SMA MEMO #18

Smithsonian Astrophysical Observatory

The SAO Submillimeter-Wavelength Telescope Array

Feasibility Study
of Telescope Concepts
and Enclosures

- Project No. 163 379 -

prepared by

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Preface

The present study is based on SAO's plans for a submillimeter-wavelength telescope array, which were described in "The SAO submillimeter-wavelength telescope array", J. M. Moran et. al., Radioastronomy in Space 1987 and "Preliminary telescope specs for the SMA project", RNM 23 June 1987. The idea for the study was borne in personal communication between P. T. B. Ho and H. J. Kärcher early 1989. 16 May 1989 an offer was submitted by MAN GHH and at 15 September 1989 an order for the study was placed under SAO purchase order SA 9-21583.

Preparation of the study has been technically supervised by E. C. Silverberg and W. R. Bruckmann of SAO.

The study has been prepared by H. J. Kärcher, J. Kühn and H. Lautner of MAN GHH.

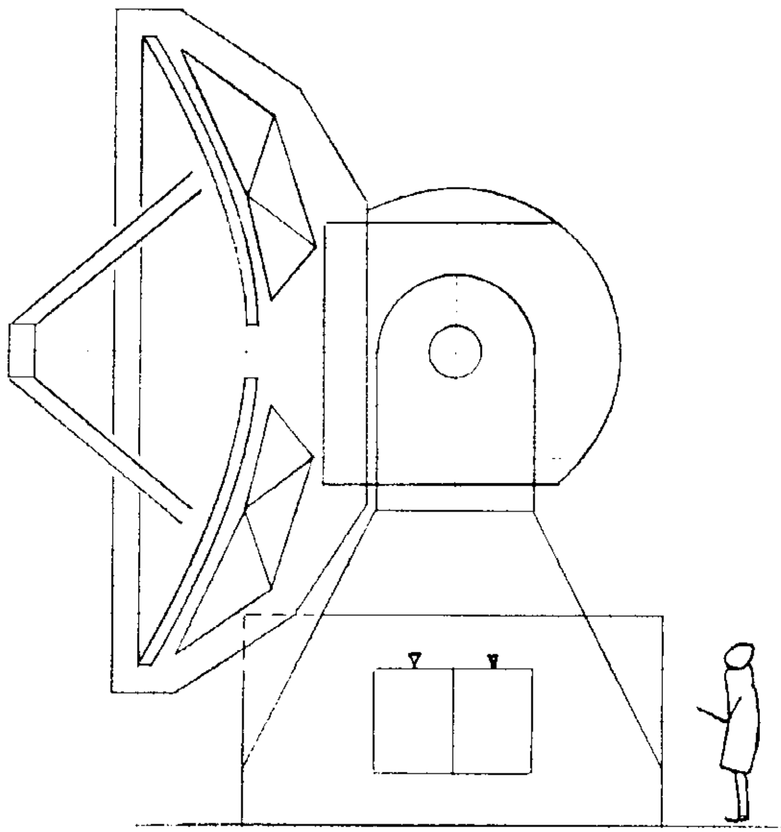
The results of the study have been coordinated with MAN Technologie, Munich, represented by D. Muser and E. Ehrhardt, which prepared in parallel a feasibility study for the reflector system of the telescopes.

The aim of the study was to show the feasibility of movable millimeter-wavelength-radiotelescopes of the 6 m class in the accuracies demanded by SAO specifications, to recommend a preferable telescope typ and to estimate the costs for development and realization of these telescopes.

The aim of the study has been reached with the recommendations of WP 50 000 and cost estimates of WP 60 000.

June 1990

Hans J. Kärcher



Lay out of a free standing 6 m telescope

WP 10 000 Project Definition

The SAO submillimeter-wavelength array will consist of some telescopes of ~ 6 m diameter, which should easily movable between different operation positions and able to receive wavelength down to an equivalent surface accuracy of 15 µm RMS. All operational and astronomical aspects are described in SAO's specifications as given in WP 11 000.

For the design of such a telescope system in the offer for the study the following main criteria were emphasized:

- excellent telescope accuracy under all weather conditions, where submillimeter-wavelength observations are possible

- reducing of all aperture blocking installations (eg. radom, subreflector supports) as far as technically feasible

- protecting the telescope against all accuracy degrading environmental effects like temperature and wind as well as possible

- ease in re-configurating the array positions by moving the telescopes to new stations

- ease in operating the telescope system for observers (overall system reliability, accessibility to the receivers, remote control)

- ease in maintaining (protection against severe weather conditions, lifetime and quality of the hardware, maintainability and accessibility of the subsystems).

