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# Low turbulence - high performance

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## ABSTRACT

Basic features determining image quality are discussed for the Nordic Optical Telescope at its site at the Roque de los Muchachos observatory. Results and implications of our site evaluation are detailed. Large fractions of our data give seeing FWHM values below an arc second. The primary 2.56 metres f/2.0 mirror with an aspect ratio of 1:13.5 delivers 80 percent geometrical energy within 0.22 arc seconds in passive mode. The telescope has altazimuth mounting and Cassegrain focus. The primary mirror is floated on pneumatic axial bellows controlled via load cells on fixed points. The secondary mirror can be adjusted laterally, axially and for tilt to compensate for tube flexure. On-line image analysis will be used to maintain optomechanical quality. Strict thermal control is maintained of telescope structure, ancillary instrumentation, building and enclosure. Heat-producing activities are enclosed in a cooling jacket. This includes a false floor below the observing floor and ensures, at the same time, freedom from heat transfer from ground-floor facilities and cooling of the observing floor. A system of wall gates provides a combination of efficient air flushing of the observing volume and wind protection. Experience from observations show a quality of the combined optomechanical system better than corresponding to 0.45 arc seconds FWHM. Thermal instabilities contribute typically less to image degradation than the optomechanical system. Atmospheric turbulence is rather low. It is mostly below one arc second, often considerably lower, with values between 0.6 and 0.8 arc seconds FWHM being rather frequent.

*Keywords:* Optical Elements - Mechanical Structure - Thermal Control - Image Quality - Site

## INTRODUCTION

In the beginning of 1984, the Nordic Optical Telescope (NOT) Scientific Association was established. It was a joint venture between Denmark, Finland, Norway and Sweden. The principal purpose was construction and operation of a telescope of the 2.5 m class, intended for the Northern hemisphere.[1,2] Design work started by the end of 1984,[3] and by the end of 1989, the telescope was ready for scheduled observations.

## PRIORITIES AND PREREQUISITES

The project had to match high ambitions with a rather tight budget. This led to the definition of a set of priorities and also to the adoption of a number of design features. Among the first priorities were high image quality and simple handling. These qualities have, together with a quest for a low-budget approach, been major guidelines for our design and construction.

## BASIC DESIGN FEATURES

A resulting image quality of high class has a number of prerequisites. Among the most important are low atmospheric turbulence, minimized contributions to turbulence generated by the telescope enclosure and building, thermal control of telescope structure and ancillary instrumentation. Evidently, the performance of optical elements and mechanical structure is crucial. The need for a chain of optimized parameters defined our efforts and decisions.

## ATMOSPHERIC TURBULENCE

In contrast to other parameters defining image quality, atmospheric turbulence can be subjected to little, if any, improvement. Thus, we are obliged to resort to selection of prime sites. Such selection has to take into account the behaviour of a number of atmospheric layers producing turbulent cells. These layers range from more than 20 kilometres above ground via the boundary layers down to the ground layer.

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For the siting of the Nordic telescope, the Observatorio del Roque de los Muchachos was an early and rather uncontroversial choice. Its location close to the highest part of the Caldera de Taburiente, dominating the island of La Palma is highly favourable, especially since it faces the predominant winds, coming from the open sea. The relation between altitude and the distance to the sea in the up-wind direction is very convenient, the corresponding ratio being close to 0.35. The vegetation is rather ideal with low bushes shielding the ground and improving thermal ground-to-air stability. This is combined with a high percentage of clear nights and low content of atmospheric water vapour.

The choice of the Observatorio del Roque de los Muchachos took care of the turbulence parameters connected with high altitude layers, or those situated more than 1000 metres above ground, as well as the upper part of the boundary layer. However, for a definite site choice, we had to investigate the behaviour of the lower part of the boundary layer as well as that of the ground layer. In particular, studies of the ground layer were important for our building

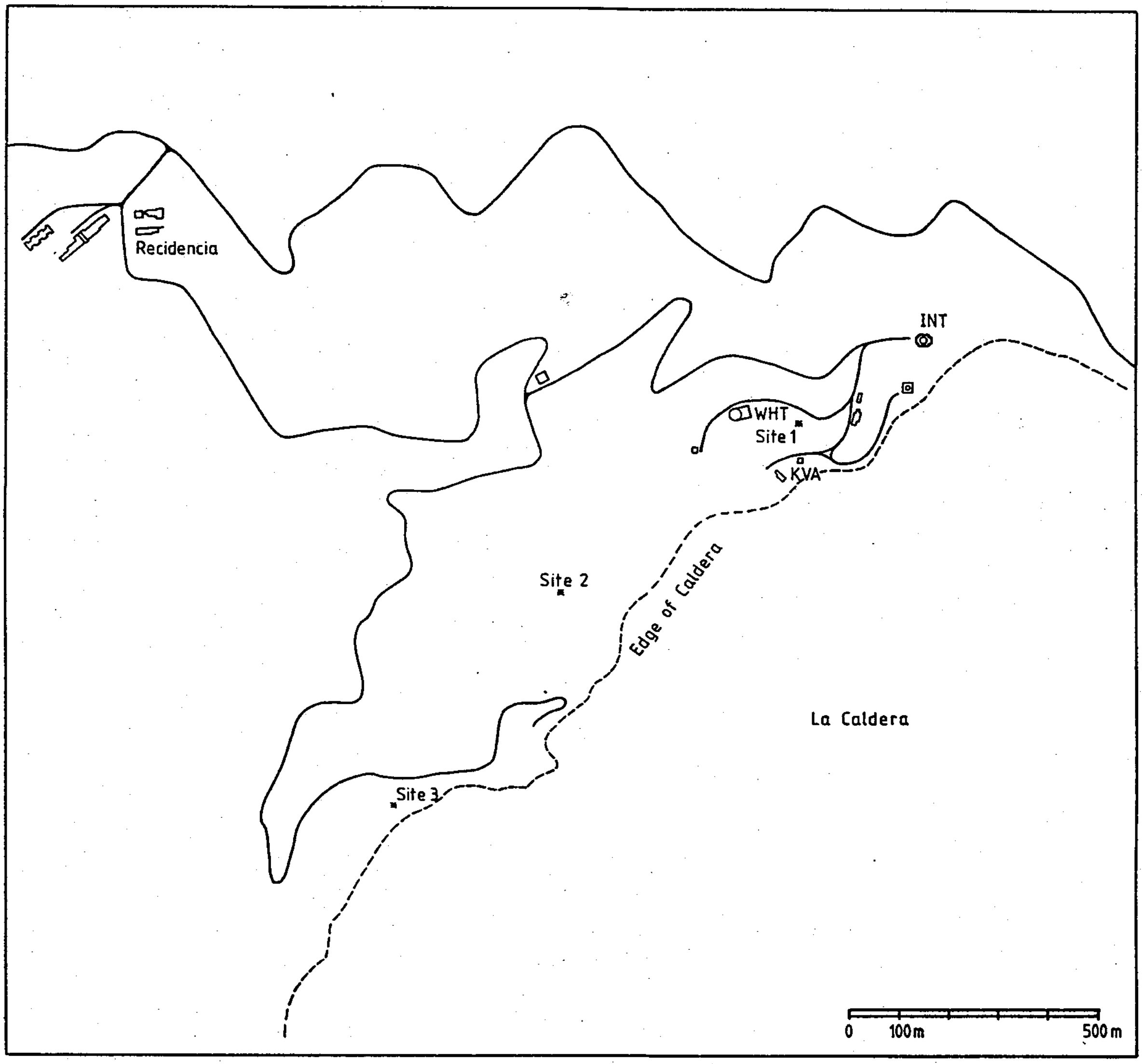

Fig. 1. Simplified map of the area of the Observatorio del Roque de los Muchachos. The common road network and the Residencia are indicated for orientation. Also the approximate position of the edge of the Caldera de Taburiente has been marked, as have some of the buildings installed prior to the start of our site evaluation programme. Positions are given for the three candidate sites, for which we made detailed studies of image quality and microthermal variations.

design, as it is a dominating parameter for the definition of the height above ground of the primary mirror.

