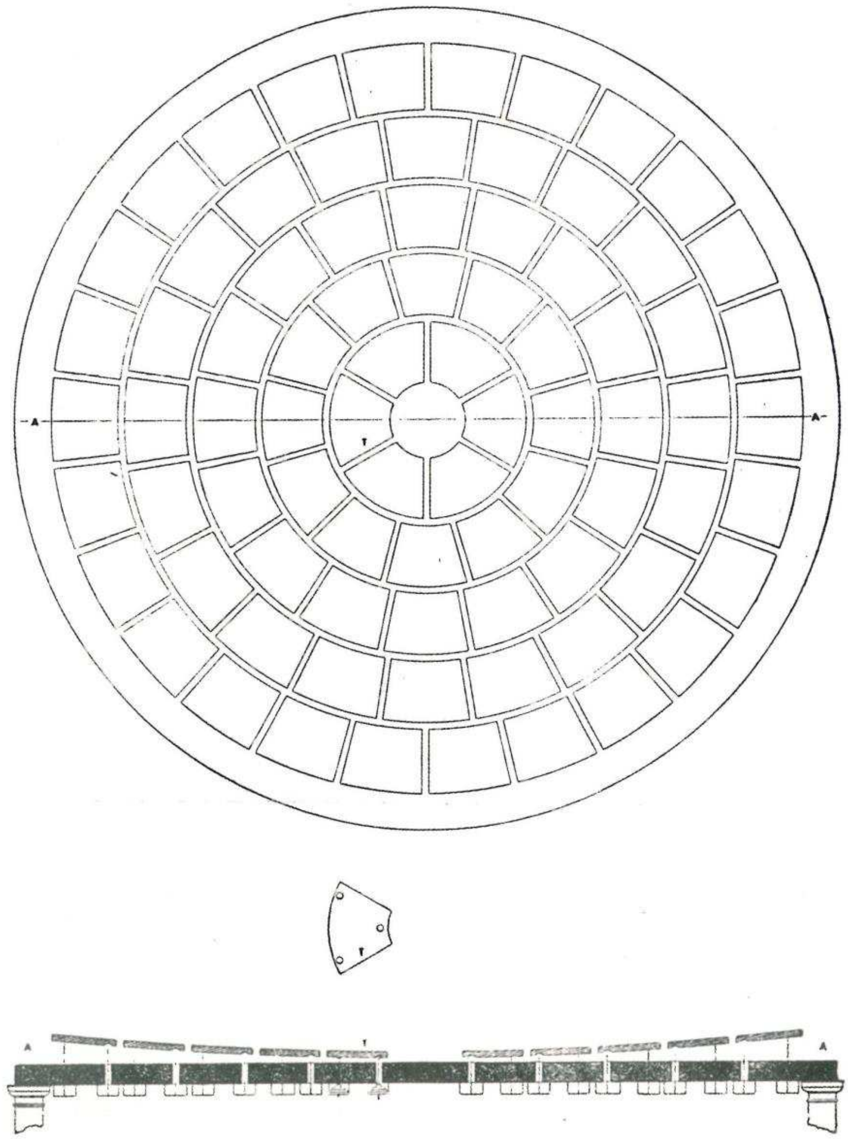

Fig. 2 ***The mirror in two projections (scale 1:90).*** *In the lower part, we can see the marble table and the screws – integral with it and supporting the tiles; the free ends of the screws enter three holes, shown by the back of the upside-down tile.*

Useless to say, in the first case one can obtain unique pictures. However, in 1932, I visited the Lick Observatory on Mount Hamilton. The director of this institute, Prof. Aitken, allowed me to carry out the experiment with the *Crossley Reflector.* Thus I lay upon the 90cm mirror a paper "net" similar to the one described above. On August 23 Dr. Trümpler, to whom I am very grateful, took two pictures of the globular cluster NGC 7092, the first one with the free mirror, and the second one with my perforated diaphragm. In this latter plate, over and above the usual radial centered on the larger stars, as well as the cutting cross oriented always in the same direction in all stars with a certain luminosity, produced by the light intersecting two crossed bars, you can see a series of concentric rings, which are almost melting in one single halo. Of course, this halo surrounds only larger stars, and has the same nature of the cutting cross, since it is produced by the diffraction of light upon the neat edges of the trapezoid areas. The effect of diffraction upon radial edges is not so clear as the one of circular edges, which divide the whole mirror continuously in five independent rings. Naturally, stars of lesser orders of magnitude are exempt both from radials and from haloes, and do not differ from ordinary single, point-like stellar images. A similar experiment was carried out in the Zeiss factory in Jena, with a square-mesh metal screen and an artificial star. The result was the same, thus showing that the intervals between tiles (which, through an accurate construction, may be reduced to a size of a millimetre, whereas in the above-quoted experiments were 1 centimetre thick) do not affect the images of weaker stars, whereas they merely produce harmless effects in the larger stars.

Preparation of tiles. Clearly, grinding such small tiles, with a spherical curvature, is much simpler than producing large-diameter mirrors with a parabolic curvature. However, our tests showed that even small tiles must be made with the best glass, better yet with melted quartz. As they did not take into account this detail at the Filotecnica of Milan, their first ten tiles were not polished so as to guarantee the production of perfectly clear images, exempt from a spherical aberration, which can in any case be corrected.

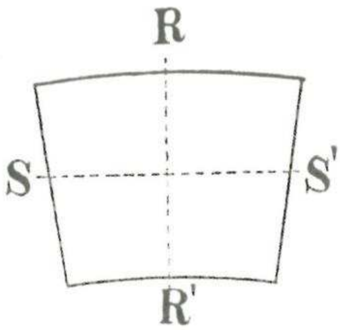

Fig. 3 The curvature of each tile was measured according to the RR^1 and SS^1 sections.

The following table contains the data related to ten tiles, used in this first experiment: in the measures of each tile, I separate the focal distance of both section RR^1 and SS^1 (see Fig.3). Of course, within strictly spherical tiles, each section – no matter its orientation – must show the same curvature radium, and therefore a focal distance, within tolerable limits of polishing.

Focal distances and astigmatism error in the ten tiles we have used

Nr. of tile	Focal distance in metres	Differences from average 10,41m		Focal distance in metres	Differences from average 10,41m		Astigmatism RR^1 – SS^1
	Section RR^1	over	under	Section RR^1	over	under	
I a	10,40		+1cm	10,42	0 cm		-2
II a	10,50	-9 cm		10,51	-10		-1
III a	10,38		+3	10,38		+4	+1
IV a	10,45	-4		10,44	-2		+2
V a	10,50	-9		10,49	-8		+1
I b	10,41		+1	10,42	-1		-2
II b	10,41		+1	10,42	-0		-1
III b	10,37		+5	10,37		+5	0
IV b	10,29		+13	10,25		+16	+4
V b	10,45	-3		10,45	-4		0

A focal distance of 10,50 mt. had been planned, which turned out to be on average 10,4 mt, except that each tile strays more or less from the average value, and sometimes this is unacceptable. Moreover, tiles present a more or less serious astigmatism flaw, since he curvatures of two orthogonal sections are different, for ex. RR[1] and SS[1] (fig. 3), as you can see in column 2, 4 and 6 of the table. While each tile shows a difference of 4 cm from the focal distance of 10,41 mt, we see - on average - a difference of 0,3 cm between two curvatures of the orthogonal sections of the same tile. Obviously, if the *Filotecnica* uses a better glass, and completes the polishing process until each tile matching its *sample* presents in its area the same number of round fringes, they will manage to remove all flaws, probably reaching a precision which will not be inferior to the one expected from huge monolithic mirrors.

ADJUSTMENT OF TILES. Once we have set up the observing room (see fig, 4 and 5) and placed the ten tiles upon their supports, with three correctings bolts, we start the adjustment.

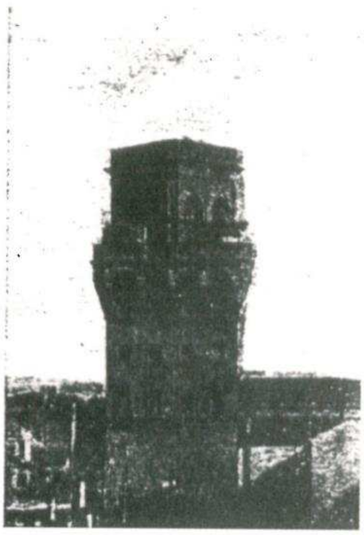

Fig.4 ***Tower of the Bologna University Observatory.*** *The highest room, showing its two walls, contains the mirror underneath and the photographic plate above.*

First of all, we should decide the place in which the focus of the whole mirror will fall. Naturally, we choose the centre of the plate, where the picture of a star is formed when it reaches the observer's zenith. Let us call this point *F*, at the centre of a cross etched on the plate (Fig. 6b).

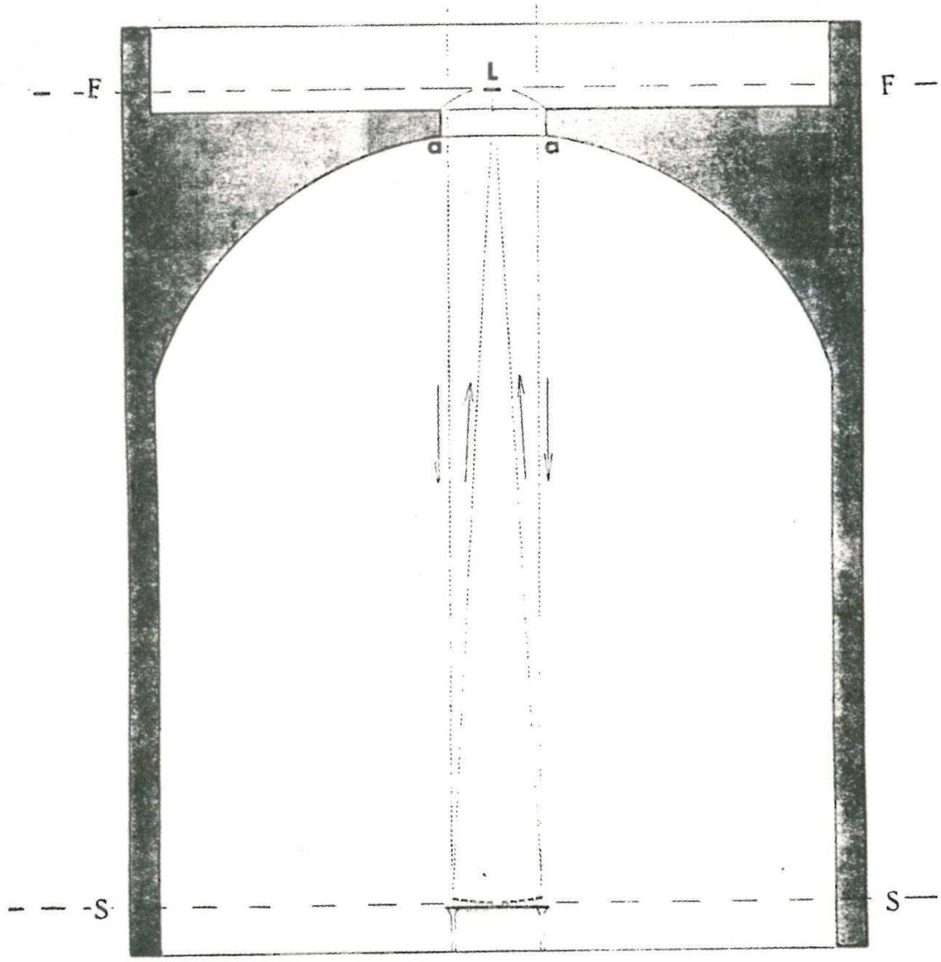

Fig. 5 Inside the room containing thr mirror on the SS plane, and the photographic plate on the FF plane (scale 1:80)

Two solid iron crossing bars bear the *chassis*, as in ordinary telescopes, and we took care that its centre lay upon the axis of the well, acting as a tube.

If the observer could just have a motionless star at its zenith available, the adjustment would be very easy. Without such an infinitely far-away natural source, we recur to an artificial source emanating parallel rays, which fall upon each tile, according to the observer's free will. To this aim, a collimating eyepiece *C* (Fig.6a) brings in the AA^1 focal plane of the objective *O* a cross of wires, indirectly lit up by a light bulb *l,* whose light is reflected along the *C* tube, through the small mirror *s*; the rays touching the wires come out parallel from *O* and form the beam *P*. However, you must be sure that, by directing the collimator *C*, and therefore the beam of parallel rays P down on the 84 tiles, also the 84 beams be strictly parallel to one another.

In order to obtain this, with the expected precision, we use the artificial horizon *B,* which is placed upon the tile before starting the adjustment. (Fig. 6a).

By positioning the collimator towards the fluid's surface, the perfect verticality of its optical axis is reached when the direct image of the wires lying in AA^1 is superimposed onto the image reflected by the horizontal fluid's surface. Once we remove the artificial horizon (Fig, 6b), the beam of parallel and strictly vertical rays P, issuing from the lit-up wires, falls upon the tile T, which, while reflecting them, generates in a point F^1 the real image of the pointing. If F^1 does not coincide with F, previously designed as the focus of the whole mirror, acting on the screws V of the support, on the same line of the marble table M, we move the tile to the position we want: the operation is repeated for the other tiles, until we obtain the overall adjustment of all pieces. We can observe F approaching F^1 through the screws V, acting upon the tile, through looking at the plate S (Fig.6b), the l lightbulb on and the L one off. Alternatively, we can put l off and L on and looking from the eyepiece *o.* The latter choice is much quicker, and the adjustment is reached when our eye sees the cross of wires of the AA^1 plane coincide with the other cross engraved on the plate (centre F), and the rays issuing from it will reach AA^1 after being reflected from T. This adjustment is not too difficult, if you use certain practical precautions. A well-organized team of two scientists, the one acting on the focal plane FF (Fig.5), and the other one on the plane of the mirror SS, with a telephone, will manage – in a few minutes – to complete the adjustment of one tile, which does not change its position all along one day, as I have seen for myself.