- low costs per unit

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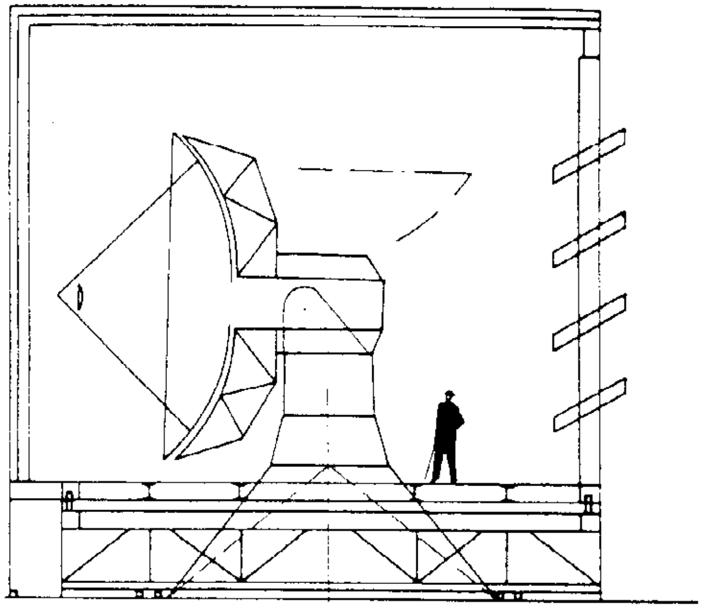
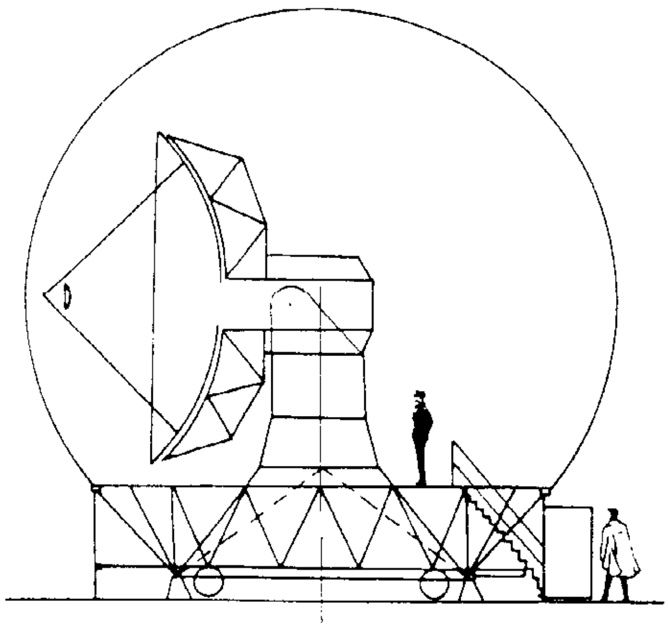
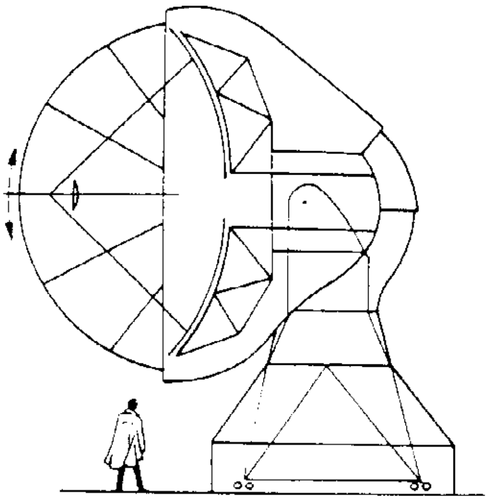
As starting point for the discussion the following telescope ideas ware described in the offer:



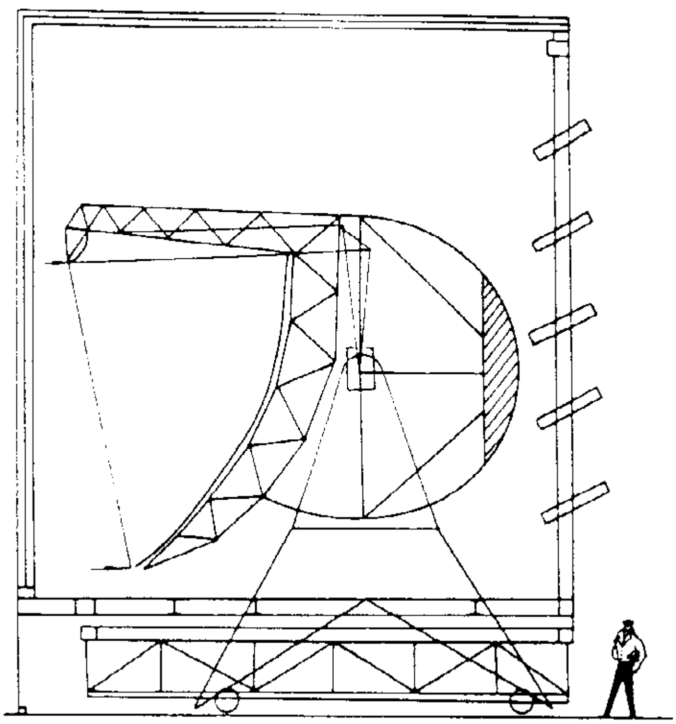
Telescope
in a
co-rotating
building



Telescope
under a
co-moving
non-rotating
radom



Telescope with integrated reflector cover



Off-set telescope in a co-rotation building

One major demand of the SAO specifications is to be able to change during operation very quick between 4 receivers. This makes it necessary to arrange 4 receiver boxis somewhere behind the main reflector, which has a main impact on the telescope lay out. Therefore at the beginning of the study work the possible arrangements of receiver boxes were studied (WP 25 100). At the end of the study an arrangement of 4 boxis in a bundle was selected (see page 25.5).

Before starting with the detailed design work, some general considerations on geometrical arrangements of the reflectors and receivers (eg. primary focus, Cassegrain, Nasmyth, Coudé arrangements etc.) should be taken in mind, which are documented in WP 20 000.

In addition to the mentioned geometrical aspects the structural considerations for an adequate support of the reflectors and receivers take a major contribution on the design and performance of the telescope, which are described in WP 21 000.

After this preparation work the lay out sketches for the overal system, including enclosure, telescope and receiver boxis, are developed in WP 22 000. Beside more conventional lay outs - using large enclosure structures like rotating buildings etc. - an "open-air" telescope on a wheel-on-track alidade is introduced, which is estimated as by far the simplest solution. The only precondition for this solution is, that it must be allowed to expose the front surface of the main telescope reflector also under severe weather conditions to the open air.