## DIFFERENTIAL SITE EVALUATION

From visual inspection of topography, soil and (sparse) vegetation, a first choice of candidate sites was made. Taking into account also constructions existing and planned, as well as negotiations with other goups on site, three candidate sites were chosen for detailed evaluation. One candidate site (Site 1) was situated in the loose cluster of telescopes already constructed at Fuente Nueva. The altitude was 2345 metres. Another candidate site (Site 2) occupied the Northern tip of Cruz del Fraile, at close to 2380 metres above sea level. The third candidate site (Site 3) was situated at the West ridge of the Caldera at an altitude of 2380 metres. These candidate sites are identified in Figure 1. For our evaluation, we constructed five refracting telescopes and three masts with equipment for microthermal sensing.[4]

The refractors had apertures of 153 millimetres and objectives with focal lenghts of around 2130 millimetres. The optical configuration gave equivalent focal lengths close to 22 metres and a focal-plane image scale of around ten arc seconds per millimetre. The telescopes were rigidly mounted as meridian instruments on towers made of concrete blocks, with the telescope objectives more than five metres above ground. This was, for reasons of construction, the lowest possible height above ground for the NOT primary mirror. One of the towers is shown in Figure 2.

Trails on film were made of the North Polar Star and of Southern stars, in order to obtain improved frequency coverage. At the three candidate sites, trails of the same stars were obtained simultaneously. These trails were then used for differential comparisons of the image quality at the three places chosen.

The bandwidth of our trail data is somewhat less than 5 Hz. Obviously these do not, alone, provide adequate information on absolute turbulence, unless simultaneous determinations are made of the turbulence spectrum. In our case, the principle aim was to establish data for the differential turbulence of our site candidates. With an internal altitude difference of less than 40 metres, horizontal distances below 1200 metres and all measurements made simultaneously, assumption of a common turbulence spectrum seems rather reasonable.

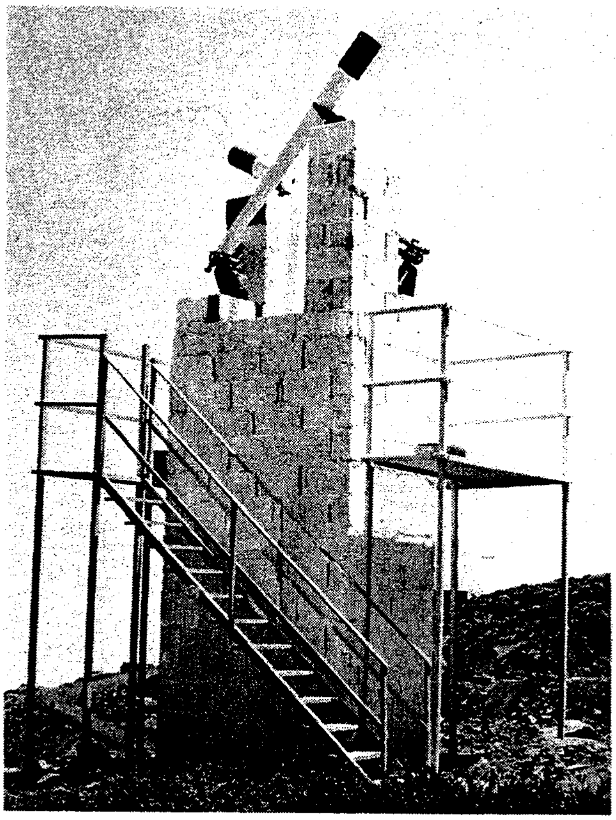

Fig. 2. One of the concrete towers with telescopes rigidly mounted as meridian instruments, one for the North-Pole star, the other for Southern stars. Both telescopes have objectives more than five metres above ground level.

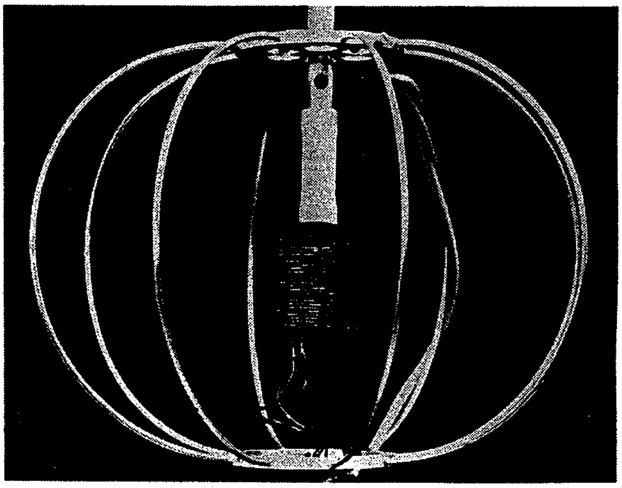

Fig. 3. One of our microthermal sensors, PVC bobbins wound with 25 $\mu$m platinum wire. The sensor is mounted in a simple cage, used for protection against birds.

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At each of the candidate sites, a mast was erected carrying microthermal sensors at four, six, eight, ten and twelve metres above ground. The sensors were PVC bobbins wound with 25 μm platinum wire. The resolution in temperature was around $10^{-2}$ °C and the response time close to $10^{-3}$ seconds. For all sensors, we recorded running mean temperatures and corresponding RMS values together with data from wind meters. An important use of these data was determination of the gradient of ground-layer turbulence for definition of an optimum height above ground of the primary mirror of the Nordic telescope. Figure 3 shows one of our sensors mounted in a cage, protecting against birds.

## RESULTS OF SITE EVALUATION

The differential site evaluation programme at Roque de los Muchachos gave rather clear results. Of the three sites studied, two came out significantly more favourable than the third one, regarding direct image quality as well as ground-layer turbulence.

In Figure 4, we show a comparison between the three candidate sites with respect to observed seeing expressed as full width at half maximum (FWHM). The values in Figure 4 are on an approximate absolute scale. We compared our seeing data to corresponding data from early CCD images taken with the Isaac Newton telescope, close in time to those obtained from our trail telescopes. For larger seeing values, the agreement was excellent, whilst for smaller seeing values the seeing measured with the Isaac Newton telescope was systematically larger than that obtained from our data. This was interpreted as due to effects of dome seeing affecting the Isaac Newton telescope.

The data displayed in Figure 4 refer to a total of more than 2500 simultaneous trails of the North-Pole star, made from the end of July until the beginning of December, 1984. Average data for 4-week periods are plotted. The time resolution adopted for data analysis is very low, around 3 minutes.

Based on trails of Southern stars, Figure 5 gives a comparison between candidate sites 1 and 2. These trails were obtained during the same observing period as those of the North-Pole star. The data in Figure 5 refer to a total of around 2000 simultaneous trails. As for the data displayed in Figure 4, those shown in Figure 5 refer to averages for 4-week periods. For the latter data, the time resolution obtained from data analysis is 0.25 seconds.

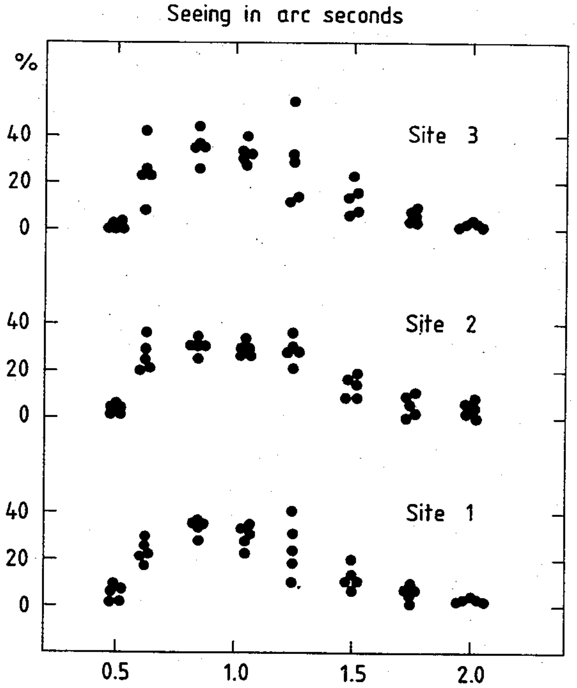

Fig. 4. Comparison of atmospheric image quality for our three candidate sites as defined by observations of the North-Pole star. Percentages of the total number of observations are plotted versus image quality expressed as full width at half maximum (FWHM) of observed seeing images. The comparison refers to more than 2500 simultaneous trails.