CAUSTIC CURVE OF A SEGMENTED MIRROR. The more the distance *y* from the mirror's axis for a generic point A (Fig.1) increases, the segment FF' – which is called longitudinal aberration – also grows, and its length is calculated with the well-known formula FF'= $y^2/8f$, where f is the mirror's focal distance. In our case, where f = 10,40 metres, and the distance of the five rings of tiles of the axis A (Fig.6c) is respectively of 10,20…50 cm. For FF' we get the following values:

Ring	y distance from the axis	FF longitudinal aberration
1	10 centimetres	0,12 millimetres
2	20	0,48 millimetres
3	30	1,08 millimetres
4	40	1,92 millimetres
5	50	3,00 millimetres

Therefore, each ring is removed from the spherical surface S by a quantity equal to the longitudinal aberration corresponding to its y and the segmented mirror takes on the appearance of a staircase, as we can see in Fig.6c, in which – however- the interval between T and S is significantly overstated, since (in our mirror) the highest value of FF' is 3 millimetres for the ring which is 50 cm far from the axis A.

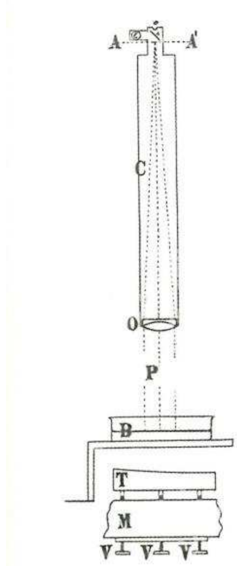

Fig. 6a

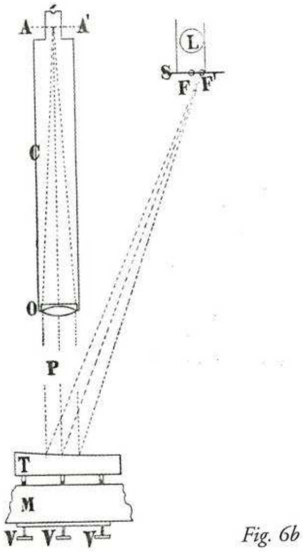

Fig. 6b

In both figures, C is the collimator, T the tile, M the marble table with the screws V. P is the beam of parallel, vertical rays. AA' is the focal plane of the objective O. In Fig.6° you can see the artificial horizon B, which is removed as you reach the verticality of the beam P. In Fig.6b, you can see the photographic plate S and the centre of the engraved cross F.

The curve P of the same figure represents the paraboloid, whose focus coincides with the focus of the spherical mirror S. Here too, the interval between P and S is greatly exaggerated, because the distance between the two surfaces is smaller than a *micron* when *f*= 10,40 mt and *y max*= 50 cm, as you can see in the following table:

y	Distance between two areas, P and S, measured in parallel with the axis A
10 centimetres	Millimetres 0,00000000013
20	Millimetres 0,0000223
30	Millimetres 0,000113
40	Millimetres 0,000550
50	Millimetres 0,000870

Fig.6c. The dotted line P represents a paraboloid confocal with the sphere S. T is the profile of the segmented mirror, corrected for the aberration of sphericity. In the mirror used in this first experiment, the focal distance was 10,40 mt, whereas the distance of the tiles'centre from the axis A was 10,20…50 cm.

Thus, it is as if we shifted the tiles with respect to the paraboloid P; naturally, the tiles endowed with the same spherical curvature must be moved *towards* the *focus*, since each of them has a curvature which is larger than the corresponding area of the paraboloid. Dr. Cavini studied in his dissertation the caustic of the segmented mirror, and will write about it in one of the next issues of these *Pubblicazioni.*

STELLAR TRACES AND POINT-LIKE IMAGES. As the dimensions of monolithic mirrors increase, difficulties also increase in making them move and rotate uniformly, according to diurnal rotation. Thus we can foresee that there will be a time when very large mirrors will only be used motionless, in a vertical position, just like the segmented mirror I am describing. The drawback is that they will only look at a single section of the sky – in our case, at the observer's zenith. Thus we place in S (Fig. 6b) the 9x12 plate, which includes 30' x 40' Min before the arc. The stars run upon it with a speed of 1 mm in 1,8 sec: this speed depends on their declination, which – for the plate's centre – is $\partial = 44^{\circ}$ 30', as well as from the focal distance of the 10,41 mt mirror. As long as the plate is motionless, stars will engrave upon it markedly straight traces. Fig.7a shows one of the traces, stamped on the evening of July 2 by the star **φ** *Herculis*, with a visual and photographic magnitude of 4,3: in it, we see the traces of 8 tiles have melted. In order to show that, in the apparently unique trace, the traces actually concur of a few tiles, on the night of June 19, I exposed the plate once again to the light of **φ** *Herculis*, only to discover – later on - the traces upon two, four, six, and finally all eight tiles: thus the combined trace turned out to be more intense and unique, as you can see in Fig.7b.

In order to obtain the dot-like imprint of stars, therefore, since the mirror is motionless, we need to follow the stars with a mobile plate, endowed with the above-mentioned speed. At first, I tried to follow the stars with the clockwork mechanism of our Cooke refractor, but I got a better result by provoking the movement with an endless screw, turning it around with both hands, just like in the self-recording micrometer. One of the plates with dot-like images, obtained during the night of August 22, with a 3^m35^s pose, is reproduced in Fig.7c on photo paper. I used as a guide star **α** *Cygni*, which is not so far away, but in any case out of the plate field, held in tracking by an eyepiece, integral with the plate and moving with it, by Mr. G.B. Lacchini, who helped me considerably during the months of July and August.

The result. In the reproduction on photo paper you can see in Fig.7c, there are only 3 stars, but all the stars which were visible in the region on the BD Atlas had left their imprint, i.e. up to the Harvard magnitude of 10,5:

STAR	MAGNITUDE			SPECTRUM	NOTES
BD	BD	Harv. Vis	Harv. Phot.		
43°3683	8,1	8,2	8,2	A*o*	The lowest star of fig.7c
43°3684	9,1				
43°3686	9,3				
43°3688	9,4				
43°3689	9,5				
44°3538	8,1	8,2	8,2	A*o*	The highest star of fig.7c
44°3539	9,5				
44°3542	8,9	9,1	9,1	A*o*	The central star of fig.7c
44°3543	9,5				
44°3544	9,2				
44°3547	9,2				
44°3548	9,5				

I will not deny that the three points visible in Fig.7c are still far from the roundness required in stellar images, but the cause of this imperfection lies above all in the different focal distance from the tiles and, during the experiments, I acquired a definite assurance that, if I could try again not only with 10, but with all 84 tiles, suitably polished like precision instruments, the stellar images would come out like the ones you can obtain with ordinary telescopes.

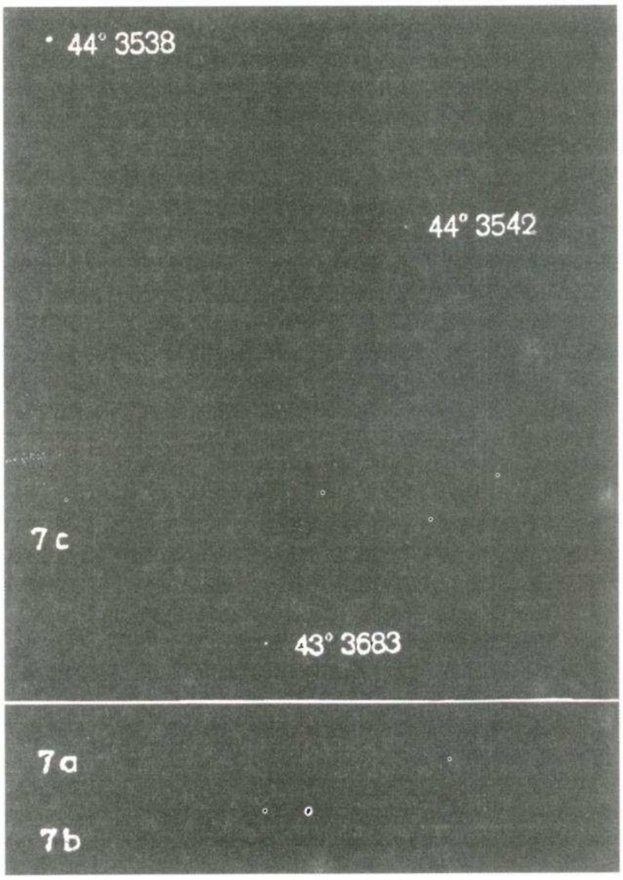

Fig.7a. Imprint of the star **φ** Herculis upon a motionless plate (July 2, 1935);8 tiles were collecting light

Fig.7b. Imprint on another motionless plate (June 19, 1935) of the star phy Herculis. 2, 4, 6, and 8 tiles were sequentially collecting the light, so as to make the imprint more intense. However, the imprint appears single.

Fig.7c.Dot-like imprints of a star south of **α** Cygni, obtained with a mobile plate and a $3^m35'$ pose (August 22, 1935); 10 tiles were collecting light: upon the plate, you can see <u>twelve</u> stars. However, on this reproduction on photo paper, you can only see three stars, identified by the BD number; any other incidentally visible point is spurious. The BD numbers are about 4 mm far on the right of the three white dot-like images.

Further Experiments with the Segmented Mirror
Publications of the Astronomical Observatory of Bologna University, vol.V, 11, 1950

ABSTRACT. *The author, taking into consideration the obstacles to the construction of huge reflectors, describes a concave mirror, formed by nineteen hexagonal tiles, which he has built and tested at the Bologna University Observatory. The mirror is motionless, and looks at the zenith; after explaining the method he has followed in adjusting the tiles, and described the mechanism for moving the mechanism which makes the photographic plate move along the focal plane, the author recalls the attempts made from 1935 onwards, and finally reports the results he has obtained, by taking pictures of the sky with this instrument all along 1949.*

HISTORY. The difficulty of building huge mirrors consists essentially in the fact that its thickness must be proportional to their diametre[1]. Indeed, if the disc is too thin, the glass may yield, so that it does not keep the shape given by polishing. Thus you get very heavy masses, which are difficult to handle during the preparation. When you have finished polishing, and you place the glass in its definitive location, it is difficult to support its back while applying the same pressure on each point. Finally, huge masses of glass, although it is a really viscous substance, may bend[2] with time, with a deformation of the reflecting surface. We may also face the problem of mirror mobility: up to a 5mt dimension, and a 18mt focal distance, the experienced technicians of Mt. Palomar have successfully managed to endow that equatorial mirror with the required uniform motion. But if we were talking, say, of a 10mt mirror, apllied at the end of a 50mt (or more) mobile barrel, this would probably be an excessive and prolonged fatigue, with current technologies, whereas motionless segmented mirrors, with a 10mt diametre, will not be counted among the largest ones. We can therefore foresee a time when scientists seriously think of using mirrors which will be constantly pointing at the zenith; the whole sky will be observed through a certain number of such telescopes, spread out in latitude. The experiments I am going to describe in this issue were actually carried out with a motionless horizontal mirror, which is made up of many pieces, or tiles, which - all together - cover an area of about 80 square decimetres.

---

1 As a general rule, the thickness is one-sixth of the diametre.
2 See *Coelum*, 1949, May-June issue, p.41.

By the end of 1935, I had published a report[3] of the tests I had managed to carry out with ten trapezoidal tiles, provided by Filotecnica-Salmoiraghi. The small reflecting surface (all together, over ten square decimetres) allowed me only to realize that it was possible to concentrate ten beams converging upon a single peak.

In 1936, the firm Zeiss provided me with ten further tiles, so that I had a total of twenty tiles, whereas the whole mirror, with a diameter of 1,05 mt, should be formed by 80 pieces[4]. Therefore, after repeated tests, in the summer of 1938, with the twenty tiles placed in a circle all along the fourth ring, I obtained encouraging results, even though they were not as good as the current ones. In the fall of the same year, the anti-Semitic persecution prevented me from continuing my work, which I could only resume after the liberation, in the spring of 1945.

After that seven-year gap, the only optical material at my disposal consisted in those twenty tiles I mentioned beforehand. In the summer of 1946, I got 60 more tiles, which had been polished – in less than one year – by our technician Aldo Galazzi, who was training on glass grinding. However, this rushed work did not give the expected results, so that we had to start all over, this time facing the challenge of a larger area to be polished. Indeed, while the first trapezoid tiles were only a square decimetre, the new hexagonal ones were about four decimetres (the circle inside the hexagon has a diameter of 198mm). Their side shaping was carefully made by S.A.L.V.O. in Florence, which provided the rough glass blocks, allowed to reduce to 2 mm the distance between two nearby tiles, whereas it used to be 10 mm. The thickness of the blocks is 3 cm. The nineteen tiles, placed side by side, with the above-mentioned interval, form a nearly circular area, with a 1m diameter, as it is shown in perspective in fig.4.

PRECISION OF CURVATURES. All tiles are endowed with a spherical curvature, with a 20,82 mt radius, namely with a focal distance of 10,41 mt; the difference from this average value is for each tile as follows:

---

3 *Pubblicazioni dell'Osservatorio Astronomico di Bologna,* vol.III, nr.3, 1935

4 Ibid., fig. 2, p.5

I	+0,1 cm	XI	-1,9cm
II	-1,9	XII	+0,1
III	-0,9	XIII	+1,1
IV	+1,1	XIV	+0,1
V	+1,1	XV	+0,1
VI	+0,1	XVI	+0,1
VII	+0,1	XVII	-1,9
VIII	+1,1	XVIII	+0,1
IX	+2,1	XIX	-1,9
X	+0,1		

This means that, if we take any two tiles, the difference of their focal distances may be at most 4 cm, i.e. 1/250 of the average focal distance. I must say that Zeiss, before working on the ten above-mentioned pieces, which I am not using anymore, stated that they could guarantee a focal distance of mt 10,50 for each of them, only within a tolerance of ± 3,5 cm, i.e. at most seven cm, between any two chosen tiles.

As you can see, there is a difficulty here, which is not shown in a monolithic mirror, where you do not care whether the pre-established focal distance, let's say 10,50 mt. shows up before the polishing of 10,45 mt, or 10,55 mt: the mirror is accepted in any case, as long as its surface is perfect, and any point of it is not far from the geometric paraboloid, other than a small fraction of micron. On the other hand, in our case, over and above the perfection of the surface, we require that the focal distances of each tile were equal, but this is not easy, not to speak of a small fraction of micron, but not even of a fraction of millimetre. Although this may seem unlikely, the results obtained by these tiles show that the differences which were discovered in focal distances did not prevent the stellar images from being compared to the ones generated by the continuous surfaces of ordinary mirrors.

Certainly, by pushing the processing beyond the usual, without taking into account the time, as it is happening now, the values will approach the average, and we would be satisfied if the differences were reduced to a fraction of centimetre, which would be equal to a thousandth of the focal distance.