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To get a comprehensive impression of the influence of the different telescope types on the receiver (front end) arrangements, in WP 25 200 the alternatives are compared in respect of simplicity and accessability and the advantages of the recommended solutions in Nasmyth arrangement, with the receivers below the elevation axis and the switching mechanism part of the receiver rack are shown.

The following two workpackages, WP 30 000 wind study and WP 40 000 temperature study, have the purpose to investigate the influence of the environment on the telescope and its performance and to analyse differences in quality between the alternatives.

The wind study (WP 30 000) shows, that with an adequate effort the demanded very high pointing and tracking characteristics could be reached not only for the enclosed lay outs but also for the open-air design, if some special measures (control of the quasi-static and low frequent wind deformations by an "active sensing" system, which is equivalent to an inprovement of the "pointing model" for standard servo systems for radio-telescopes) are taken into account.

The temperature study (WP 40 000) shows, that by an adequate thermal design the open-air-lay out, together with a controlled, but simple air-conditioning system for the observer cabin is sufficient to reach the specified pointing performance. It is also shown, that for the reflector back-up-structure the use of CFRP is excellent, but not mandatory and that the choice of material therefore should be based on the results of the reflector study.

The servo system (WP 23 000) has the task, to control and integrate all operational functions of the mechanical systems of the telescope and to communicate them to the operator. In WP 23 000 principle comments on the lay out, achievable performances and ideas for the verfication in the design phase are made.

The last hardware subsystem not yet described is the transportation system for the telescope. As a simple solution, the movement of the telescope on steel wheels on rails and external traction by a tractor on tire-wheels is recommended (WP 26 000).

For the telescope assembly (WP 27 000) it is suggested to preassemble the first unit completely in the workshop and test it as a prototyp. For the following telescope units a preassembly and testing only on subsystems level is sufficient.

From the view point of technical availability (WP 24 000) it is assumed, that - except for the reflector system, as studied in the special reflector study - all telescope subsystems are designed in normal available state-of-the-art components, which need no further long-lead-item development.

To define the further work necessary for realizing the telescopes in WP 12 000 the main interfaces between the telescope subsystems are enlisted. In WP 13 000 a work package plan for the definition study as predecessor of the manufacturing phase is given and in WP 14 000 a time schedule for the realization steps is laid down.

WP 11 000 Specification

- Check of specifications for telescope system and requirement for supplementary data

1. SAO's preliminary specification, date Oktober 27, 1989

I. Diameter: Approx. 6 m $\pm$?

II. Configuration: Alt-Az

III. Pointing:

A. Altitude axis, -2 to + 95 degrees

B. Azimuth axis, $\pm$ 270 degrees

IV. Optics: Classical cassegrain, f ratio approx. f/10

V. Environment

A. General:

1. Elevation, approx. 3000-4000 meters
2. Temperature, -30 to +40 degrees C
3. Dust, occasionally heavy

B. Precision Operations:

1. Wind $\leq$10 m/sec
2. Relative humidity <20 %
3. all sun angles

C. Degraded Operations:

1. wind $\leq$25 m/sec
2. relative humidity <60%
3. all sun angles

D. Instrument Survival:

1. in winds to 75 m/sec in dish-up stow position; 50 m/sec all alt-az positions
2. humidity: 0-100%
3. snow: up to 1 meter fall in unattended status

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4. ice: up to 3 cm coverage on all surfaces; deicing provisions included
5. instrument must drive to stow position in winds to 50 m/sec

VI. Surface Accuracy, Primary

A. Precision Operations: better than 15µm RMS

B. Degraded Operations: better than 35µm RMS

VII. Secondary:

A. Surface accuracy: better than 5µm RMS, all operating conditions

B. Mounting: Secondary spider support points located outside the diameter of the primary. All mechanisms at secondary shadowed by the reflecting surface. Require minimal blockage by the secondary support structure

C. Positioning

1. Mechanism: three axis motorized stage
2. Position Stability
   a. Precision Operations: Better than 20 µm, all elevation angles
   b. Degraded Operations: Better than 50µm, all elevation angles

VIII. Pointing Accuracy (as measured at the Cassegrain focus)

A. Precision Operations:

1. max error: $<\pm 1$ arc sec each axis when offset from known standard within 20 degrees
2. max error: $<\pm 2$ arc sec each axis for >18 hours following development of mount model

B. Degraded Operations: max error $<\pm 3$ arc sec each axis

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WP 12 000 Interface Definition

- Definition of interfaces to subsystems

The subsystems, between which interfaces are be existing are:

- Receivers (front ends)
- Reflectors
- Pedestal
- Servo
- Claddings
- Air conditioning
- Transport system
- Foundations
- Operator center

Main interfaces are:

Receiver front ends to

- Reflectors	:	type of reflector arrangements
- Pedestal	:	available space for the receiver racks
- Servo	:	interlock system for the telescope operation modes, switching system for the receivers
- Claddings	:	apex-window
- Air conditioning	:	temperature, humidity conditions in the receiver room

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- Transport system : weight of the receivers, changing procedure for the receivers
- Foundations : connectors to the operating room
- Operation center : location of the back-ends.

Reflectors to

- Pedestal : reflector supporting system
- Servo : status monitoring system
- Claddings : structural arrangement
- Air-conditioning : ./.
- Transport system : weight
- Foundations : ./.
- Operator center : ./.

Pedestal to

- Servo : encoder units) drive units) elevation axis and azimuth axis dynamics) arrangement of servo racks
- Claddings : structural arrangement
- Air-conditioning : arrangement of air-conditioning units, thermal behaviour
- Transport system : structural arrangement, weight
- Foundations : structural arrangement, weight
- Operator center : ./.