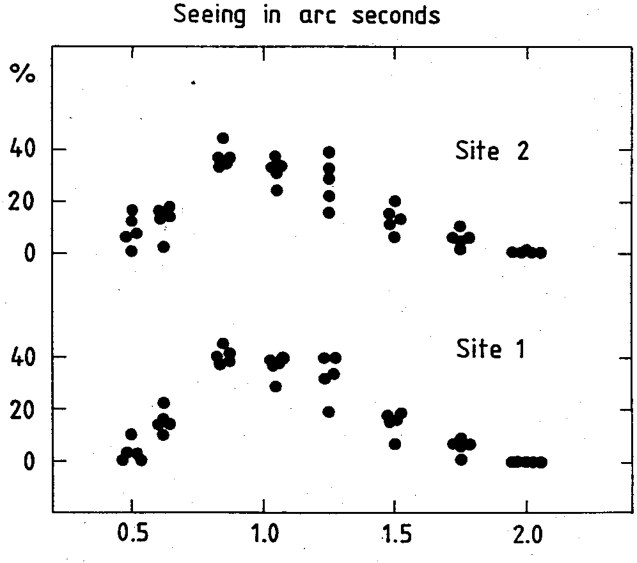

Fig. 5. Comparison of atmospheric image quality for two of our candidate sites, Sites 1 and 2, as defined by observations of Southern stars. The plot is analogous to that of Figure 4 but refers to around 2000 simultaneous trails of Southern stars.

Our observations of image quality were interpreted as showing candidate sites 1 and 2 to be more favourable than candidate site 3. At the same time, we concluded that observations of Southern stars gave better results for site candidate 2 than for site candidate 1.

Data for determination of ground-layer turbulence are shown in Figures 6 and 7, giving results of measurements with our microthermal sensors during night time and daytime, respectively. Figure 6 gives comparisons for 26 nights with simultaneous measurements, whilst Figure 7 gives corresponding comparisons for 14 days.

From our microthermal data obtained during night time, some conclusions seemed relevant. First, we identified a lowest recommendable height of the primary mirror above ground, being somewhat more than six metres. Second, leveling-off of microthermal activity seemed to take place close to eight metres above ground. Third, these results were quite similar for the three candidate sites investigated. Finally, site candidates 1 and 2 came out more favourable than did site candidate number 3.

The site finally selected is situated at the Northern tip of Cruz del Fraile, a ridge penetrating some 350 metres from the highest point of the Caldera to the North, close to the prevailing up-wind direction. Facing the wind over a major part of the time, the installation is, up-wind, completely unobstructed with a steep fall of the ground level to the North, West and East. In the South, the ridge has an approximately constant level over around 200 metres. The telescope is installed at an altitude of 2382 metres above sea level, being the highest one chosen for a telescope at the observatory. At the telescope site proper,

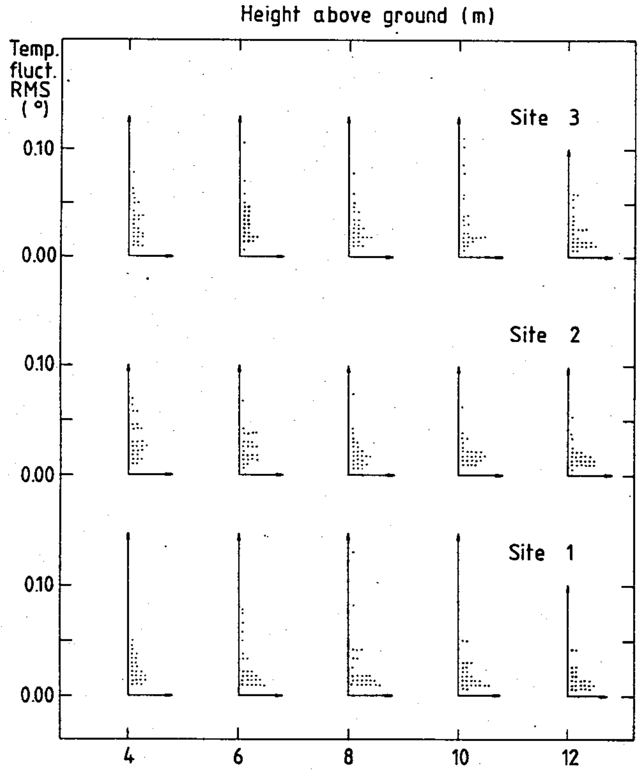

Fig. 6. Comparison of ground-layer night time turbulence for our three candidate sites as defined by microthermal measurements at different heights above ground level. Temperature fluctuations, expressed as rms data, given in degrees Kelvin, are plotted separately for each height, expressed in metres. The comparison refers to 26 nights with simultaneous measurements.

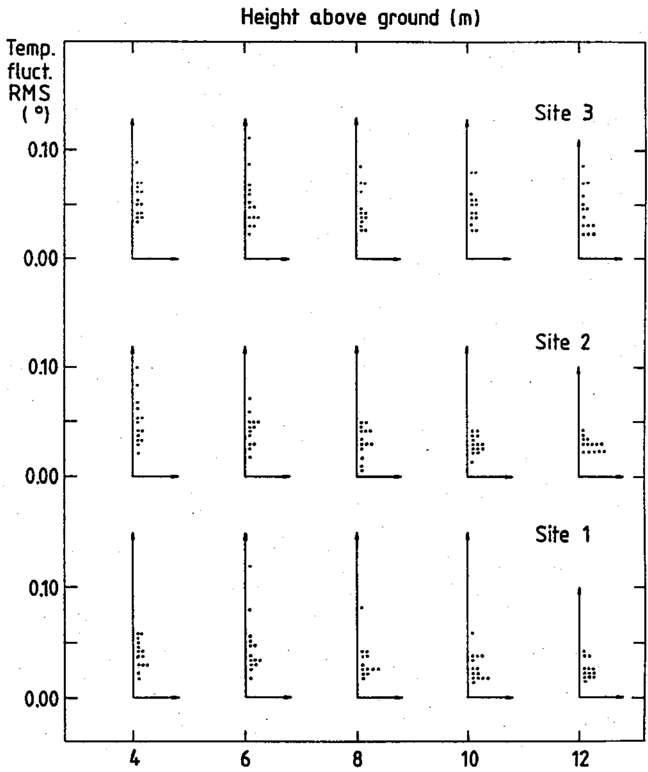

Fig. 7. Same as Figure 6 but for daytime turbulence. This comparison refers to 14 days with simultaneous measurements.

vegetation is practically absent, whilst it is sparsely present below the ridge in the West, North and East directions. In Figure 8, one of our test concrete towers can be seen with two telescopes mounted. The prevailing wind direction is from the left in the figure.

Our site evaluation showed image qualities of sub-arcsecond levels over about half of the time investigated. With best image qualities for objects situated to the North, also stars observed in directions above the Caldera showed very good images.