I will not dwell on a failed attempt to obtain the same focal distance for all tiles, by using an equipment in which the movement of the patina was led by two matching shapes, one concave, the other one convex, endowed with a pre-determined curvature radius. Once this trial failed, we went back to the classic method, consisting in passing back and forth countless times upon the glass surface, first with a cast-iron patina, then with an ancient Roman "*focaccia*", and using smaller and smaller abrasives. The Ducati workshop in Borgo Panigale kindly loaned me a polishing machine, with which the afore-mentioned Galazzi completed the work in the month of February 1949.

TILES' PLACEMENT. Each tile was placed upon three screws passing through the holes of a suitably pierced marble table, attached to it through nut screws. The back of each tile bears three metal rings, corresponding to the screws: one of the rings is smooth, while the second one has a conic dent, and the third one has a straight mark. The tile's weight guarantees its immobility, and the operator, sitting underneth the table, provides the desired inclination, by turning the screws, as I will explain in detail further on. The tiles, supported by the screws, can be seen – outlined - in the lower section of fig. 1a and 1b.

CORRECTION OF THE SPHERICAL ABERRATION. One of the various advantages coming from the fragmentation into tiles of the reflecting area consists in the chance to correct the effect of spherical aberration, which the images would present if the adjustment led to a single spherical surface, namely when the curvature centres of all tiles coincided in one point only. Instead, the images will be exempt from this aberration if each ring forms a single spherical surface, but the curvature centre of the outermost rings will be conveniently higher, in comparison with the innermost ones, in which case there will be a coincidence with their focus rather than with the curvature centres, just like it happens in parabolic mirrors. The drop between the central tile and the first ring is represented in fig.2.

In our case (since the focal distance is 10,41 mt., and the width of tiles is 20 cm), we can easily calculate that it will be enough to raise the six tiles of the second ring by 0,48 mm, as compared with the central tile, and the twelve tiles of the second ring by 1,44 mm as compared with the second one, so as to make the foci of the nineteen tiles coincide in one single point, which will also constitute the focus of the whole mirror. This placement in higher and higher rungs is made with a metal arm, which is as long as the mirror's radius, rotating around its axis. This arm is fitted, below, with pegs of a certain height, and the tiles are pushed through the screws against these pegs, thus reaching their approximate place, which will later be corrected with the optical adjustment. The metal arm must be held in a strictly horizontal position, by means of a spirit level.

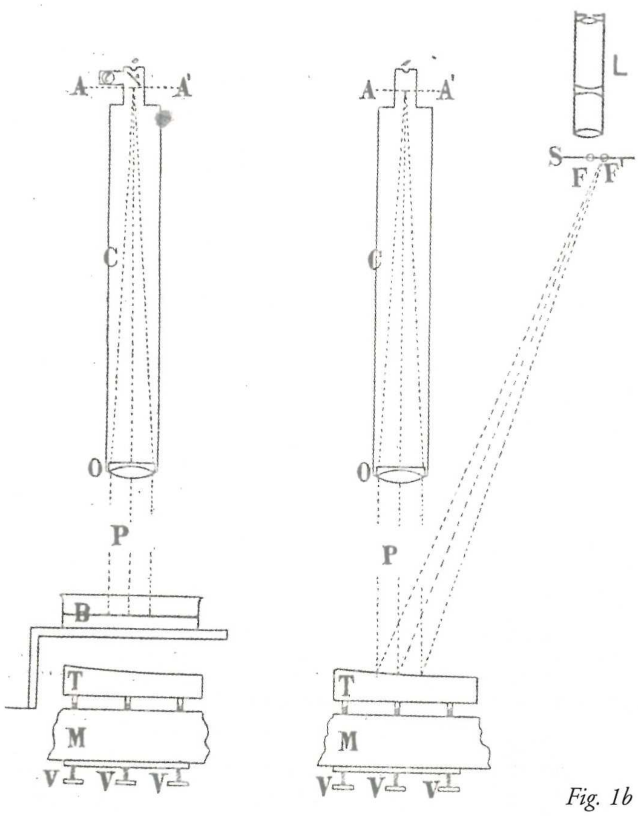

Fig. 1a *Fig. 1b*

In both figures, C is the collimator, T the tile, M the marble table with the V screws. P is the beam of parallel and vertical rays. AA' is the focal plane of the objective O, which contains a cross of spiderwebs. In fig.1a you can see the artificial horizon B, which is removed when the verticality of the P beam is reached. In fig.1b you can see the plane S where, during the adjustment a cross of spiderwebs lies, with its centre in F, and, later on, the photographic plate. In F' you find the real image of the cross AA', which is made to coincide with F, by appropriately turning the screws V.

If one day we manage, once we establish a certain radius of curvature, to endow the polished surface with exactly that radius within the fraction of millimetre, it will be easier to assign to the tiles of the outermost rings longer and longer curvature radii, as it happens in the paraboloid, so as to avoid a drop from one ring to the next, which is currently used in order to correct the aberration we are talking about.

It may be objected that, since the differences in focal distances are of the order of a centimetre, it would have been useless to correct the longitudinal aberration, which is of the order of a millimetre. However, the correction of a small error is never wasted, and will bring its fruits when, with a long-term work, we shall manage to endow all tiles with practically the same focal distance.

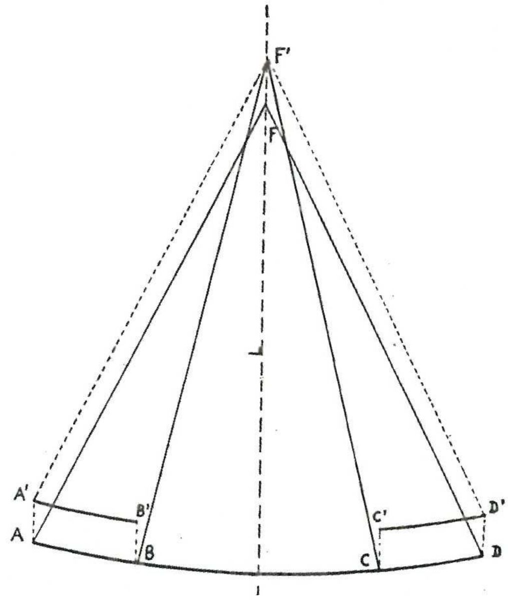

Fig.2 Correction of the spherical aberration. CB represents the central tile, which occupies the lowest position. AB and CD are the tiles of the 1° ring, which are raised by 0,48 mm, up to the position A^1B^1, C1D1, so that the focus F coincides with F^1.

OPTICAL ADJUSTMENT OF TILES. As I wrote in 1935, if the observer had a motionless star at its zenith available, the adjustment would be much easier. Failing this natural source, infinitely far-away, we recur to an artificial source, which should issue, like the zenith star, parallel and strictly vertical rays, so as to have an impact, in turn, upon each tile, at the observer's free will. To this aim, a collimating eyepiece C (fig.1) brings in AA^1, i.e. in the focal plane of the objective O, a cross of threads, indirectly lit up by a lightbulb l, whose light is reflected along the tube of C through the semi-transparent small mirror s: the rays hitting the threads come out parallel from O and form the beam P; once we have fulfilled the first requirement, we must fulfill the second one too, namely that the rays of the beam P be strictly vertical. In order to obtain this as precisely as possible, we use an artificial horizon B, which is place upon the tile before starting the adjustment (fig.1a). Once we point the collimator C towards the fluid's surface, the perfect verticality is reached once, putting our eye in O, we see in AA^1 the cross of wires overlapping exactly upon its image, reflected by the fluid's surface. With a side device, missing in this drawing, you can vary the inclination of C, until the above-quoted overlapping is made.

Once removed the basin B (fig.1b), the beam P hits upon tile T, which, while reflecting it, generates in a point F^1 the real image of the cross lying in AA^1; if F^1 does not coincide with the point F (designed in advance as the focus of the whole mirror, and lying on the meeting point of another couple of crossing wires), acting on the screws V one can consider the tile adjusted, as F^1 coincides with F. The same process will be repeated for the other tiles, so that the whole mirror will be able to converge in one single point – without distortion – not only the vertical beam we have now considered, but also any beams - no matter their inclinations with respect to the vertical – until the tested limit angle – which is 49' 30". With the eyepiece L you can observe F^1 approaching F thanks to the screws. The point F lies exactly in the focal plane S, while F1 is there with a certain approximation (see the table). This adjustment method does not present difficulties if you use certain precautions, based on experience.

A well-organized team may work, one on the screws V, the other one at the eyepiece L, and manage to adjust the tile in a few minutes. An operator can simply apply a key on top of the screws'head, while a scientist, looking at the eyepiece L, turns the screws, until he thinks that the point F^1 coincides with F.

The current situation of our mirror is rather unfavourable for adjustment, because the coloured water of the artificial horizon, placed at 40 mt above street level, is affected by the oscillations of the Tower, especially during the day. That is why we usually prefer to make adjustments in the second half of the night. Well-trained collaborators can complete the adjustment of nineteen tiles within a couple of hours, and this adjustment may last more than a week. In the new facility, which I am hoping to complete, both the mirror and the water basin will be placed a few metres under the street level, sheltered from any jolt provoked by city traffic.

Before the above-mentioned definitive adjustment, we can make another one with the convex calibre, namely a 23-cm diameter disc, endowed with approximately the same curvature of the tiles, but of opposite sign. By placing it over the concave surface of the tiles, fringes are formed, which should have the same number for each tile. Now, if we cover two nearby tiles in the same ring, we may consider them as adjusted when the half fringes of the one are continued by the half fringes of the other. We go on in this way, a couple of tiles after the other, until we complete a ring. Obviously, jumping the step from one ring to another allows this type of adjustment only inside the same ring, rather than between nearby tiles of different rings.

The adjustment would be much more precise and much faster if we placed the lit-up wires in the mirror's *curvature* centre instead of the focus, in fact in the *curvature centres* of the various rings, which in our case, as we saw earlier on, are at a distance of 0,48 mm and 1,44 mm from one another. Thus we would remove the problem of a mobile artificial horizon, and should only take care of the overlapping of the lit-up grid and its real image, rebounding on one tile after the other. Incidentally, this would complicate the masonry, since we would need a tower twice the height of the focal distance, so that we would have three floors instead of two. Indeed, the third floor would be used for the adjustment, the second one for the photographic plate, and the first one for the mirror. In the new facility, I would like to test also this method of adjustment.

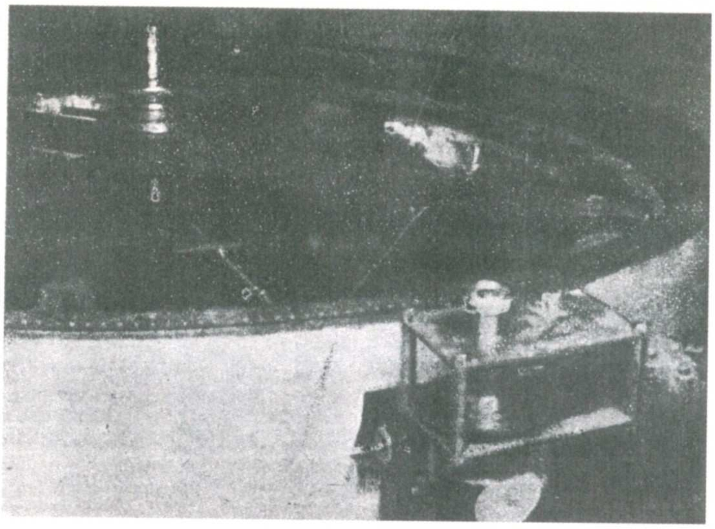

Fig.3 Entrance to the well on top of the tower. In the centre, you can see the chassis, on which the plate-carrier runs, and the flexing shaft with turns the endless screw. To the front, we see the engine joining the shaft, as well as the device for the automatic control, illustrated in fig.6 and 7.

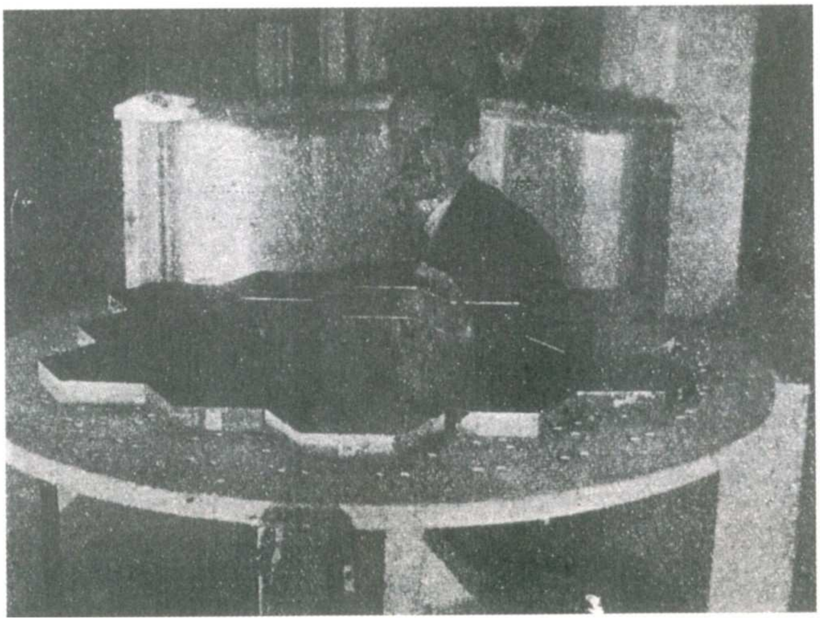

Fig.4 Marble table with nineteen tiles, placed upon the screws. Tile diametre= 20 cm; diametre of the whole piece= 1 mt. In the thin white margins within the surface of the mirror, you can see a 0,48 mm gap between the central tile and the ones of the first ring, and a 1,44 mmm gap between the second and third ring. The image – upright and inverted – represents the tile polishing mentioned above.

The distance between the photographic plate (fig.3) and the mirror top (fig.4) is 10,41 metres.

COMA. The stellar image distorted by *coma* is symmetrical in comparison with a line joining the image itself with the centre of the plate (or, more precisely, with the point of the plate which is intersected by the mirror axis); the height of such image in the sense of the joining line is given by the following expression[5]:

---

[5] About this, see: *Pubblicazioni dell'Osservatorio Astronomico di Bologna,* vol.III, nr.6, p.66, the note: *La deformazione delle immagini stellari detta coma scomposta nei suoi elementi [The distortion of stellar images, called coma, broken down into its elements]*: this formula applies in fact only to paraboloid mirrors. However, in the preceding issue (Vol.iii, nr.5), entitled *Immagini stellari extrassiali generate dagli specchi parabolici, sferici, ed a tasselli [Extra-axial stellar images, generated byparaboloid,*

$$L_y = (a/p^2)\ y\ (3a + 4y)$$

Where y is the distance of the image from the axis, a the mirror's radius (here 500 mm); p the double focal distance (here 20,82 mt). I am reporting in the following table the values of L_y for the different y:

y	L_y
10 cm	0,018 mm
30	0,056
50	0,098
70	0,144
90	0,193
110	0,246
130	0,303
150	0,363

from which we can see that, if we trace upon the place a circle centering upon the mirror's axis, with a 10cm radius, all the stellar images included present a distortion, depending from *coma*, smaller than two-tenths of mm. Even though we extend the radius to 15 cm, the distortion exceed a third of a mm, and is lost in the diffusion disk.