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<u>Servo</u> to

- Claddings : ./.
- Air conditioning : operating instructions for the air-conditioning via the servo-system
- Transport system : interlock system for the telescope operation modes
- Foundations : connectors to the operating room
- Operator center : central operating computer

<u>Claddings</u> to

- Air conditioning : lay-out data for heating- and cooling capacity
- Transport system : weight
- Foundations : sealing of gap between telescope and ground
- Operator center : ./.

<u>Air conditioning system</u> to

- Transport system : ./.
- Foundations : connectors to operating room
- Operator center : operating instructions via cables

<u>Transport system</u> to

- Foundations : transportation rails, azimuth track, pintle bearing
- Operator center : interlock system for telescope operation modes

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WP 13 000 Statement of Work

- Setting up a work package plan and description for the definition phase

The purpose of the definition phase is to define the overall system and the subsystem incl. all interfaces up to a level, that:

- the performance could be checked and verified

- the cost for the realization of the system could be estimated ($\pm$ 10 %)

Therefore the following activities are necessary:

- system engineering

- description of the subsystems by specifications and drawings

- engineering analysis of the overall and the subsystems

- work and quality assurance planing

The activities could be detailed as given in figure 13.1

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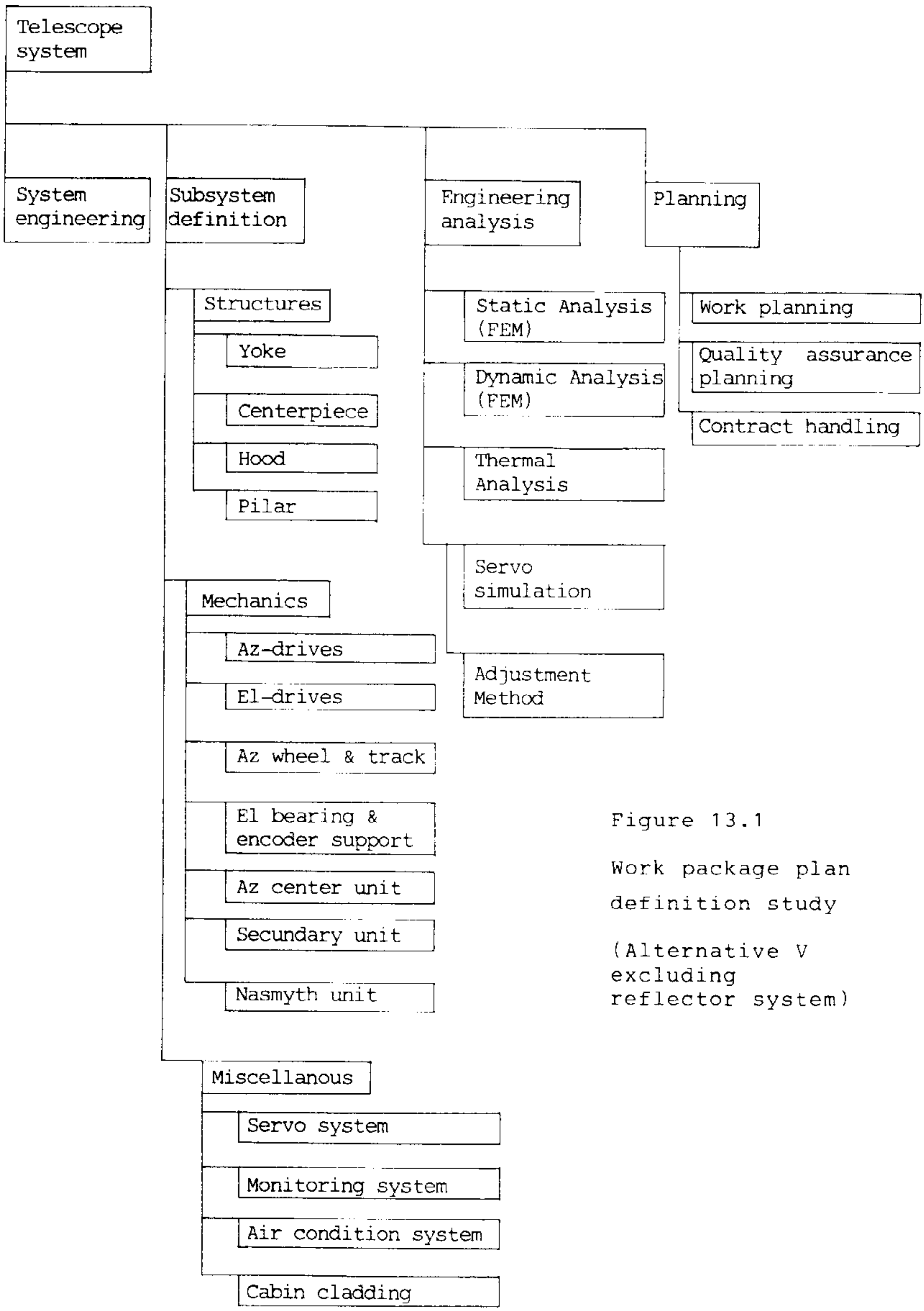
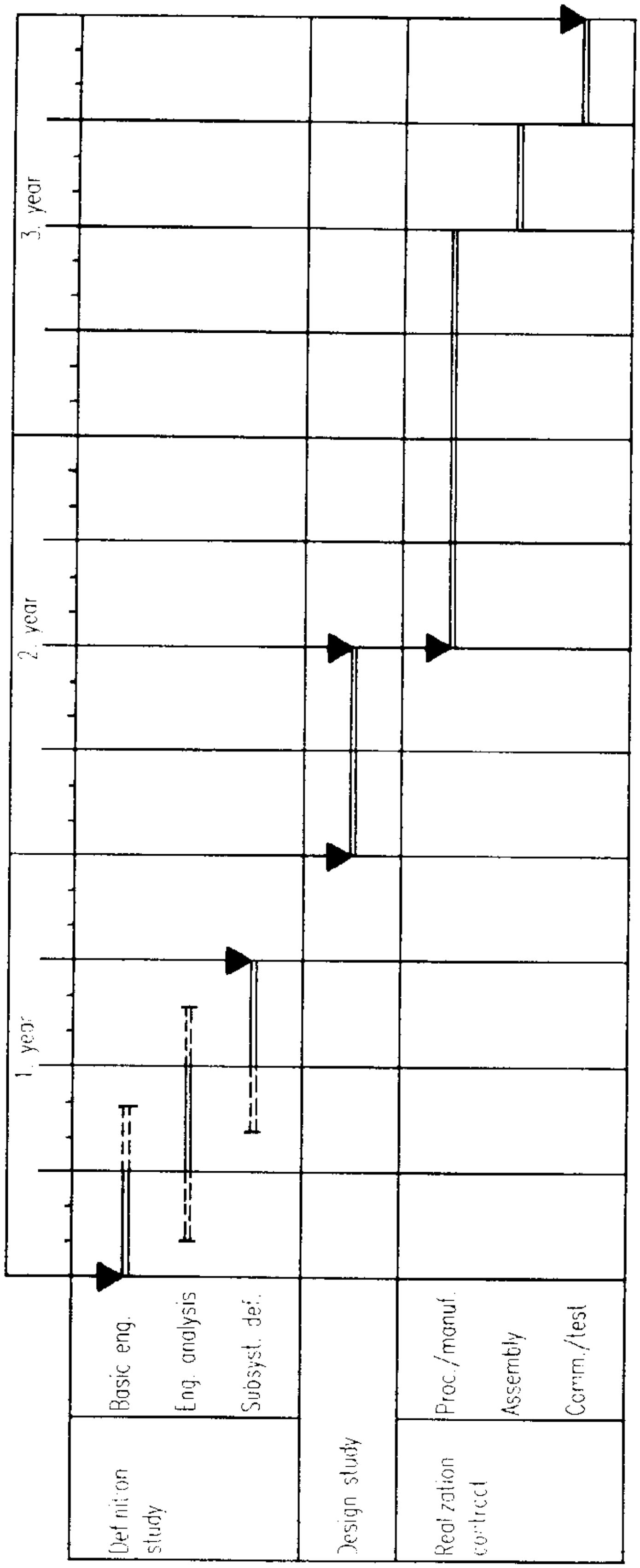