Results from the microthermal sensors gave rather clear indications concerning the elevation of the telescope above ground level. First, it was clear that ground-layer turbulence was considerable at lower levels, being significantly higher at four metres above ground than at higher elevations. Second, there was, at night time, a clear effect of leveling-off for layers close to eight metres above ground. In daytime, ground turbulence was, in general, more pronounced than at night, with leveling-off occurring at elevations above twelve metres. An interesting feature of the daytime microthermal activity pattern is the relatively short duration of peak activity. Such peak activity is limited to less than six hours around the time of solar meridian transit.

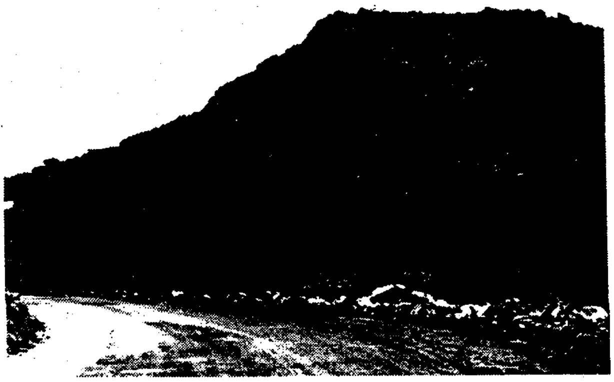

Fig. 8. One of our concrete test towers, barely visible, on top of the Cruz del Fraile ridge. The heavy tower carries two test telescopes, one pointing the North Polar Star, the other Southern Stars. Telescope objectives are more than 5.5 metres above surrounding ground, being at 2382 metres above sea level. North, the prevailing approximate up-wind direction, is to the left in the picture. The telescope was placed a few metres South of the position of the concrete test tower.

Taking into account local topography and results from a geotechnical investigation of our chosen candidate site, we decided to locate the telescope rather close to the Northern end of Cruz del Fraile. The telescope was elevated to have its primary mirror around nine metres above ground level as seen from the South, considerably more from other directions.

## OPTICAL ELEMENTS

The mirrors of the Nordic telescope are made of Zerodur. In all respects they are of very high quality. Figuring was made at the Tuorla Optical Laboratory of the Turku University, Finland, by a small group headed by Korhonen.[5,6] Principal parameters are a primary mirror diameter of 2.56 metres, a primary focal ratio of f/2.0 and a corresponding focal ratio for the combined system of f/11.0. The primary mirror has an aspect ratio of 13.5 and a weight of 1925 kg. The telescope has a Cassegrain focus with provision for optional future installation of a Nasmyth focus.[7]

With a Ritchey-Créthien surface, the primary mirror has been polished to an accuracy corresponding to 80 percent geometrical energy within 0.22 arc seconds in passive mode. This may also be expressed as the equivalence of an FWHM (full width at half maximum intensity) value of around 0.15 arc seconds, again in a purely passive mode. For the combined optical system, the corresponding figure is 80 percent geometrical energy within 0.29 arc seconds or, equivalently, an FWHM value of 0.19.

## MECHANICAL STRUCTURE

The telescope has an altazimuth mounting. Its Cassegrain focus carries an adapter/rotator allowing mounting of any type of ancillary instrumentation in parallel to a standby CCD camera, which can, at any moment, be introduced in a matter of seconds. In addition, provision is made for connection of ancillary instrumentation via optical fibre cables. Figure 9 shows the Nordic Optical Telescope at the time of test assembly of mechanical structures and electronics in early 1987.

Support for the primary mirror is provided in 45 axial and 20 radial points.[8] The axial supports are pneumatic steel bellows on three concentric rings. They are arranged in three 120 degrees sections. For each section, the force of the mirror is determined as measured by a load cell on a fixed point.[9] With radial

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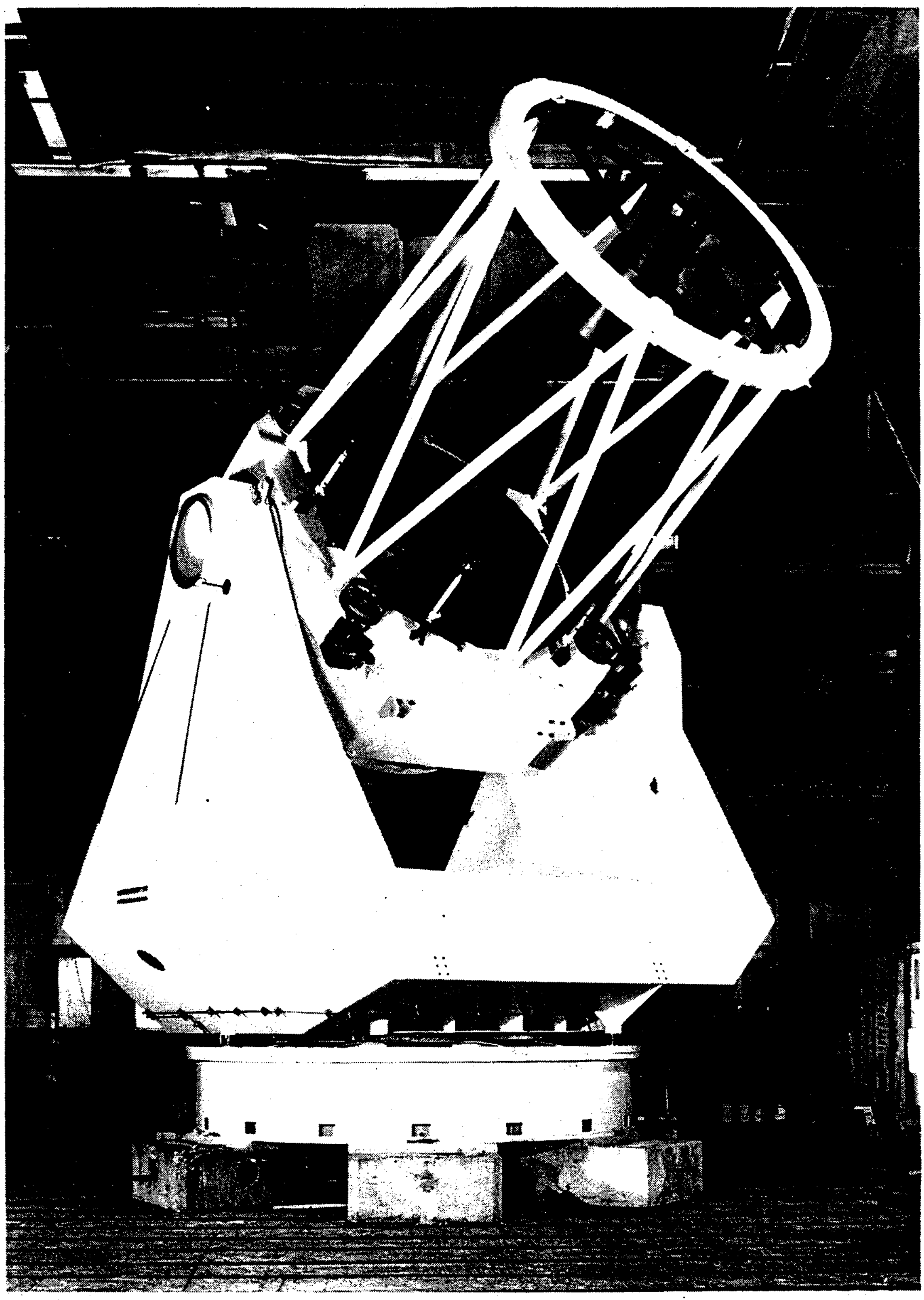

Fig. 9. The Nordic Optical Telescope at the time of test assembly of mechanical structures and electronics in early 1987.

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supports of mechanical lever type and the forces on the three fixed points maintained equal and very small, the mirror is floated. The basic bandwidth of the support system is around 2-3 Hz.[10] The eigenfrequency of the fixed-point suspension of the primary mirror is 11 Hz. For the corresponding oscillation mode, we have added an electromechanical active damping device.