In order to get an idea of the quality of images, have a look at the photographic reproduction on photographic paper (fig.5): it was printed in contact with the original plate nr.650, exposed for $6^m\ 15^s$ in the evening of August 4, 1949.

---

spherical and segmented mirrors], I had showed that *the coma* produced by the segmented mirror hardly differs from the one produced by paraboloid mirrors. The usual *Y* distortion, i.e. the one determining the width of the image, is still smaller, according to the formula $L_z = 2y\ (alp)^2$*, see I.c., p.66.*

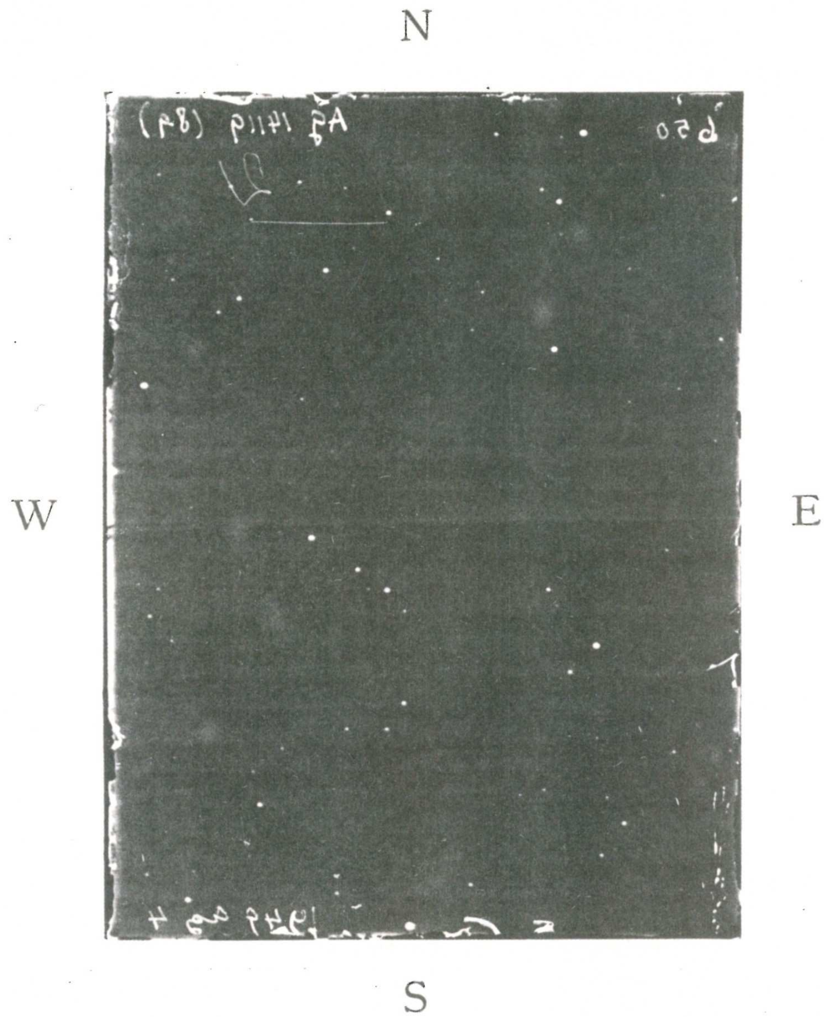

Fig.5 Reproduction through contact with the original plate n.650, photographed in the evening of April 24, 1949. Photographic pose: $6^m\ 15^s$. The largest star, in the lower margin of the print, is BD 43° 3581, of the ninth magnitude, which culminates 28' south of the Observatory's zenith. The weaker stars, visible on the plate, are included between the 15th and the 16th magnitude. Scale: 1' = 3mm.

The large star, visible in the lower side of the printout, is BD 43° 3581, of the ninth magnitude. With a magnifying glass, you can easily notice that all images – even in their edges and corners – are equally round. Let us take into account the fact that the stars on the sides (along the longer side of the rectangle) were photographed while they were – the ones at the start of the pose, the others at its end – at a distance of almost 15 cm from the mirror's axis. In fact, as the photographic pose – as we said beforehand – was $6^m 15^s$, equal to a 203 mm trajectory, you must add to the half of this value the 45 mm, corresponding to the half of the shorter side of the plate, i.e. in total 146,4 mm. Thus we can say that the mirror's useful space would cover a 9x30 cm plate, since its longer side is oriented according to the meridian.

Since thirty centimetres on the focal plane are equal to a 1° 40' declination, with a series of six identical mirrors, spaced 185 km in the sense of latitude, one would control all ten degrees of Italy's zenithal sky.

Another proof of the degree of concentration of the 19 overlapping images is given by the separation of double stars; for instance the triple star ADS4765, which in 1908 presented a distance between its main components of 6" 85, appears clearly separated upon the plate nr. 838 by a shiny space, i.e., in the tiny fraction of a third of a mm (since a millimetre is equal to 20"), there are two discs and a clear space dividing them. Thus, in the plate nr.805, the double star ADS 4057, with a space of only 5" 6 between its components, presents – even though a clear interval cannot be seen – two disks overlapping at their edges, whereas their centres are at a distance of little more than a quarter of a millimetre between them.

MOTION OF THE PLATE ON THE FOCAL PLAN. The motionless mirror forces us to follow the rotation of the sky with a plate moving on the focal plane. Therefore the chassis must cross this plane with the speed of stellar motion. This is done through a 24*v* battery-operated direct current electric engine. I shall describe later on how a uniform motion is achieved. The stars' trajectory, projected upon the focal plane, is - in general – a conic. It is a circle if the horizontal mirror has at its zenith one of the poles of the diurnal rotation. It is a straight line, if it lies on the line of the Equator; an ellipse, between the latitudes of 90° and 45°: an hyperbole between 45° and 0°; a parabole – which is practically the case of Bologna (phi= 44° 29' 53" 77). It was therefore necessary to have the chassis follow this parabole, whose parameter - as you can easily see - is *f*, if *f* is the mirror's focal distance. Therefore the curvature radius in the vertex is equal to *f*. If we take into account the remarkable length of *f* = 10,41 metres, it is reasonable to mix up the parabole curvature with the one of the osculating circle, not only at the vertex, but also all around for about ± 10 cm. Thus we build an iron lattice pendulum, 10,41 mt. high, and fix on its free end a carbide wheel, which will describe the wished-for curve while accompanying the pendulum oscillation, thus cutting up two metal shapes, one concave and the other convex. If we fix the concave shape on the focal plane with a convenient orientation, the other shape, bearing the chassis, moves along with the first one, without deviation, thanks to a spring, which keeps them matching. In this way, the stellar image never abandons the point of the plate it has occupied since the start of the exposure. The one and the other travel along the same route together, for the six minutes of the pose, as it is proved by the unique, perfectly round pictures.

This unchanged clinging of the stellar image to the same point of the plate is only reached when the wire of the metal circular segment, which constitutes the shape, is strictly oriented in the east-west direction; otherwise, the image becomes a small straight segment, parallel or oblique with respect to the direction of the meridian, according to whether the speed set by the engine is equal to the calculation, or not. The strict east-west orientation is obtained through photographing, by discovering first the still plate, until the star stamps a short trail; later on, one moves the plate onwards, so that it accompanies the star in the longest possible time, and the star may stamp a point-like image. Finally, one stops the open plate in order to obtain the second trail of the star: if one of the trails is the exact continuation of the preceding one, the orientation is perfect.

One can easily calculate that for $\boldsymbol{\varphi} = 44^\circ\ 29'\ 52''\ 77$ and for $f = 10.41$ m. the speed of a star of this declination in the focal plane is 1 millimetre each $1^s,852$ seconds sideral time. This speed is maintained by the engine headed by a gear-wheels mechanism. The last of these wheel rotates together with a 2 mm perpetual screw, and makes it rotate on itself, completing a round every $3^s,704$.

Thus the nut - which spans it - proceeds along the focal plane, together with the chassis, at the calculated speed. In fact that star, as well as the chassis-box forced by the shape, describe a circular segment, whereas the nut proceeds along a straight line, but the difference between the arc and the wire is only 0,003 mm in the 20 cm stretch, which are covered in $6^m\ 15^s$. Chassis-box and engine are represented in fig.3. We shall talk about the engine in our next chapter.

AUTOMATIC CORRECTION OF THE MOTION. No matter how uniform is the current provided by the accumulators, it does not manage to spin the shaft for the required rpm, so as to make both star and plate proceed at the same speed. On the other hand, one could not follow a guide star and correct the motion in the ordinary way, since the plate moves in the field centre, and the observer's body, while following the star, would have subtracted too much light. If one thinks of operating in the Newton's focus, one would complicate this model too much, since this mere model was built with the few means available at the Observatory. Here the talent of the mechanic

Irio Grasso came to the rescue. Grasso had worked as a technician at the Loiano astronomical station. He invented a device for the automatic correction, which was perfectly suitable to the aim. I shall briefly describe it. The two discs A and B (fig. 6 and 7) look at each other without touching, and are ideally co-axial. However, a conductor *c*, united with *A*, touches the coils of the resistance *r*, united with *B*; the disc *A* (prompted by the engine through a gear mechanism *R*) would complete a turn within a minute of sideral time, if an absolutely uniform speed were guaranteed by the engine. The disc *B* is moved by a clock, and completes the turn in a minute of sideral time too. We are pretty sure about the motion of *B*, during the short time of the pose, i.e. $6^m\ 15^s$; the problem is to force *A* to keep its position unchanged with respect to *B* during six turns, and this is achieved through the automatic correction. If *A* advances with respect to the exact time, the conductor *c*, moving over the resistance *r* (fig. 6 and 7) excludes one or more coils. Thus the engine delays and the acceleration of *A* stops. On the other hand, if *A* delays, *c* moves in the opposite direction and the number of coils increases, the engine accelerates, and so on. Figure 6 shows the scheme of the circuit, and figure 7 shows the two discs in perspective.

A similar device was mounted in Loiano, in order to replace the Zeiss regulator, which had been destroyed during the War. In any case, with that device, the observer follows the guide star and makes corrections with electric controls: however, automatic correction exempts the observer from the hassle of continuous attention.

The roundness of stellar images is an infallible sign of uniform motion. Either a delay or an advance of one second within the six minutes of pose would intolerably lengthen the image by a half millimetre, in the sense of the parallel.

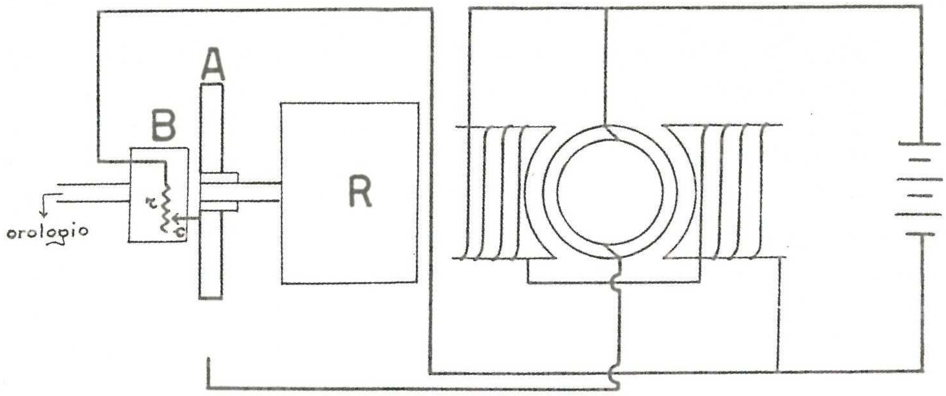

Fig.6 Electronically-controlled engine.

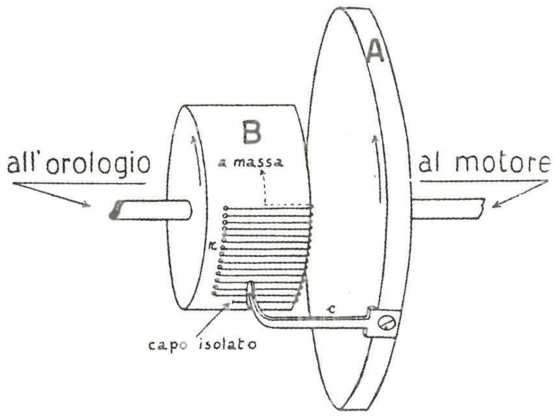

Fig.7 Perspective view of the engine.

The Future of the Segmented Mirror. Of course, it will be more and more convenient to build 1 mt. mirrors, like ours, out of one piece only. On the other hand, if you prefer to build huge mirror, you need to cut it up into tiles, and we may perhaps imagine a future in which we shall excavate 100 mt.-deep wells, in order to place upon them segmented mirrors occupying hundreds of square metres. If we think about Italy itself, there are natural sheer drops, which might be suitable hosts for such instruments: for instance, the St. Patrick's well in Orvieto, and the Castellana caves (Bari). The Superintendet's Office for Fine Arts of the Region Umbria had taken in consideration my request, which, however, was not realized, mainly for financial reasons. In any case, the soil would have been too damp, and always covered by water, which would damage the silvering of tiles. Aluminized surfaces would be less affected and, after all, there are means to tackle humidity, so that the well, which is 63mt. deep, with a 7mt. aperture, would represent the ideal frame for a 5mt. diameter mirror, with a 60mt. focus. As it is known, you can reach the well bottom through the twin staircase, carved into the rock, which is a masterpiece of the architect Sangallo.

Another suitable location is represented by the main hall of the Castellana caves, which is 45 m deep and receives light from the top of the vault, through a natural elliptical opening, with a major axis of 14 mt. and a shorter one of 11 mt. Here, because of the abundant circulation of air, and the free access to sunrays, there is no humidity. If you want ro remove the floor debris, composed of waste poured into the sinkhole and piled up since time immemorial, one could get back to the pristine floor of the cave, thus increasing the ceiling by 15 and more metres. Thus, the mirror placed on the floor might have a 9mt. diametre and a focal distance of about 70 mt., raising itself a bit to the outside. The worthy director of the caves, prof. Franco Anelli, arranged the underground access, by having a slanted side gallery excavated, which is crossed through a handy staircase. They are planning a cable railway, which would exempt visitors from walking over the steep vertical drop.