Figure 13.1

Work package plan definition study

(Alternative V excluding reflector system)

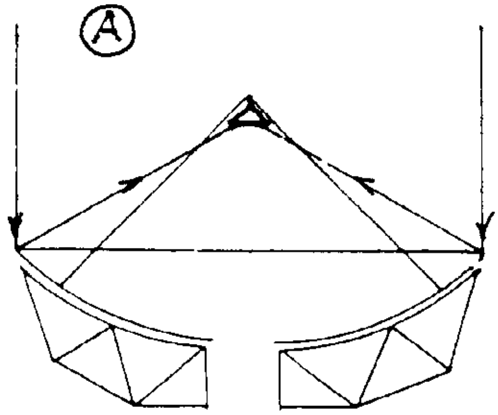
WP 14 000 Time Schedule



Bar and milestone plan

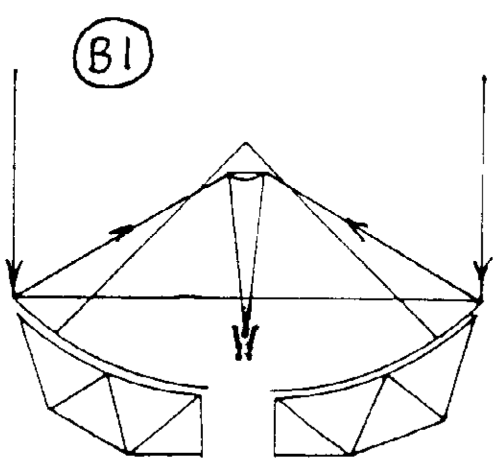
WP 20 000 System Design

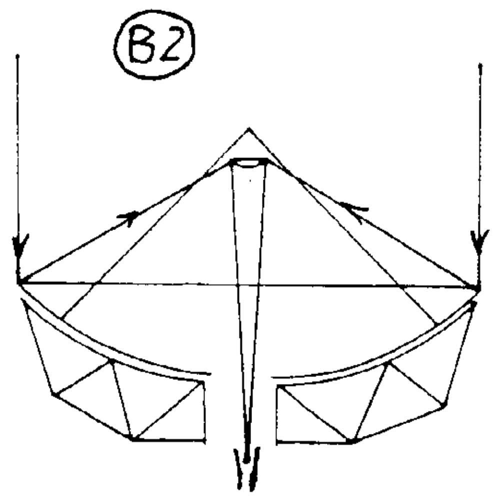
Before starting with the detailed design work for the telescope, some general considerations on the geometrical arrangements of reflectors and receivers should be token in mind. Classical Reflector arrangements are:



Primary Focus

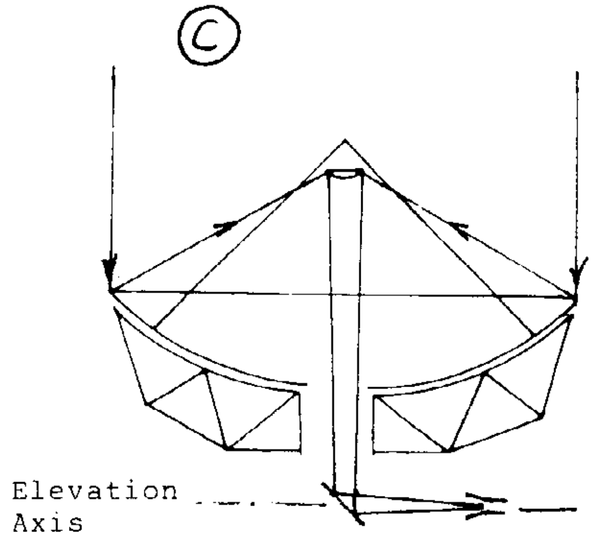
Cassegrain Focus





Near field

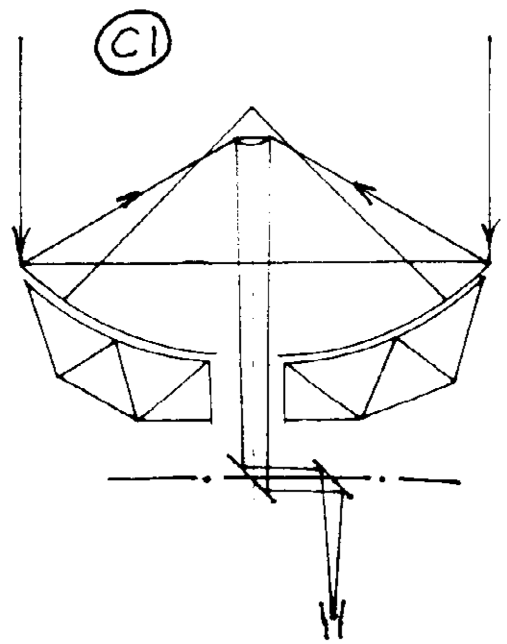
Far field



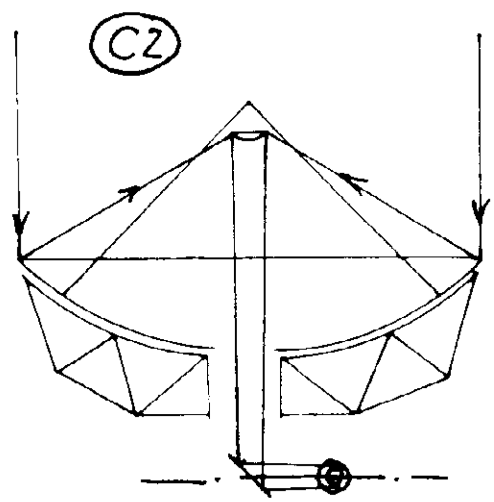
<u>Classical</u>
<u>Nasmyth</u>

Receiver
moving
in azimuth,
fixed
in elevation
(no changing
gravity loads)

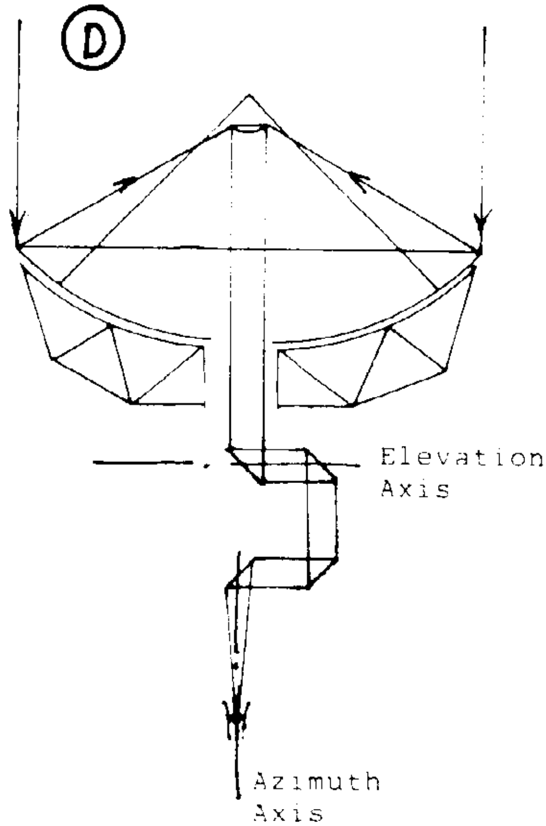
<u>Modified</u>
<u>Nasmyth</u>



Receiver below
elevation axis



Receiver behind
elevation axis



"Beam-waveguide" System
(Coudé-Focus)

Receivers fixed in azimuth and elevation

Task of the telescope design is, to place the "switching-focus" receiver boxis of WP 25 000 in the focus of these alternatives and to fullfill the structural demands for adequate support of the reflectors and receiver boxis. Therefore first some structural aspects as described in WP 21 000 should be token in mind.

WP 21 000 Telescope Concepts

- Design for two telescope concepts with
  * rotational symmetric reflector
  * offset-reflector

- Reasons for the selection of these concepts

- Technical data for both concepts

In addition to the aspects of geometrical arrangements of the reflectors and receivers, as described in WP 20 000 and WP 25 000, structural considerations on an adequate support of the reflectors and receivers take a major contribution on the design and performance of the telescope. For submillimeter telescopes with accuracies as given in the SAO specifications is the design and the construction of the reflector system the leading item for all other design considerations and decissions. For a rotational symmetric reflector there are two principly different methods to design the supporting system (figure 21.1):

alternative a.1	with a central hub as connecting element to the pedestal
alternative a.2	with a yoke as connecting element to the pedestal

The two alternatives are principly different in

- the space which they provide behind the reflector apex for the location of receiver boxes, Nasmyth mirrors etc.

- the load carrying features between reflector and pedestal.