For compensation of tube deflection, the secondary mirror is moved perpendicularly to the altitude axis and axially. Although this is normally not necessary, the secondary mirror can also be tilted. All support and movements of mirrors are controlled by an integrated loop including also telescope and rotator movements, rotation of building, autoguider control and corrections due to meteorological parameters.[11] The meteorological parameters are obtained from a meteorological station, installed behind the telescope in the prevailing down-wind direction.

A special optical system is used to check alignment of the optical elements. It is based on spherical surfaces on the primary and secondary mirrors and an alignment detector in the adapter. An image analyzer of modified Hartmann type will be used to define transverse and angular positions of the secondary mirror as functions of altitude. The calibration relations are stored for use with the servo control loop.

## ENCLOSURE

For enhancement of image quality, the enclosure of the Nordic telescope has been minimized. The dome has a diameter of eleven metres. In addition to the observing floor, the building includes a ground floor and a basement. The entire steel building rotates with the telescope.

## THERMAL CONTROL OF TELESCOPE

Determined efforts have been made to maintain the telescope structure as close as possible to that of ambient temperature. This includes ancillary instrumentation and support systems.

For vertical loads, the azimuth axis has a hydrostatic bearing with an inverted pad system. Because of the minimized conducting surface, heat transfer from the bearing oil to the telescope structure is very small, the major heat exchange occurring between the oil and the telescope base. In addition, this base is under thermal control (see below). Further, the oil is cooled to around 8 degrees C.

Electronic devices and motors on the telescope structure have been minimized in number as well as concerning heat production. As much as possible, such units have been placed under thermal control in the ground floor. Active cooling has been applied to remaining devices with significant heat production. Similar principles are applied to ancillary instrumentation, although not yet fully implemented.

## THERMAL CONTROL OF ENCLOSURE

Major sources of heat are concentrated to the ground floor of the telescope building, containing rooms for observing, electronics and support installations. These facilities are maintained under strict thermal control through a specially designed system.

Ground-floor installations are kept at constant temperature, controlled by air conditioning. Excess heat is ducted away and transferred to a water cooling system. This ends in a heat exchanger placed 80 metres from the telescope in the prevailing down-wind direction. Further, all ground-floor facilities are heavily insulated. Finally, they are completely enclosed in a cooling jacket. For more details, reference is made to Figure 10.

The cooling jacket is constructed in a manner similar to that of a thermos flask. It contains a powerful air circulation system with a flow of more than two cubic metres per second. The air flowing through the cooling jacket is temperature controlled with a minimum temperature of -6° C. This system efficiently prevents heat transfer from ground-floor installations.

Between the ground-floor facilities and the observing floor, the cooling jacket extends into a false floor or heat trap with an interior height of 150 centimetres. It includes the telescope base, the hydraulic bearing and the lower part of the telescope structure. The air contained in the heat trap is completely exchanged every minute. In addition to heat-transfer prevention, this provides cooling of the observing floor. This floor is made of iron slabs and has low thermal inertia. The observing floor is maintained at a temperature slightly below that of ambient air. The entrance of the telescope building acts as a heat sluice. It is kept at a temperature below that of ambient air.

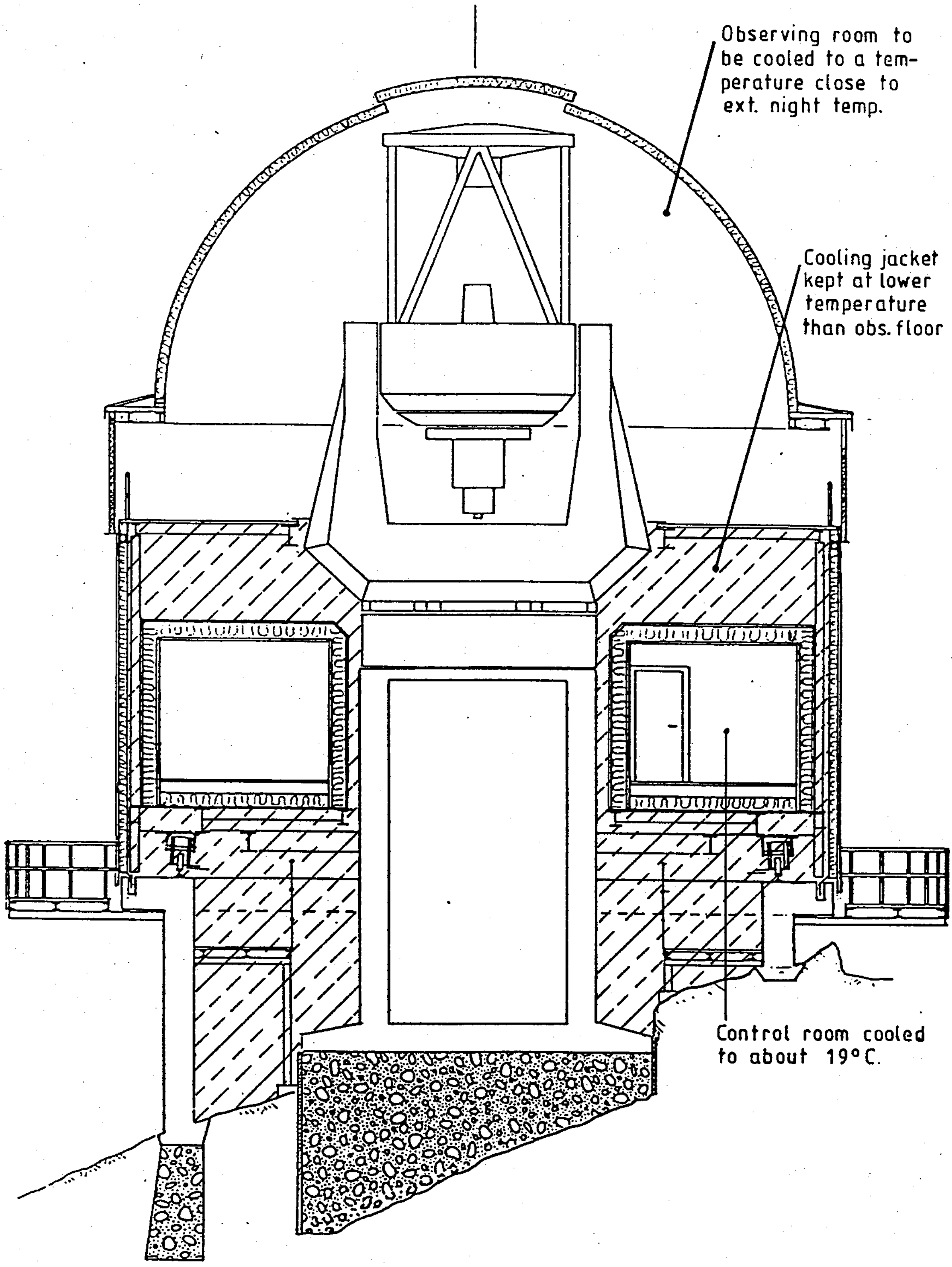

Fig. 10. Some details of our system for thermal control of telescope ambience. The inclusion of all ground-floor facilities in a cooling jacket is noted. Below the observing floor, the cooling jacket extends into a false floor. At the same time as the cooling jacket eliminates thermal gradients, it provides cooling of the observing floor.

## TEMPERATURE CONTROL OF OBSERVING FLOOR

With the cool observing floor and telescope structure combined with absence of heat-producing installations, the dominant source of heating of the telescope ambience is radiative daytime action of the telescope enclosure. Presence of observers on the observing floor is strongly discouraged.

Heating of the air volume enclosing the telescope is prevented in three ways. First, the dome is insulated with plastic foam. Second, the dome volume is air conditioned with excess heat ducted away as for ground-floor installations. Third, the observing walls are provided with large gates. There are 16 wall gates, 170 centimetres high and symmetrically distributed. Operated in an overlapping manner, these gates allow openings from 0 to 240 degrees, providing optimal combination of air flushing and wind protection. A large air flow is obtained without additional turbulence. The system of observing wall gates is presented graphically in Figure 11. Telescope and enclosure can be seen in Figure 12. Both hatches are open as is one of the wall-gate sections.