However, the segmented telescope, like any precision instrument, would need first-quality materials, different from the ones used for this first sample, starting from the glass, down to the supporting screws and the marble table. These materials should have respectively been *pyrex, invar,* and *porcelain.* In this way, we would increase precision and save time and hard work. Moreover, once removing faulty materials, one would ascertain any defects in the method.

Finally, I would like to mention an asset of this instrument, which might represent an advantage if we replaced the plate (which must be changed every six minutes) with a permanent film, which winds and unwinds on opposing reels, and moves at a pre-defined speed. Thus we would obtain one film with all the images covering a large portion of zenithal sky during the whole night. This uninterrupted documentation of the sky history is certainly useful, and should not require more than an occasional monitoring on the part of the operator.

Before concluding, I would like to mention the valid support I received in this enterprise, not only from the Observatory staff, but also from external scientists, such as the astronomer Lacchini of the Trieste Observatory, the surveyor Ferri of the Institute of Geodesy, and the mechanic Grassi of the Institute of Physics, who worked patiently with me from the start, namely since 1934. A particular mention is due to the Observatory technician Aldo Galazzi, to whom I mostly owe the realization of the segmented mirror. Indeed, he has polished all the tiles from coarseness to finishing, and built almost all mechanical and electrical devices. Finally, he has proved to be a master of adjustment, even though he lacks his right hand.

The finished 1,80m aperture segmented mirror placed in the tower of the Bologna University Observatory
Coelum, 5-6 (1955), pp.66-68

The older readers of *Coelum* will remember the first mention of the construction of non-monolithic concave mirrors, which I made in the June issue of the year 1932, as the idea had not been tested yet. In 1935[1] I reported the exhausting tests of the following years: at the time, the reflecting surface was made up of just ten tiles, provided by the Filotecnica of Milan, and each tile had an area of about 1 square decimetre. In 1937 we added ten more tiles, made in the Zeiss workshop. With those twenty tiles, we photographed 242 plates, until Fall 1938, when I was prevented from going to the Observatory. After the end of the War, I got back to work. During the Spring 1945, we started to polish sixty more tiles, which in 1947, together with the preceding twenty, formed a 1mt-diametre surface. The images we obtained were certainly not perfect, but they gave us hope that, once made the instrument more stable, the plate motion on the focal plane more uniform, and the adjustment method quicker (from the curvature centre instead of the focal plane), we might get better results.

Therefore we abandoned the square decimetre format and tried to polish areas of about 3,5 square decimetre, which became the definitive format. AS you can see in the figure, these tiles are hexagons with a double 20 cm apothem, while the focal distance still was 10,41 m. Nineteen tiles were completed in 1950, anc helped form the total 1m diametre surface, with which we obtained stellar images which, though not as clear as the current ones, were quite satisfying. This is shown by the plate, reproduced in the booklet entitled: *Altri esperimenti con lo specchio a tasselli [Further Experiments with the Segmented Mirror]*[2]. Meanwhile, the drilling works at the tower of the Observatory were in progress. Thus they would create a ceiling of 21 n, which could allow us to make the adjustment from the curvature centre, thus saving a lot of time. Beforehand, the adjustment was made from the focal plane, thus obtaining vertical rays through the artifical horizon.[3]

At the same time, we went on grinding further tiles, and by 1952 we had thirty-seven finished tiles, with a total diameter of 1,40 m. All the improvements we had made finally led us to overlap – in a quick and

---

[1] See *Pubblicazioni dell'Osservatorio Astronomico di Bologna*, Vol.III, nr.3 (1935)
[2] Id. id., Vol. V, nr.11 (January 1950)
[3] see *Pubblicazioni dell'Osservatorio Astronomico di Bologna*, Vol.III, nr.3 pp.10-11 (1935)

perfect way – thirty-seven images, as I showed in the note *L'aggiustamento dello specchio a tasselli effettuato dal centro di curvatura [The adjustment of the segmented mirror starting from the curvature centre].*[4]

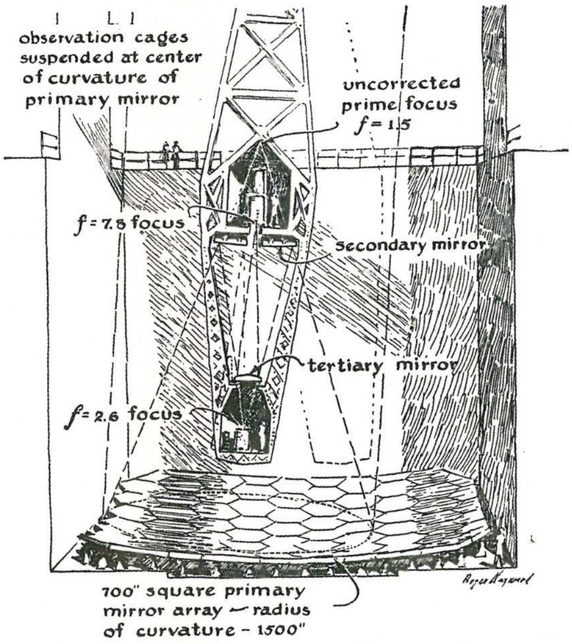

Fig.1 Project of Mr. L.T. Johnson. Mirror diametre = m.1,75

Finally, after completing 24 more tiles, which formed the fourth ring, in the Summer of 1952 the mirror composed of 61 tiles, with a 1,80 m. aperture was complete. Everything made us think it would be possible to add a fifth ring, which would extend the aperture to 2,20 mt., but unfortunately the dimension of the tower prevents us from any further enlargement.

Since the focal distance had remained constant at 10,41 mt., the relationship between aperture and focal distance (which had been 1 mt. with a diametre of 60 cm, and 1,40 mt. respectively of 1/18,2, 1/10,4, and 1/7,1) became a steady 1/5,7. With this mirror, which was used every night - weather permitting - we photographed almost six thousand plates since June 1952, and we have now about eight thousand.

[4] Id. id., Vol.V, nr.17 (January 1952)

The value of this homogeneous photographic material[5] will increase over time: the 9x12 cm plate covers 40' declination and almost three minutes right ascension. Thus the whole area included between 44° 10' and 44° 50' of northern declination[6] is contained in about 500 plates. Therefore, each sector of the zone was photographed – on average – more than ten times. From the comparison between plates of the same right ascension, sofar we found ten variable stars, which had not been considered as such beforehand. The first four were recently reported:[7] one of these is a classic Cepheid, with a period of 9^d 77, and an amplitude of about one magnitude, the results related to the other six stars will be the subject of another publication.

In photozincography, the smaller stars are lost, but the smaller images, visible in the American Kodak plates 103 *a O* go down to the magnitude 18,5[8], as from the comparison with the *Selected Areas* of the Mount Wilson Observatory (1930).

In the tables, there are photozincographies of various regions, over and above the segmented mirror with 61 tiles, which has been used for photos. In the *recto* of the second table, you can see the trajectory of a falling star. The reader can notice that the images are exempt from *coma* up to the field edges, until the border of the 9x24 plate reproduced full-size. The apparent distortion of the large star in the upper right corner of the plate depends on its doubleness.

The segmented mirror system aroused interest in the press of various countries: England, USA, Sweden, Spain, and Mexico. Mr. A. G. Ingalls, in the *Scientific American*, reported the projects of two astronomers, presented with explanatory drawings.[9] The first one was made by Mr. J.P. Hamilton, of the Astronomical Society of Victoria (Australia), and is identical to the instrument of the Observatory of Bologna, when it was composed of only 37 tiles and had a 1,40 mt. aperture. The second one was made by Mr. L.T. Johnson, a well-known observer of planetary surfaces in La

---

5 Except a few cases, in which we recurred to the American films – Kodak 103 *a O*, the plates we generally used were Cappelli ultrasensitive, which *Ferraria* prepared specifically for the Observatory, with the following dimensions: 9x12 and 9x24 cm.

6 The mirror lies horizontally, and is motionless. The Observatory's latitude is phi=44°29'53". For everything related to the adjustment and the motion of the plate, see *Coelum*, 1952, May-June, p.65

7 See in Vol.VI, nr.7 of the *Pubblicazioni dell'Osservatorio di Bologna*, the note by G. Horn D'Arturo and G.B. Lacchini, *Variazione luminosa di quattro stelle ecc. [Brightness variation of four stars, exc.]*, January 1955

8 *Pubblicazioni dell'Osservatorio Astronomico di Bologna*, vol.VI, nr.6, p.2

9 *Scientific American*, 1954: May issue, pp.100 and 102; June issue, p.102

Plata, Maryland. We are reproducing the drawing published in the *Scientific American*, as a matter of interest for the reader. Judging from this drawing, the surface would have a diameter of 17,5 m., since each tile measures 1 square metre!

The developer, while concerned about extending the pose, moves over the segmented mirror a tube carrying the secondary mirrors, as well as the photographic plate. However, in this way, he does not take advantage of all the light reflected by the main mirror.

Once again, both sketches were not subject to a test. However, it is interestng to notice that scientists are gradually accepting a principle which was generally refused beforehand, namely: 1) that we may recur to a segmented reflecting surface and 2) that we may use a motionless mirror.

The latter circumstance obviously curbs the freedom of the instrument, which only dominates the zenith and the sky region which passes there in that moment. On the other hand, this region is less depleted by atmospheric absorption, and stellar positions are exempt from refraction. Thus, each zenith should have its telescope. If we keep a 10mt. focal distance, with a 9x24cm plate, we can include 1° 20' of declination: if we had ten telescopes similar to the one in Bologna (φ = 44° 30'), spaced out by one degree in latitude, we could cover the whole of Italy's sky. These telescopes should be placed in the following places (or nearby):

	φ		φ
Bolzano	46° 30'	Taranto	40°30'
Brescia	45°30'	Cetraro	39°30'
Arezzo	43°30'	Rosarno	38°30'
Narni	42°30'	Catania	37°30'
Cassino	41°30'	Capo Passero	36°30'

With the above-mentioned 9x24 cm plates we would obtain not only the zenithal region 1° of declination, but also 10' north and south, which would overlap the same areas of nearby stations.

I am hoping to build in Brescia an instrument just like the one in Bologna, the second of a series. The *Torrione dei Francesi [French donjon]* embedded in the hill of the Cidnea Observatory in Brescia, looks like it was made on purpose to host a segmented telescope: towers like that can be found anywhere in Italy, but the expense of the equipment would be remarkably reduced.

However, in order to carry out this project, I should build – out of this series – a 5mt. mirror, with a 34mt. focal distance, to be placed in the Castellana Caves (Bari). With a suitable rock drilling, we might achieve a cylinder-shaped space, 68mt. high. The 217 hexagonal tiles – necessary in order to form a 5,10m. diameter, would have a double apothem of 30cm. I will get back to this topic as soon as this dream project can be transformed into a reality.

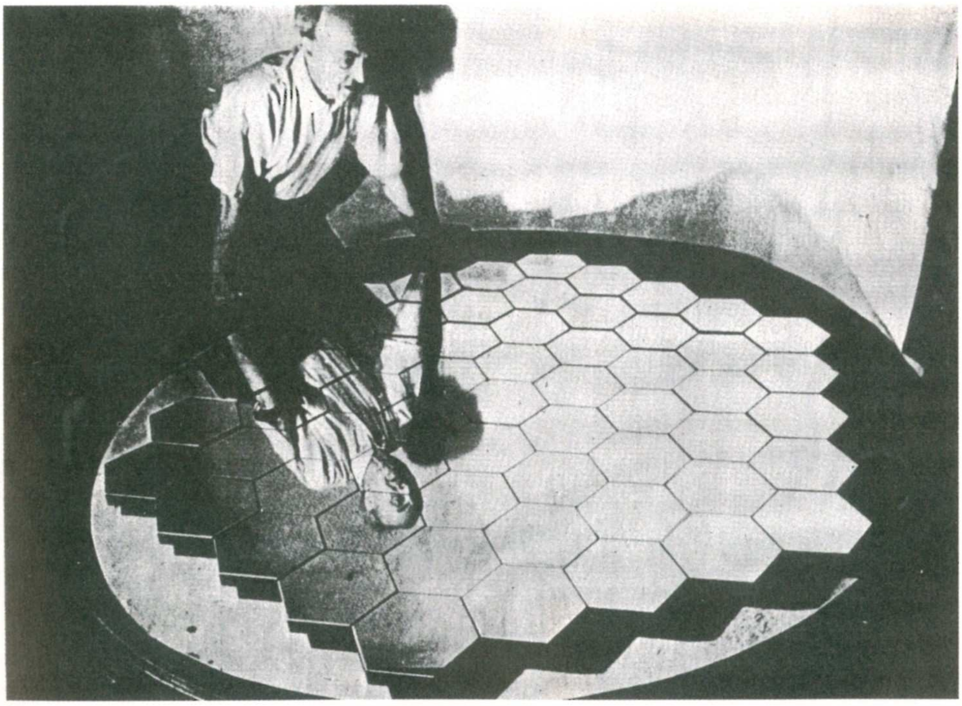

Fig.2 Bologna University Astronomical Observatory Mirror, composed of 61 tiles. The diameter of each tiles is 20cm. The diameter of the whole mirror is 1,80 m. The mirror's focal distance is 10,41 m.