Whereas in alternative a.1 the available space behind the apex is very restricted, the load distribution by the hub

cont. page 21.3

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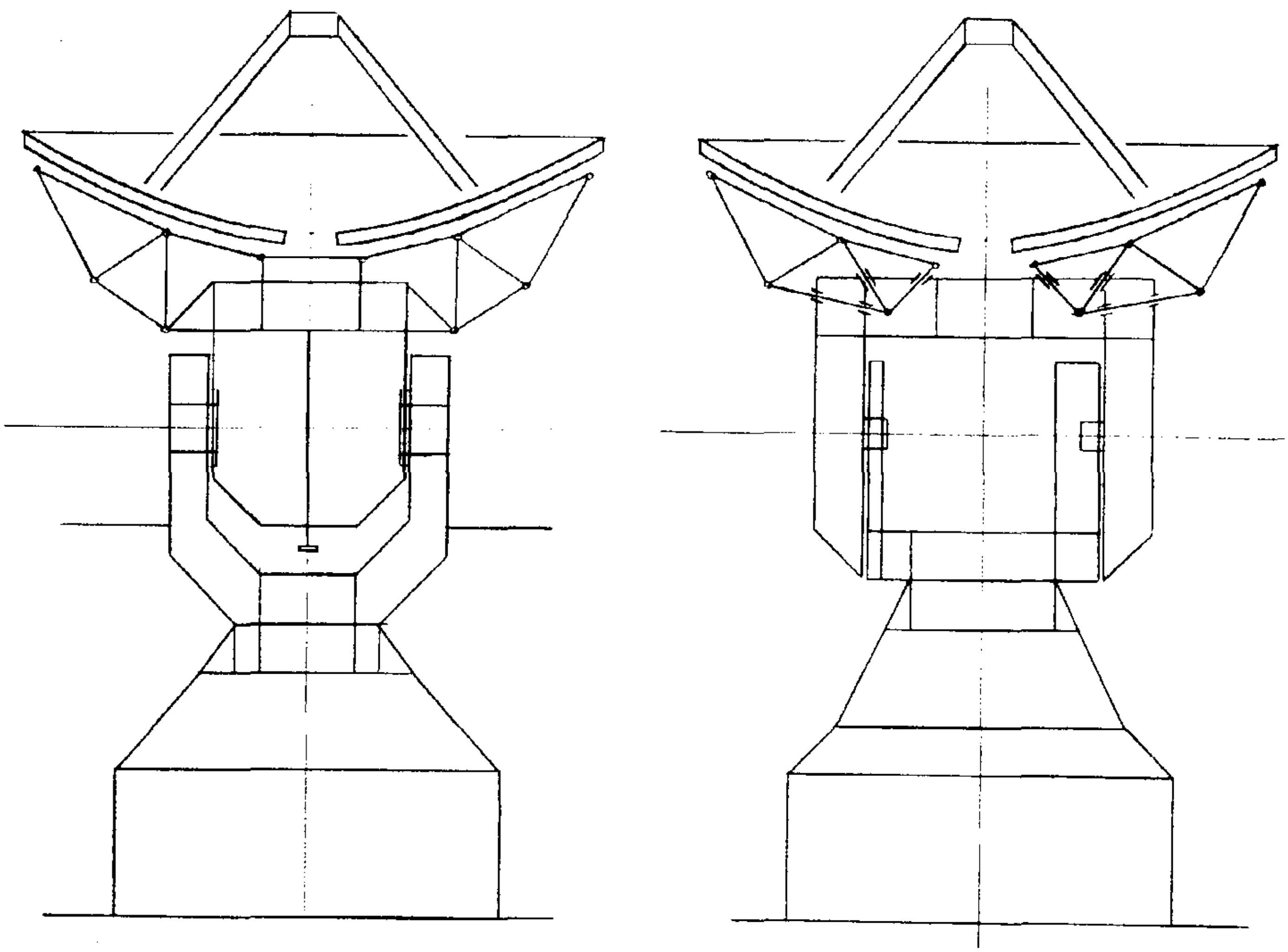
Telescopes with rotational symmetric reflector



Alternative a.1

Main reflector support with

Central Hub

Alternative a.2

Main reflector support with

Yoke

Figure 21.1 Reflector supporting systems is very direct and therefore stiff. For the other alternative a.2 the space behind the apex is much better accesable, but the load distribution via the yoke is more complicate and weaker than that of the central hub solution.

Due to the requirements for quick change of the receivers during operation and the arrangement of the receiver boxes (see WP 25 000) the variety of solutions with central hub is much more restricted than with the yoke arrangement. From the point of related accuracies the central hub solution may be a little bit easier to handle; but the yoke solution is also suggested as feasible in the required accuracies.

For the connections between the back up structure and the pedestal the hub alternative implies a lot of supporting points (figure 21.2). These points have the advantage of stiffness, but also the disadvantage that an injury of the reflector surface by thermal deformations of the hub and by the pedestal via the elevation bearings may occur. For the yoke alternative an "astatic" seperation between the back up structure and the pedestal could be reached by adequate designed supporting elements.