## SOME RESULTS OF THERMAL MONITORING OF STRUCTURES

In order to optimize our active thermal monitoring and control system, we have conducted a programme of thermal monitoring of a number of selected structural details of the telescope and the enclosure. Results from this programme will serve as an aid in the implementation of the final thermal control system.

Figure 13 displays a series of results of thermal monitoring of some structures. From the top to the bottom of the figure, boxes show run of temperatures of ambient air, internal dome air, observing floor, telescope structure and primary mirror. The time covered is from late afternoon beyond midnight.

Below the lowest box in Figure 13, the left-hand arrow indicates the time when observing wall gates were opened to 240 degrees in the early evening. The right-hand arrow indicates the time when three staff members entered the observing floor. They left half an hour later.

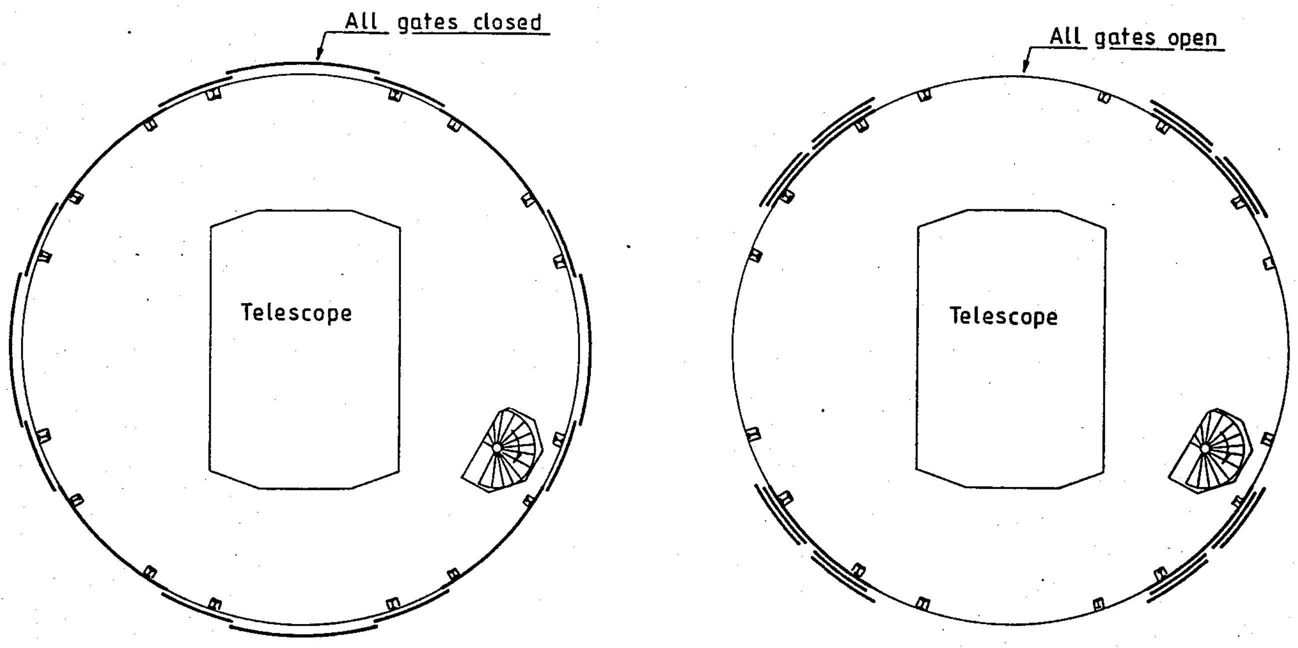

Fig. 11. Schematic representation of our system of observing wall gates. Except for indications of the positions of telescope and access staircase, the left and right drawings indicate the positions of the 16 wall gates when fully closed and fully open, respectively.

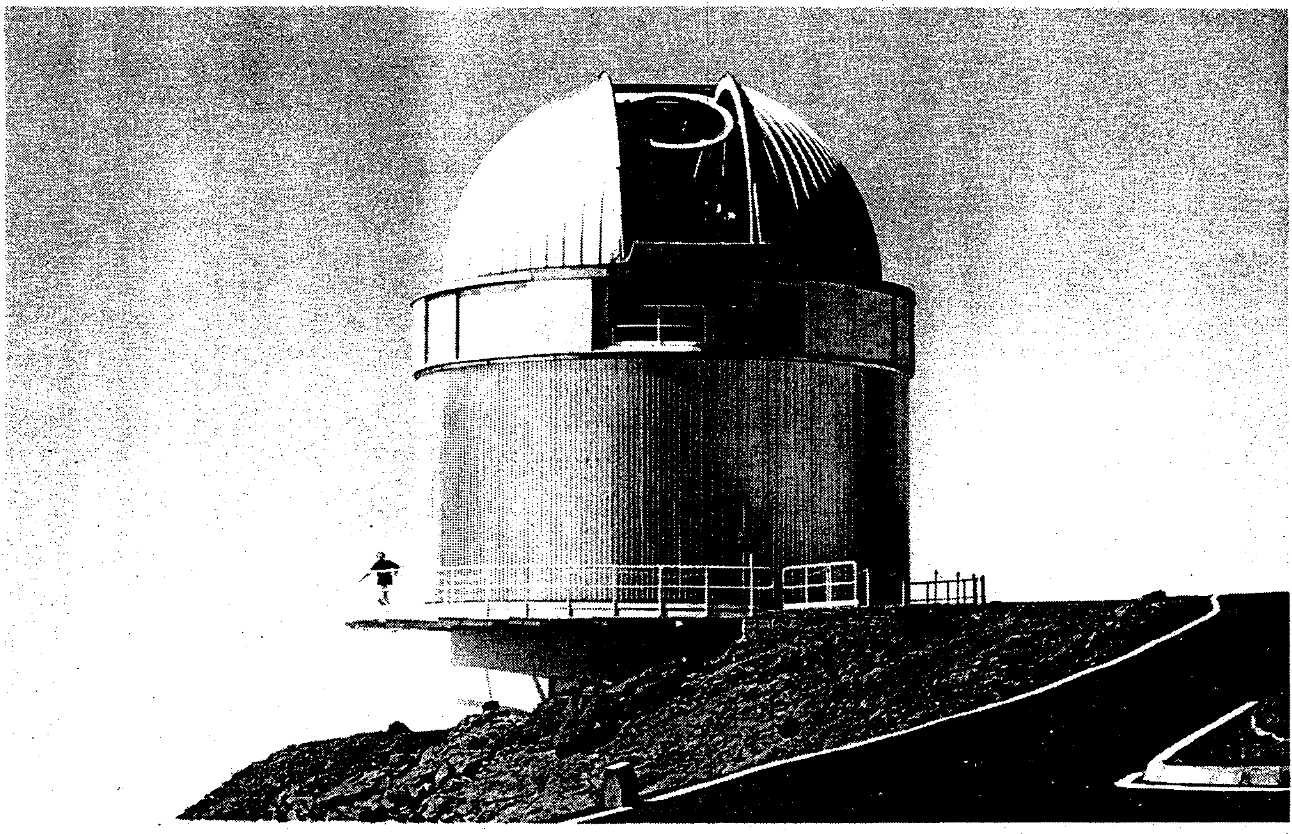

Fig. 12. The Nordic Optical Telescope and its enclosure on Cruz del Fraile. The picture shows both hatches and one section of the wall gates fully open.

The run of ambient air temperature shows a fairly typical diurnal-cycle behaviour. A long-term trend is obvious as well as more rapid fluctuations.