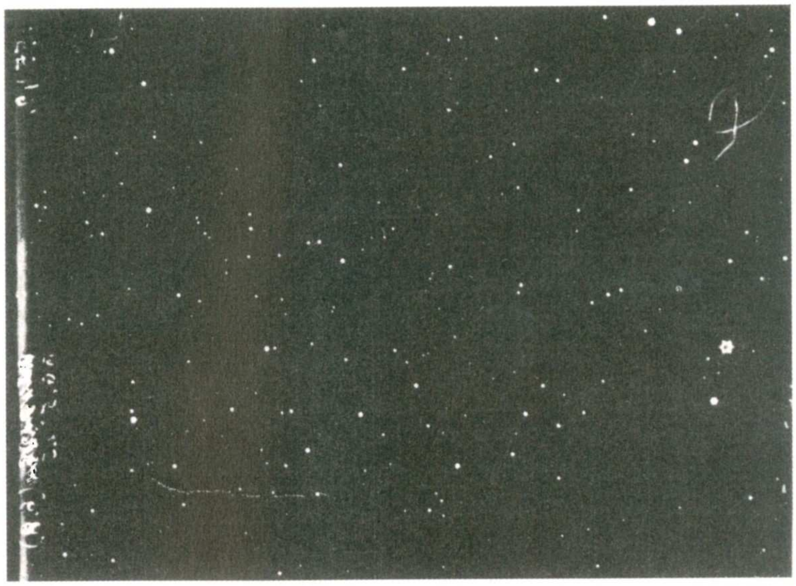

Fig.3 Plate nr.5542, photographed with the wholly free segmented mirror (diameter m.1,80)

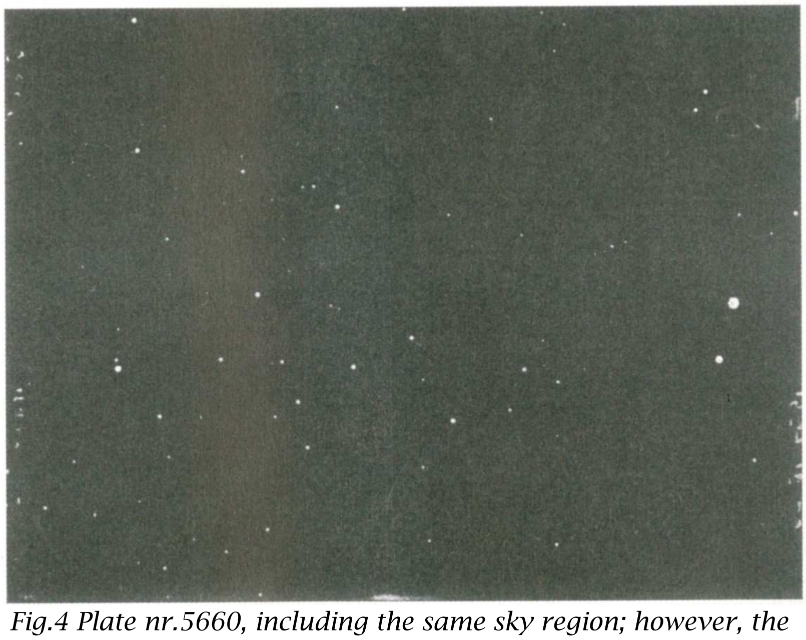

Fig.4 Plate nr.5660, including the same sky region; however, the stellar magnitudes have decreased by one whole unit because the diaphragm overlaps the mirror (free diameter m.1,58).
The circled star on the right edge of both plates is AG 15825, with a magnitude 6,8 (AR= $21^h35^m4^s$: D= $43^\circ51'59''$ 1875,0). The two plates – full-scale, are 9x24 cm. The north is left, the west down below.

The figure of Diffraction surrounding stellar images, photographed with the segmented mirror
Coelum, (1957), 7-8, pp.102-106

It is well-known that M. Grimaldi was the first scientist[1] who observed the phenomenon which he defined as *diffractio luminis*, i.e. the deviation suffered by a beam of sunrays hitting the edges of a small matte screen, or of a tiny slit; he also got the idea that the alternating light and dark bands around the shade of the screen, or the slit, should depend on a *minutissima agitatio* [*tiny stir*] of the light, which is not immediately perceptible to the eye[2].

Even though Grimaldi's experiment had been repeated by Newton[3] and Young[4], to name just the major ones, the explanation of the phenomenon was given by the brilliant scientist A. Fresnel, in a series of *Memories*, started in 1815[5]; he had made use of the interference theory showed by Young[6], as well as of the principle of the propagation of light, stated by Huygens[7]. Once recognized the cause for diffraction, Fresnel managed to identify for the first time the wavelength of red light. Thus the astronomers realized the reason why the images of brighter stars were surrounded by alternatively light and dark haloes. These haloes were iridescent if the light was white. The beam of parallel rays hitting the edge of the objective was affected by diffraction, thus provoking those undesirable, unavoidable aureoles. However, one could make the rings narrower with the growing diametre of the objective. That is why scientists wished for larger lenses, and consequently, narrower diffraction rings, so as to obtain better *defined* stellar images.

The first theoretical studies on diffraction in objectives were done by Airy[8] and Schwerd[9]; in the strictly experimental field, Fraunhofer[10] and J.F.W.

---

[1] *De lumine etc.,* Bologna, Benazzi, 1655.
[2] Ibid., p.12; *Lumen videtur esse quid fluidum perqum celerrime et saltem aliquando etiam undulatim, fusum per corpora diaphana.*
[3] *Optices,* book III, p.127 of the Padua edition, Manfré, 1749; about the cause of this phenomenon, see p.12 and elsewhere.
[4] *On the theory of light and colours, Phil. Trans.,* 1802.
[5] *Oeuvres d'A. Fresnel,* Paris, Impr. Royale, 1866.
[6] *Phil. Trans.,* l.c.
[7] *Traité de la lumière,* Leiden, 1691.
[8] *Cambridge Transactions,* Vol.V, P.VIII.
[9] *Beugungserscheinungen,* Mannheim 1835.
[10] *Neue Modification des Lichtes durch gegenseitige Einwirkung und Beugung der Strahlen, und Gesetze derselben,* Schumacher's Abahandlungen Bd VIII f. 1821-22.

Hershel[11] had studied the effect, as a round hole or a slit, the rays limiter was replaced by other geometrical figures. Later on, Schwerd[12] made numberless experiments with the objected framed by triangles, hexagons, prallelepipeds, trapezes, etc. and by multiple holes, with identical or different shape, thus obtaining figures which, though bizarre, were exactly defined in advance, thanks to calculations. Among the scientists who continued these experiments, we may quote J. Scheiner and S. Hirayma[13], who made tests with a 4m focal objective, framed by multiple, irregular figures. As for papers of a strictly astronomical interest, we may mention the essay by H. Struwe[14] who, resuming Airy's theory, showed that the calculation of interferential rings could be simplified by using the 1[st] degree Bessell function. Finally, H. Burns[15] handled the effect of diffraction produced by the twin semi-objectives of the *Heliometer*.

---

[11] *Poggendorf's Annalen* Bd XXIII, p.281.
[12] l.c. p.VIII and ff.
[13] *Photographische Aufnahmen Fraunhofer'schen Beugungsfiguren* in: *Anhang zu den Abhandlungen der K. Akad. D. Wissenschaften aus dem Jahre 1894.* Berlin, Remer, 1894.
[14] *Mèmoires de l'Acad. Imp. d. Sciences de St. Petersbourg,* Tome XXX, nr.8, 1880.
[15] *Astr. Nach.,* vol.104, nr.2473.

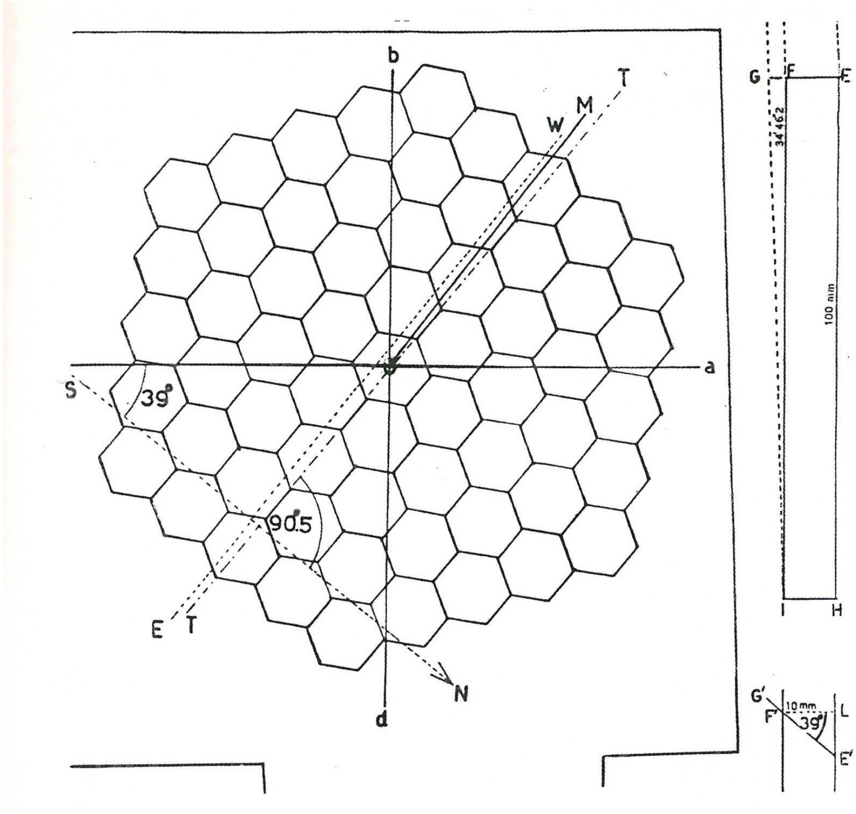

Fig.1 Mirror composed of 61 hexagonal tiles. The diametre of the whole mirror is 1,80 m. Double apothem of the tiles= 20 cm. The sides of the adjacent hexagons represent 2mm-wide gaps (which are defined as "slits" in the text).
Ac, bd are arms of the cross, which is 10,41 m, far from the mirror, lying on the focal plane, and carries the chassis with the mobile plate. AC, BD also represent the second cross, superimposed ono the first one, lying on the plance of the urvature centre, at a distance of 20,82 m. from the mirror.
T is one of the three directions of the slits. OM is the directiomn of the motor shaft: it forms with TT an angle of about 1°. NS is the direction of the meridian. EW is the direction of the parallel, according to which the photographic plate moves. The arn Oc forms with the meridian an angle of 39°.

On the right handside: Vertical section (top) and horizontal section (bottom) of the Oc arm of the cross (lifesize). GI is the dricetion of the extreme radius, forming with the vertical an angle of 24'46"2. E'F'G' represent the trajectory of the star over the cross.

All this concerns the diffraction in the images generated by Rifractors. On the other hand, in Reflectors, the effect is complicated because of the unavoidable interception of the beam on the part of the support of the secondary mirror, or prism, and the *chassis*. Therefore, over and above the effect produced by the edge of the main mirror, or by the diaphragm which covers its margin – similar ot the one mentioned above for the objectives – you can see four orthogonal appendixes being detached from the stellar images. This happens when the support is a cross attached to the barrel coat, crossing the whole field.

Let us now consider the segmented mirror which presents a second – and not minor – cause of diffraction in the gaps between adjacent tiles, acting like slits, with an average width of 2 min. in the Bologna instrument (Fig.1). The hexagonal shape of the tiles ensures that the slits must be oriented according to three directions, which enclose 120° angles. Therefore the figure of diffraction is composed as follows: 1) by six radii caused by slits, marked in Fig.2 with A, B, C, D, E, F; 2) by 4 more radii marked with a, b, c, d, due to the two crosses, one which is 10,41 m. far from the mirror and bears the mobile plate, and the other one superimposed onto the first one as accurately as possible, which is 20,82 m. far from the mirror. Attached to this cross, we find the eyepiece, endowed with an illuminated reticle, useful for the adjustment of tiles[16]: the reticle's centre coincides with the mirror's curvature centre.

The fundamental difference between traditional telescopes and the segmented telescope consists in the fact that in the first ones the length of the pose does not alter all the time the diffraction figure, since the beam of light rays coming from the star under study is always inclined in the same way with respect to the supporting cross. On the other hand, in the segmented telescope, since the mirror is motionless and plate is mobile, the beam hits upon the slits and the crosses with inclinations which always vary during the pose: therefore we cannot expect to distinguish in the figure of diffraction a maximum and a minimum, cancelled by their overlapping.

Let us consider first of all the diffraction produced by the gaps between tiles, which should all be 2 mm. wide, according to the project. Since the moulding – no matter how accurate – cannot be a fraction of millimetre precise, and the tiles, after the adjustment, can be nearer or further away

---

[16] ee: *L'aggiustamento dello specchio a tasselli effettuato dal centro di curvatura [The adjustment of tiles made from the curvature centre], (Pubbl. Oss. Astr. Univ. di Bologna,* vol.V, nr.17, 1952)

from each other let us make a calculation for an average 2 mm. gap, certain that we are not too far from being correct.

Therefore, if the gap width is constantly $d = 2$ mm, and the wavelength $\lambda = 0{,}00045$ mm, matching the maximum intensity of the *Ao* spectrum of the star ß *Aurigae*, reproduced in fig.2, while $D = 10410$ mm is the mirror's focal distance. Here then we can use the following well-known formulae:

		d sen $\alpha = \lambda$	D tan α = min.	
1° min	$\lambda = 0{,}00045$	sen $\alpha = 0{,}000225$	D tan α = 2,34 mm	1° min.
2°	$3\ \lambda = 0{,}00135$	0,000675	7,03	2° min.
3°	$5\ \lambda = 0{,}00225$	0,001125	11,71	3° min.
4°	$7\ \lambda = 0{,}00315$	0,001575	16,40	4° min.

and the following maximum values:

1° max	$2\ \lambda = 0{,}00090$	Nnsen $\alpha = 0{,}00045$	D tan α = 4,68 mm	1° max
2°	$4\ \lambda = 0{,}00180$	0,00090	9,37	2°
3°	$6\ \lambda = 0{,}00270$	0,00135	14,05	3°
4°	$8\ \lambda = 0{,}00360$	0,00180	18,74	4°

The extreme value is given by the 4° maximum, which is 15 mm far from the stellar image, namely what can be observed in fig.2[17]. Obviously, the other lax and min values, produced by slanting rays, go beyond the calculated ones, because they hit narrower gaps, but are invisible because the light is subdued. The reader should notice that the rays A, B, C, D, E, F – produced by the gaps - are stronger than the *a, b, c, d* provoked by the crosses, as we shall mention further on. This has to do with the fact that each the active part of the crosses' arms which cross the field measure only 1,80 m. each (i.e. just like the mirror's aperture), whereas the sum of the active sides of the hexagons in the three directions amounts to about 6 m. (52 slits x side length = 11,43 cm), not to mention the 18 marginal sides which do not form a slit.

If we now consider the supporting crosses, we see first of all the effect caused by the light hitting upon the arm *bd* (fig.1) of the lower cross, which carries the plate and is 10,41 m far from the mirror. Let us suppose a zenithal star appearing at the incoming edge of the mobile plate: since the pose lasts 6^m30^s, within this time the star travels for 69'32" 4, therefore at

[17] On the plate, the measure is 19 mm; the figure is reduced to 4/5 of the original size.

the start of the pose it is 34'46" 2 far from the zenith. This is the angle of inclination of the parallel rays coming from it, and now hitting the edges E, F, and I of the beach – seen in vertical section and represented by fig.1. Therefore the occulting segment is GFE, and in its horizontal projection G', F', E', which indicates also the direction of the star's motion (which is E',F',G'). Now, since: G'F' = FI tan 34'46"2 = 100mm x 0,0101, we have G'F' = 1,01 mm, since F'E' = F'L cos 39° = 10 mm 0,777146 = 12,8676 mm; finally, G'E' = G'F'+F'E' = 13,8776 mm.

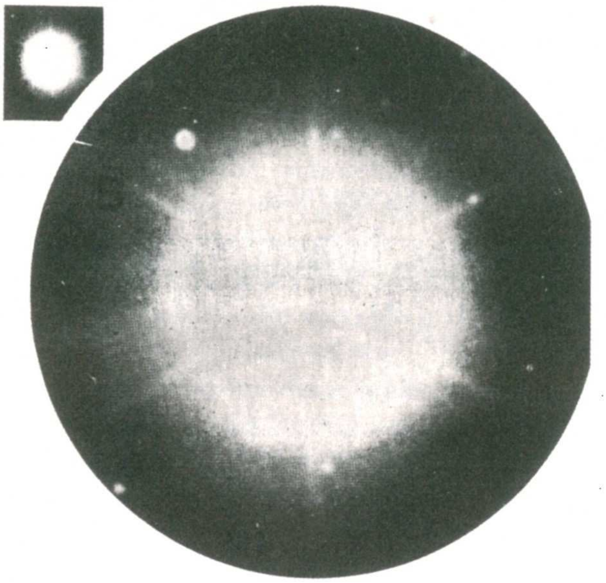

Fig.2 – Picture of the star ß Aurigae, photographed on the plate nr. 12174 on January 9, 1957. On the right, the same star, magnified 6 times. The rays ABCDEF of the figure of diffraction depend on the slits, whereas the rays abcd depend on the crosses.

If we take into account the fact that the (focal) distance of the lower cross from the mirror is 10410 mm., and the distance of the upper cross is 20820 mm., without prejudice to the wavelength λ = 0,00045 mm, we can easily calculate the places of both maximum and minimum values, as follows:

LOWER CROSS			UPPER CROSS		
1° min	**λ**	**0,34 mm**	**1° min**	**λ**	**0,68 mm.**
2°	3 λ	1,01	2°	3 λ	2,02
3°	5	1,68	3°	5	3,36
4°	7	2,36	4°	7	4,72
5°	9	3,04	5°	9	6,08
6°	11	3,71	6°	11	7,42
7°	13	4,39	7°	13	8,78
8°	15	5,06	8°	15	10,12
9°	17	5,74	9°	17	11,48
10°	19	6,41	10°	19 λ	12,82
15°	29 λ	9,79	15°	29 λ	19,58
1° max	**2 λ**	**0,68 mm**	**1° max**	**2 λ**	**1,36 mm.**
2°	4	1,35	2°	4	2,70
3°	6	2,02	3°	6	4,04
4°	8	2,70	4°	8	5,40
5°	10	3,36	5°	10	6,72
6°	12	4,05	6°	12	8,10
7°	14	4,72	7°	14	9,44
8°	16	5,40	8°	16	10,80
9°	18	6,08	9°	18	12,16
10°	20	6,75	10°	20 λ	13,50
15°	30 λ	10,13			

Since the distance between the upper cross and the mirror is twice the distance between the lower cross and the mirror, as a consequence *all* the minimum values produced by the upper cross 1°, 2°, 3°, etc., overlap with every max second produced by the lower cross 1°, 3°, 5°, as you can see from the table. This is the second reason which prevents us from distinguish, in the picture, maximum values from minimum values. As you can better see in the negative (less clearly in the photo-mechanic reproduction, fig.2), while the six orthogonal rays produced by the slits can be followed – as we mentioned above – until 15 mm from the centre, namely almost until the 4° max, the four orthogonal rays produced by the crosses can only be followed until about[18] 10 mm. from the centre, namely until the 10° max.

[18] 12 mm in the original.

We should take into account yet another element upon which the light hits before getting to the mirror, namely the shaft of the chassis, represented in fig.1 by the segment OM: since this vector forms – with one of the three directions of the OT slits – an angle of little more than 1 degree, the diffraction thus produced approximately coincides with the ones of the OC ray (fig.2) which indeed appears slightly enlarged.

The figure of diffraction is no longer visible around the stars of the seventh magnitude.

Stellar Interferometer, constituted by two specular tiles, at any distance from each other
Coelum, (1965), 3-4, pp.33-39

A.A. Michelson was the first[1] scientist who put into practice a casual idea expressed, 22 years earlier, by A.H. Fizeau, who announced the possibility, offered by interferential phenomena, to be useful in measuring such tiny angles, that no telescope enlargement was sufficient to visualize.

"…pour le dir en passant il est peut-etre permis d'esperer qu'en s'appuyant sur ce principe et en formant, par example, au moyen de deux larges fentes trés ècartées, des franges d'interference au foyer des grands instruments destinés à observer les éetoiles, il deviendra possible d'obtenir quelques données nouvelles sure les diamétres angulaires de ces astres"…[2]; the concept of this genial French physicist was later developed by his pupil J.E. Stephan in 1873 and 1874[3].

Michelson experimented the new method in 1891[4] on the refractor of the Lick Observatory, by measuring the diametres of Jupiter satellites. Almost thirty years later, in the month of August 1919, he resumed observations with the 1m aperture reflector of Yercks Observatory, and immediately after that, with the reflector of Mt. Wilson[5], and was convinced that the measurements were possible even with a mediocre visibility. Finally, J.A. Anderson, to whom we owe the remarkable simplifying of the device, which consists in covering the mirror, not adjoining the reflecting surface, but rather near the focal plane, managed to measure the angle separating the two components of the spectroscopic double star α *Aurigae*, in 0", 0545 arcseconds[6].

---

1 Philosophical Magazine, Vol.XXX, series N. CLXXXII, July 1890, p.1: On the application of interference methods to astronomical measurements; see also vol.XXXi, XXXIV, 1890-92.

2 Comptes rendus, Vol.66, 1868, p.934. [Just in passing, we can probably hope that, according to this principle, if we form, for instance, between two large slits, a few interference fringes on the focus of a large instrument destined to observe stars, it will be possible to obtain a few new data on the angular diametre of these stars…]

3 C.R. Vol.76, 1873, p.1008 and Vol.78, 1874, p.1008.

4 Mem. Astr. Soc. of the Pacific 1891.

5 Aph. J., 1920, June.

6 Contrib. From M. Wilson Observatory, nr.185.

Several attempts were made later on by P.W. Merrill[7], L. Richardson[8], F.G. Pease[9], R.H. Wilson[10], A. Danjon[11] and W.M. Sinton[12], and I do not know whether I mentioned all of them. Finally, I would like to recall the experiments made, with very modest means, by our colleague M. Maggini[13].

As it is well-known, the device consists in covering the whole mirror, or the objective, except two small areas, lying over a diametre, and establish at what distance between them the interference fringes – produced by the fixed star lighting up the two areas - disappear on the focal plane. This was why scientists tried to get larger and larger mirrors, since, the smaller is the angle we want to measure, the greater must be the distance between the areas. Recently, an attempt was made by the Australian Observatory of Narrabri[14], to use huge segmented mirrors, which would gather up a lot of light, which was concentrated on two *detectors*: thus they bypassed the problem, by asking electricity what could not be obtained by optics.

On the other hand, still in the field of Optics, the use of segmented mirrors invented at the Observatory of Bologna[15] can be useful, as follows. You can do without the whole mirror, and use two tiles only, with the same round concavity, at any distance from each other, placed so as to be considered areas of the same spherical surface. The adjustment method, tested numberless times in Bologna, leaves no doubt as to its rigour.

The cheapest mount for this sort of interferometer would be constituted by a cylinder-shaped well 35m deep and a diametre of 12 m., so as to allow the two tiles to keep a distance of at least 10 m. from each other, which is the distance suggested by Michelson for measuring the spectroscopic double stars.

The tiles *TT'* (fig.2) would be *poised* upon three screws *VV'*, parallel with the supports *SS'*; the latter would be moved arbitrarily by the observer, sliding along a track GG' in order to reach the established distance; the track would rotate around a vertical axis *A*, so as to orientate the tiles according to the required azimuth of components. The nadir collimators *CC'* would be useful for the adjustment of tiles, as I will now explain. A lift

---

[7] Aph. J., Vol.56, pp.40-52.
[8] J.B.B.A., Vol.37, pp.311-17.
[9] P.A.S.P., Vol.42, 1930, p.253.
[10] P.A.S.P., VIII, p.152; Publ. Univ. Pennsylvania (Astr. Ser.), VI, p.4, 1941.
[11] Ann. D'Astroph., Vol.VII, p.135, 1944.
[12] A.J., Vol.59, p.369, 1954.
[13] Catania, Tip. Salesiana, 1925; Mem. Ed osserv. Dell'Osservatorio di Teramo, I, 1929.
[14] Sky & Telescope, XXVIII, August 2, 1964.
[15] Coelum, 1932, p.120: Telescopi dell'avvenire e specchi a tasselli.

L would allow the operators to reach the bottom of the well, and respectively the focal plane *F* and the top of the well.

All this would apply if we wanted to use the interferometer, both for measuring the diameters of fixed stars, and for the distance of spectroscopic double stars. On the other hand, if we just want to search for diameters, we would not need to take into account the azimuth, and we would use two pillars instead of a well.

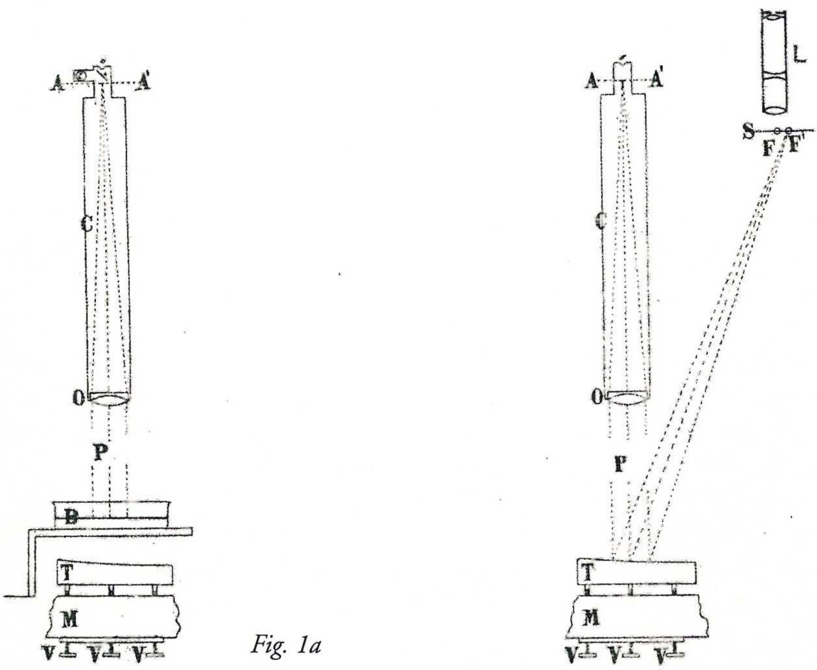

Fig.1. In both figures C is the collimator, T the tile, M the drive, called GG' in fig.2 with the screws V. P is the bundle of parallel, vertical rays; AA1 is the focal plane of the objective o, which contains a spiderweb cross. In the fig.1 you can see the artificial horizon B, which is removed when the verticality of the beam P is reached; in fig.1b you can see the S plane where, during adjustment, lies a spiderweb cross, centered in F, and then the sensitive plate. In F1 you can find the real image of the cross AA', which coincides with F by properly turning the screws V.

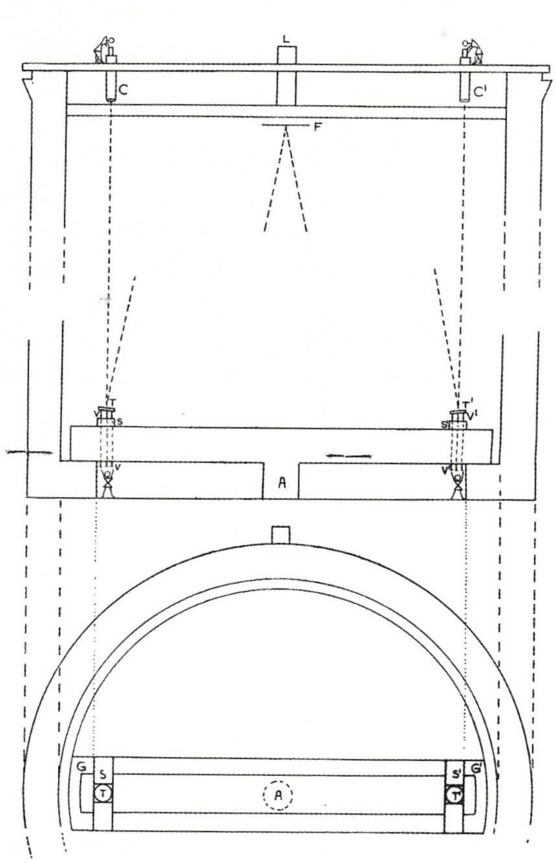

Fig.2. Cross-section and map of the well described in the text. Depth of the cylindrical box = 35 m.; width = 12 m.; distance between the two tiles = TT': 10 m.

As for the adjustment, if the observer had a motionless fixed star at its zenith on hand, the adjustment would be much easier: failing this natural source, which is infinitely far away, we must recur to an artificial source, which should issue, as the supposed fixed star at its zenith, parallel and strictly vertical rays, which should hit two tiles in succession. To this aim, we should use a collimator eyepiece, with the objective aiming at the nadir (fig.1°), carrying on the focal plane AA' a cross of lit-up threads. The rays issuing from this cross will be strictly parallel. In order to obtain their verticality, we let them hit an artificial horizon B, placed over the tile; when the observer sees the direct cross coincide with the reflected one, we have reached the goal of having parallel and vertical rays. At that point, we can remove the basin B and let the rays issuing from the collimator hit the tile directly (fig.1b). Once established the focus *F* on the focal plane, when looking at this point with an eyepiece, you will see also the cross reflected in *F'*, which in general does not coincide with *F*; on order to have them coincide, you act upon the screws, by appropriately moving the tile, so that the adjustment may be completed.