The temperature of internal dome air shows a rather rapid decrease responding to opening of wall gates. From around three degrees above the temperature of ambient air, it falls, over less than 15 minutes, to within one to two tenths of a degree above it. Subsequently, the dome air temperature follows that of ambient air very well. At the same time, the temperature response to the entrance of staff members on the observing floor as well as to their departure half an hour later is both rapid and clear. We emphasize, that for our telescope, presence of staff or observers on the observing floor during observing is not foreseen.

From the corresponding graph, it is obvious that the observing floor had too high a temperature in the evening. However, already before initiation of the observing night, the observing-floor temperature had adjusted rather favourably to that of ambient air. The adjustment can be ascribed to the combined effects of cooling via the false floor and the cooling jacket, opening of wall gates and radiation cooling. During the night, thermal behaviour of the observing floor was quite reasonable.

In this context, it should be noted, that the initial afternoon thermal anomaly presented by the observing floor was mainly due to the fact that our active thermal monitoring and control system is still not implemented. The corresponding installation is now given high priority.

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Like that of the observing floor, the thermal behaviour of the telescope structure suffers from the fact that implementation of our thermal control system remains pending. As a result, the temperature of the telescope structure stays too high also into the observing night, although opening of the observing wall gates initiates a considerable improvement, supported by the action of radiation cooling.

Not astonishingly, the primary mirror demonstrates relatively high thermal inertia. However, also the temperature of the primary mirror reacts very positively to the air flushing induced by opening of the wall gates. Still, with a residual temperature around one degree above that of ambient air, the thermal behaviour of the primary mirror tends to emphasize the urgency of timely installation of our temperature control system.

In an early part of the night, during which the temperature curves in Figure 13 were obtained, CCD imaging was made. Resulting stellar images showed FWHM (full width at half maximum intensity) values close to 0.50 arc seconds. The fact that such a relatively good image quality can be derived also with the primary mirror having a temperature around one degree higher than that of ambient air, can be explained by the mounting of this mirror. The primary mirror has a mounting leaving it open to ambient air. The resulting air flushing reduces any possible building-up of a convective air layer on the surface of the primary mirror. Especially in connection with our system of wall gates, providing air flushing irrespective of the relation between directions of observing and wind, this decreases significantly the vulnerability of image quality with respect to the temperature difference between the primary mirror and ambient air.

Our active temperature monitoring and control system will include around 150 thermal probes. Further, it comprises a unit for analysis of temperature data and adjustment of cooling facilities. The installation of the system is dealt with as an item of priority. At the same time, from experience as that related, we find clear evidence for the importance of the air flushing resulting from operation of our system of observing wall gates as well as the exposure to air flushing of the surface of the primary mirror.

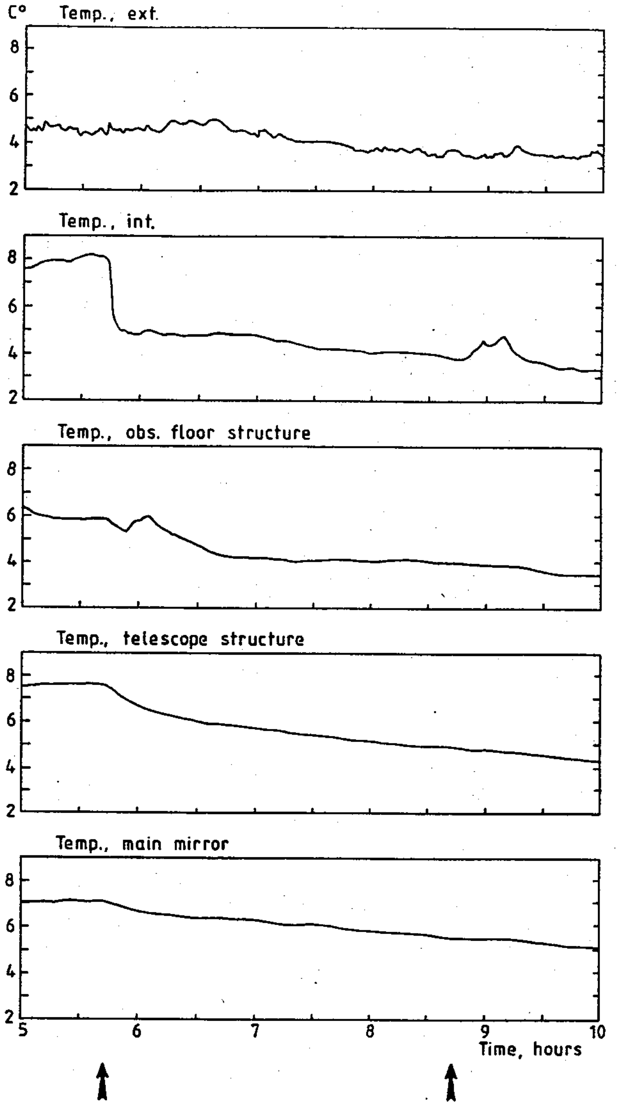

Fig. 13. A series of results of thermal monitoring of some structures. Boxes show, from the top to the bottom of the figure, the run of temperatures of ambient air, internal dome air, observing floor, telescope structure and primary mirror. The time interval covered is from late afternoon to beyond midnight. Below the lowest box in the figure, the left-hand arrow indicates the time when observing wall gates were opened to a full 240 degrees. The corresponding right-hand arrow indicates the time when three staff members entered the observing floor, leaving it half an hour later.

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## THERMAL CONTROL OF ANCILLARY INSTRUMENTATION

Adequate thermal control of telescope ambience has to include that of ancillary instrumentation attached or close to the telescope structure. In the case of the Nordic Optical Telescope, ancillary instrumentation includes a CCD camera, a polarimeter/photometer, a high-speed photometer and a spectrometer for infrared wavelengths, these instruments already being installed and brought into operation. Due to arrive soon are a six-channel photometer and a low-resolution spectrograph, to be followed by two further spectrographs, delivering spectral resolutions from intermediate to high. With additional pieces of ancillary instrumentation under consideration, the need for rational thermal control of these instruments is evident, whether they are directly attached to the telescope structure or connected with optical fibres and located on the observing floor. For this reason, our active thermal monitoring and control system includes a branching exclusively intended for use with ancillary instrumentation.

## EXPERIENCE FROM OBSERVATIONS

Recent completion of basic telescope functions in combination with continued technical work by a small staff has permitted only rather few and short observing series. Still, some limited experience has been gained concerning observing conditions. Except for photometry and polarimetry with specialized instruments, imaging has been made with a cooled CCD camera with an image scale of 0.2 arc seconds per pixel, an image scale converter giving optional scales of 0.1 and 0.3 arc seconds per pixel, respectively.

Our observing experience refers mainly to the summer period. The results obtained point to excellent observing conditions, concerning transparency and extinction stability as well as image quality.

For determination of image quality, stellar exposures have been used with exposure times between a few seconds and one hour. For exposures longer than five minutes, autoguiding has normally been used. The majority of the exposures referred to have exposure times of the order of several minutes. It is emphasized that these exposures have been obtained without final alignment of the telescope, as the alignment system is only now under installation. Further, tracking has still not reached its final level. Finally, cooling of the adapter awaits implementation, the heat flow from electronic components still adversely affecting image quality.

From our CCD exposures, image qualities have been determinated in a rather straightforward manner with a simple yet efficient reduction programme. Essentially, raw images have been deduced of single stellar objects of intensities covering typically ten to thirty percent of the dynamical range of the detector. To these images, Gaussian functions were fitted and values deduced of the full width at half maximum power (FWHM).

Whilst no definite statistical conclusions should be drawn from our limited and non-systematic observations, our results strongly indicate a number of encouraging facts. These refer to optical and mechanical quality of the telescope, quality of thermal control of our installations and to the quality of the atmosphere.

For an estimate of the optical and mechanical quality of the telescope, the exposures with best FWHM data are taken into account. This points to a total optomechanical quality for zenith distances less than 30 degrees of around 0.45 arc seconds or better. Especially taking into account the non-definite state of telescope adjustment, this is a rather satisfactory result of a completely passive optical system, for which no additional image sharpening or improvement has been attempted. In Figures 14 and 15, we show a simple exposure and a tracing of its central object, giving an illustration of our so far limiting practical image quality.

In order to get some impression of the quality of the thermal control of our installations, we have compared results obtained during nights characterized by temperature drifts larger than normal with these from nights with more stable temperature conditions. Attempting to correct for intrinsic atmospheric effects due to temperature variations, we feel it clearly indicated that our thermal control is basically rather good, at the same time as it can be further improved. The turbulence contributed by thermal excesses and/or instabilities of the telescope and its surroundings seems to fall typically between 0.25 and 0.50 arc seconds. We feel convinced that termination of installations for further thermal control will improve these data significantly.

Regarding turbulence of the atmosphere, our data do, in spite of statistical weakness, indicate predominance of conditions marked by low activity. Evidently, intrinsic image qualities superior to (smaller than) one arc second FWHM are in majority, whilst corresponding values between 0.6 and 0.8 arc seconds are rather frequent. Tentative frequency diagrams come out quite similar to those defined in Figures 4 and 5. Major variations of image quality do not seem typical on time scales smaller than hours. At our site, variations of atmospheric turbulence with observing direction can be demonstrated. However, it is of limited significance as long as larger zenith distances are avoided. This is in agreement with results from our site evaluation and as illustrated by Figures 4 and 5. This seems indicated also for observations made in the direction of the Caldera de Taburiente, closely coinciding with that of the direction of the Cruz del Fraile ridge.

From our limited data, we draw the following tentative conclusions. The optomechanical quality of the Nordic Optical Telescope is better than 0.45 arc seconds FWHM in passive mode. Contributions from thermal instabilities around the telescope are typically below those given by the optomechanical system but may accidentally exceed it. Completion of control installations will quite clearly decrease these contributions. The level of atmospheric turbulence at our site is rather low and stable, mostly below one arc second, often considerably more favourable. The latter conclusions refer to observations during the summer season. They are in good agreement with the results obtained during our site-evaluation campaign in 1984. This may be taken as an indication of long-term stability.

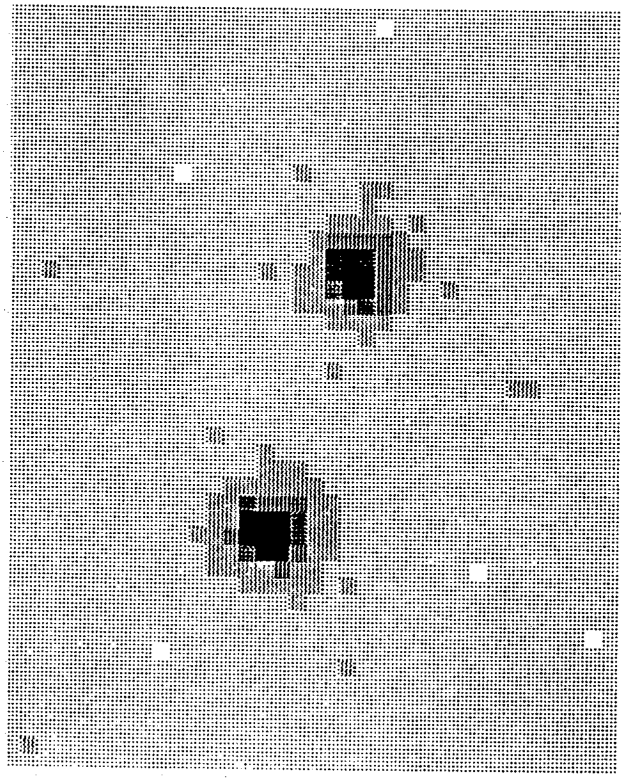

Fig. 14. Exposure of SAO 122730, made with the Nordic Optical Telescope. The picture represents the raw image without processing.

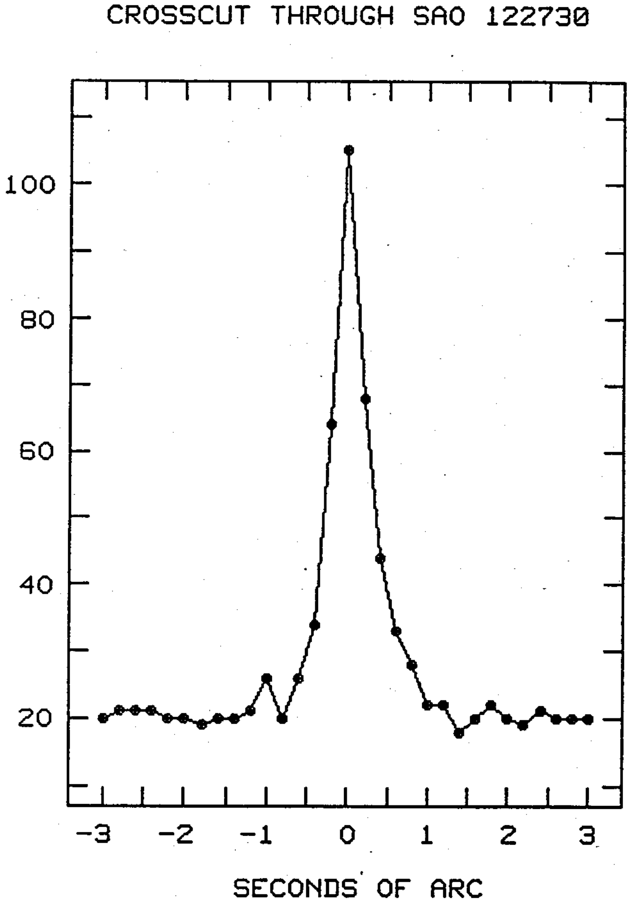

Fig. 15. Cross-cut tracing through the image of SAO 122730, displayed in Figure 8. The resulting FWHM value is 0.45 arc seconds.

### BUDGET AND STAFF

The Nordic Optical Telescope was constructed on a tight budget. Including telescope, telescope building, a service building, handling devices and road construction, the total cost was around 6.5 million US dollars, expressed in 1989 values. It should be noted

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that this sum includes full coverage of costs for staff performing design and construction work.

Also concerning operation, budgetary considerations are strict. As a consequence, full operation of the telescope and adhering facilities at Cruz del Fraile will be limited to a total of six staff positions plus two Ph.D. students. In addition to dedication of operation staff, this is possible due to very easy handling routines, largely relying on convenient software interfacing. This allows for single operator observations of the telescope and ancillary instrumentation.

It is added that the Nordic community of astronomers, as that of other countries using the Nordic Optical Telescope, represents a very wide variety of scientific interests. This is due to define a considerable challenge concerning maintenance and updating of telescope and instrument facilities.

## REMOTE CONTROL

For the Nordic community of astronomers, remote operation of the Nordic Optical Telescope from home institutes defines an attractive option. From our side, preparations for such operation have been ambitious. Unfortunately, this has not been matched by local Spanish telephone connections, which are astonishingly poor. Pending a drastic improvement of local communication facilities, we are thus forced to rely fully on direct control of our telescope and its ancillary instrumentation.

## FURTHER UPGRADING

In addition to improvements of alignment, tracking and thermal control, some projects are in course for further upgrading of our telescope. Among these projects we mention, first, installation of a system of temperature probes designed to monitor temperatures of ambient air, enclosure, air volume around the telescope, on and below the observing floor and of various parts of the telescope, including both optical and mechanical elements. Resulting data will be used for further improvements of routines for thermal control. Second, with an aspect ratio of 1:13.5, the primary mirror is well suited for active mirror support corrections. We have taken up design of corresponding modifications and supplements. Third, advanced laboratory simulations, supported by activities for the design of the Large Earthbased Solar Telescope, entrusted to our telescope group, strongly indicate that air flushing of the surface of the primary mirror can significantly improve turbulence conditions. We intend to follow this up, and a possible design is under discussion.

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