In the interferometer (fig.2), the point F results from the intersection of its axis, which is at the same distance from the two tiles with the focal plane. The above-mentioned procedure must be made for each tile[16]. I must admit that I adopted the adjustment with the aid of the artificial horizon, namely starting from the focal plane, thirty years ago[17], when I was confined in a room 1,05 m high, which corresponded to the focal distance of tiles. Later on, with the new instrument inside the Observatory Tower, which had been pierced for this purpose, I had at my disposal a 21 m. space, so that I abandoned the method of the artificial horizon - in theory very precious, but time-consuming - waiting for mercury to subside. It was difficult to obtain this process inside a tower, no matter how solid, but not immune from vibrations. It would have been easier to do this at the bottom of a well; on the other hand, at the time we had to adjust many tiles, whereas, nowadays, it is a matter of two tiles only. The other method of adjustment, made from the mirror's curvature centre[18], formed first by 37 tiles, then by 61 tiles[19], is much quicker, though equally rigorous. If we fix in the mirror's curvature centre a cross of bright rays and cover all the tiles, except one in the field of an eyepiece with which you look at the cross itself, its image also appears, as reflected by the uncovered tile. Therefore, if we turn appropriately the tile's supporting screws, we make the reflected image coincide with the direct one, and this will happen for all the other tiles in turn.

---

16 In order to make sure that the two tiles be almost horizontal before adjustment, we recur to communicating vessels, which are on the same plane of the slide S, and make the screws' top emerge to the water surface. The vessel device is not included in this drawing.

17 First experiments with the segmented mirror (Pubbl. Oss. Astr. Di Bologna, vol.III, n.3, 1935).

18 L'aggiustamento dello specchio a tasselli effettuato dal centro di curvatura [The adjustment of the segmented mirror, made from the curvature centre], (Pubbl. l.c. Vol.V, nr.17)

19 Lo specchio a tasselli di metri 1,80 d'apertura collocato nella torre dell'Osservatorio ast. Universitario di Bologna [The 1,80m. segmented mirror in the tower of the Bologna University Astronomical Observatory], Pubbl. l.c., vol. VI, nr.6

In our case, one could not, without an increased useless spending, reach the curvature centre, because, while planning a 30m. focal distance (fig.2), the well should be twice as deep as it is in order to make the adjustment from the centre. Let us therefore stick to the adjustment with the artificial horizon. Since we only have two tiles, the time we employ in the adjustment will be insignificant with respect to an unvaried position of the tiles, especially if we use *pyrex* mirrors and *invar* screws, while counting on the absolute absence of vibrations and the minimum temperature variations. I can say, from many years' experience, (17.000 photographed plates until November 1957) that the adjustment of tiles made of any kind of glass, supported by iron screws, just like the 61 tiles of the Bologna mirror, lasted unchanged much longer than the usual three uninterrupted hours of work, from 9 until midnight.

Obviously, the adjustment of all 61 tiles was repeated every night, before passing to the photographic work, and many tiles remained in the place assigned to them by the adjustment of the previous night.

I already answered elsewhere[20] the usual objection about the limited area of sky covered by the tiles, which aim at the zenith at all times. Once again, it is preferable to multiply the number of instruments, rather than make mirrors mobile with giant devices. Sofar, we could apply this method to a limited number of cases because of the small area between the two slits, or reflecting areas. If we have greater distances, the number of stars to be measured will grow remarkably, and the sedentary astronomers will be satisfied if, working all their lives, they will have submitted to measure all the stars passing over their zenith, as well as a small part of the zone which includes them. In the Bologna instrument, this zone embraced a declination of 1° 20'.

More than once I suggested placing the two tiles at the bottom of the well, to be excavated on purpose, but an easier solution would be taking advantage of a natural underground cave, which should have a pierced ceiling, as I had designed some time ago for the Castellana caves (Bari)[21]. This difficult project was not realized, but it was a matter of building a 5,10 m. mirror, composed of 217 tiles. Nowadays, instead, it is a matter of two tiles only.

---

20 Pubbl. id., vol.VI, nr.6, p.8, 1955.

21 La più grande superficie riflettente del mondo nelle grotte di Castellana [The greatest reflecting surface in the world in the Castellana caves], Edizioni del Comune di Castellana grotte, Putignano, 1957

Applications of the Segmented Mirror
Coelum, (1966), 11-12, pp.164-167

In 1955[1] I had pointed out three mobile segmented mirrors, which had been planned respectively by J.P. Hamilton, with a 14 m. diametre, by L.T. Johnson with a 12,5 m. diametre and again by L.T. Johnson with a 17,5 m. diametre. I have not heard from them since, therefore I guess these plans were not realized.

In 1964 the Australian Observatory of Narrabri[2] built two segmented mirrors, to be used as interferometers. One of them is here reproduced. I briefly described this instrument in 1965[3]. Unfortunately, they did not describe the adjustment of tiles, which must be very strict if the mirror has an optical function, and perhaps less strict if the light which is channelled into it actually hits the electric device, as it happens in the Narrabri instrument.

The impossibility of obtaining better defined images, as long as we remain in the Earth atmosphere, which alters them with varying refraction because of turbulence, poor visibility, etc., push astronomers to carry optical tools outside the atmosphere. One of the obstacles is represented by the weight of the monolithic mirror, with a thickness which is 1/6 of the diameter, we end up recurring to the segmented mirror which, with the minimal thickness of each tile, allows us to obtain large reflecting surfaces which are not too heavy.

We read in a paper by W.S. Beller[4] that a few big manufacturing companies went into partnership – namely *Perkin Elmer, Boeing Co., American Optical Co.,* in order to set up an extraterrestrial telescope, which will be put into orbit in 1979!

---

[1] *Pubbl. Osserv. Astr. Univ. Bologna,* Vol.VI, nr.6, pp.5-6-7.
[2] *The Journal of the Astronomical Society of Victoria,* October 1964.
[3] *Pubbl.* Ib., Vol.IX, nr.1, 1965, p.2.
[4] *Missiles and Rockets,* 1966 Apr.25.

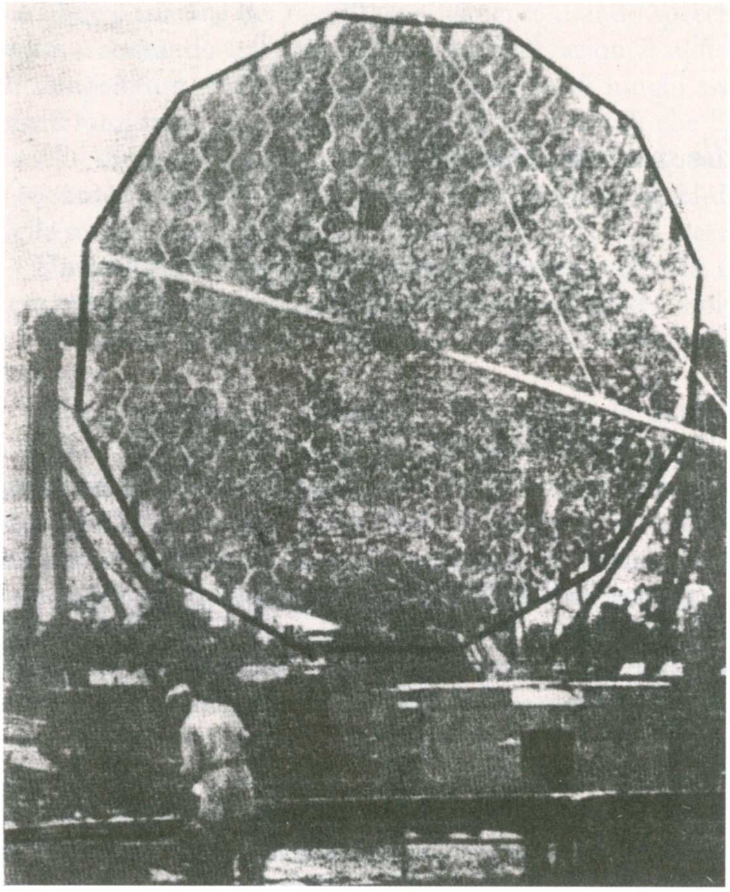

Fig. 1

Since we cannot sum up here all the details of this construction, we refer you to Beller's paper. However, we are reproducing here two sketches of the mount supporting the segmented mirror, for those who are interested in this topic (fig.2, fig.3).

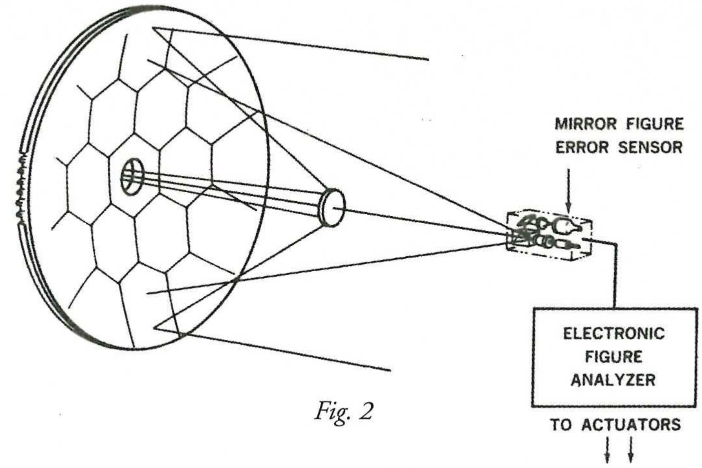

Fig. 2

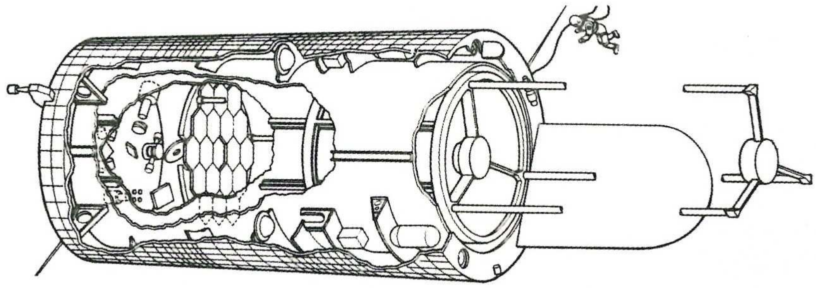

Fig. 3

Keeping to the subject of the large telescopes, R.H. Miller – a lecturer at the University of Chicago – suggests building a Michelson interferometer with a 1km basis, and highlights all the advantages which Astronomy would gain from such an instrument. We do not doubt its usefulness, but we must not disregard the difficulties involved in such construction. The plane mirrors channelling the star's light would be placed at the end of a *crossarm* along 1 km. The author underlines that the crossarm should be parallel to the Earth axis, but points out the difficulty of adjusting plane mirrors in a slanted crossarm, its upper end at 700 mt. above the ground, at a latitude of 45°; therefore, it would be better to place it horizontally. Another difficulty would be making a mobile crossarm in the azimuth direction. In case it were motionless, on the other hand, it would simply be used for measuring stellar diameters, not at the distance of double stars.

I proposed a smaller interferometer, consisting of two tiles only[5], 10 mt. away one from the other, with which it would be possible to gather a huge quantity of observations. Obviously, the higher the distance between tiles, the more difficult would be the adjustment through the artificial horizon (see fig.4), due to the spherical shape of the Earth. Indeed, for a 1km distance between the tiles, the vertical rays obtained with the artificial horizon would no longer be parallel, and the vertical rays would form between them a 32",6 angle, as shown in the figure.

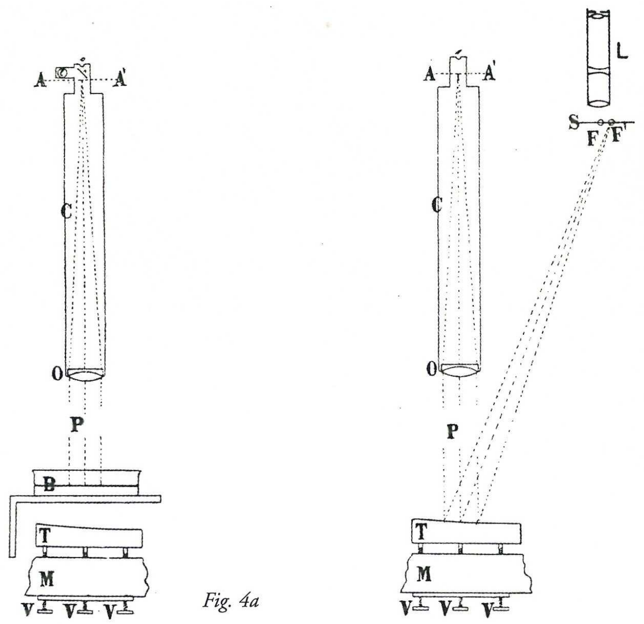

Fig. 4a *Fig. 4b*

Fig. 4

Finally, we read in *Sky & Telescope* (June 1966 issue, p.538), that the *Smithsonian Astrophysical Observatory* in Cambridge (Mass.) chose Mount Hopkins (3000 m, 60 km south of Tucson) for its new telescope. They are also planning the construction of a 15mt-diameter Reflector, composed of

[5] *Pubbl. Oss. Astr. Univ. Bologna,* 1965.

concave 60x60cm tiles. It will be useful for the study of the atmospheric luminosity depending from gamma rays coming from sky sources.

On the other hand, it would be easier to build an interferometer, composed of two tiles only, which would be 10mt., far from each other, which I mentioned above. I would like to see it built, without all the obstacles we can foresee at the moment.

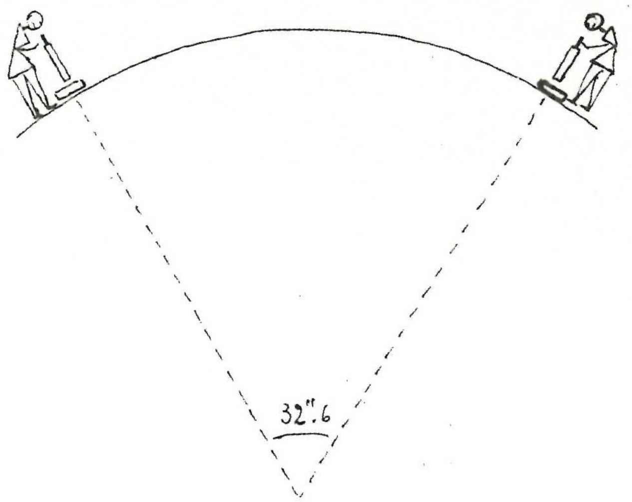

Fig. 5