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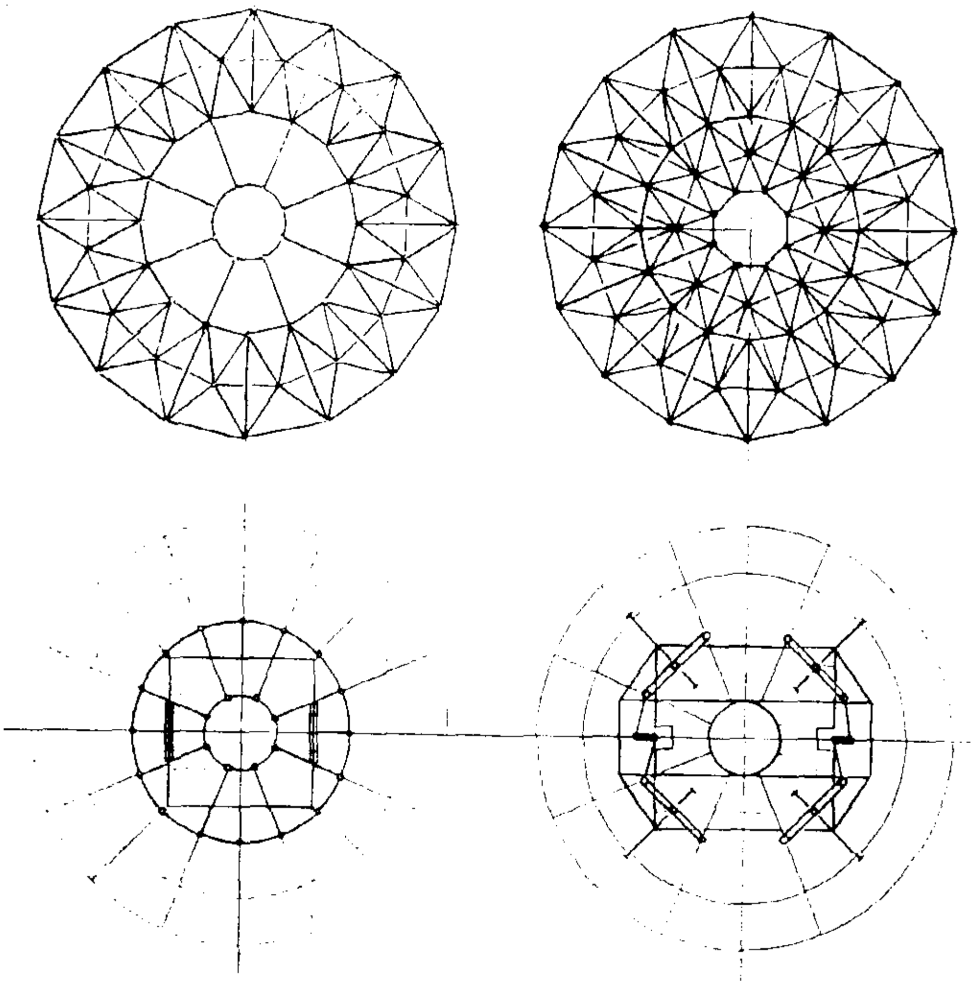
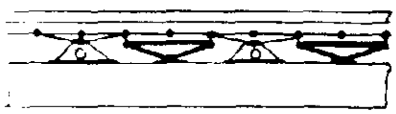
Reflector supports

Central Hub | Yoke



Stiff connection between central hub and reflector trusswork

Quasi-optical reflector support



with "astatic" supporting elements

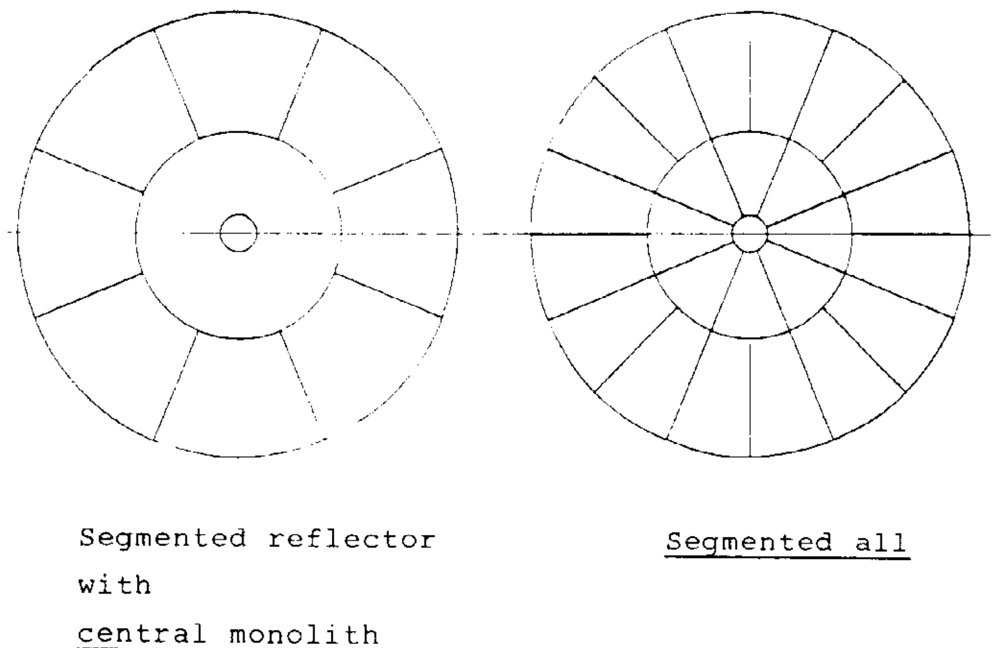
Figure 21.2 Ideas for the support system of the reflector backup structure on the pedestal

Concerning the quadropod for the hub alternative it should be directly supported on the backup structure (figure 21.3; also an arrangment with supporting points at the outer edge of the reflector may be possible). For the yoke alternative a seperate support independent from the backup structure may be advantageous (figure 21.3). The final arrangement should be decided after finite element calculations of the complete reflector system executed in the definition phase.

Concerning the arrangement of the reflector panels itself in figure 21.4 two possible solutions are sketched. The arrangement has influence on the principle deflection patters under temperature loads (WP 43 000).

Figure 21.4

Reflector panel arrangement



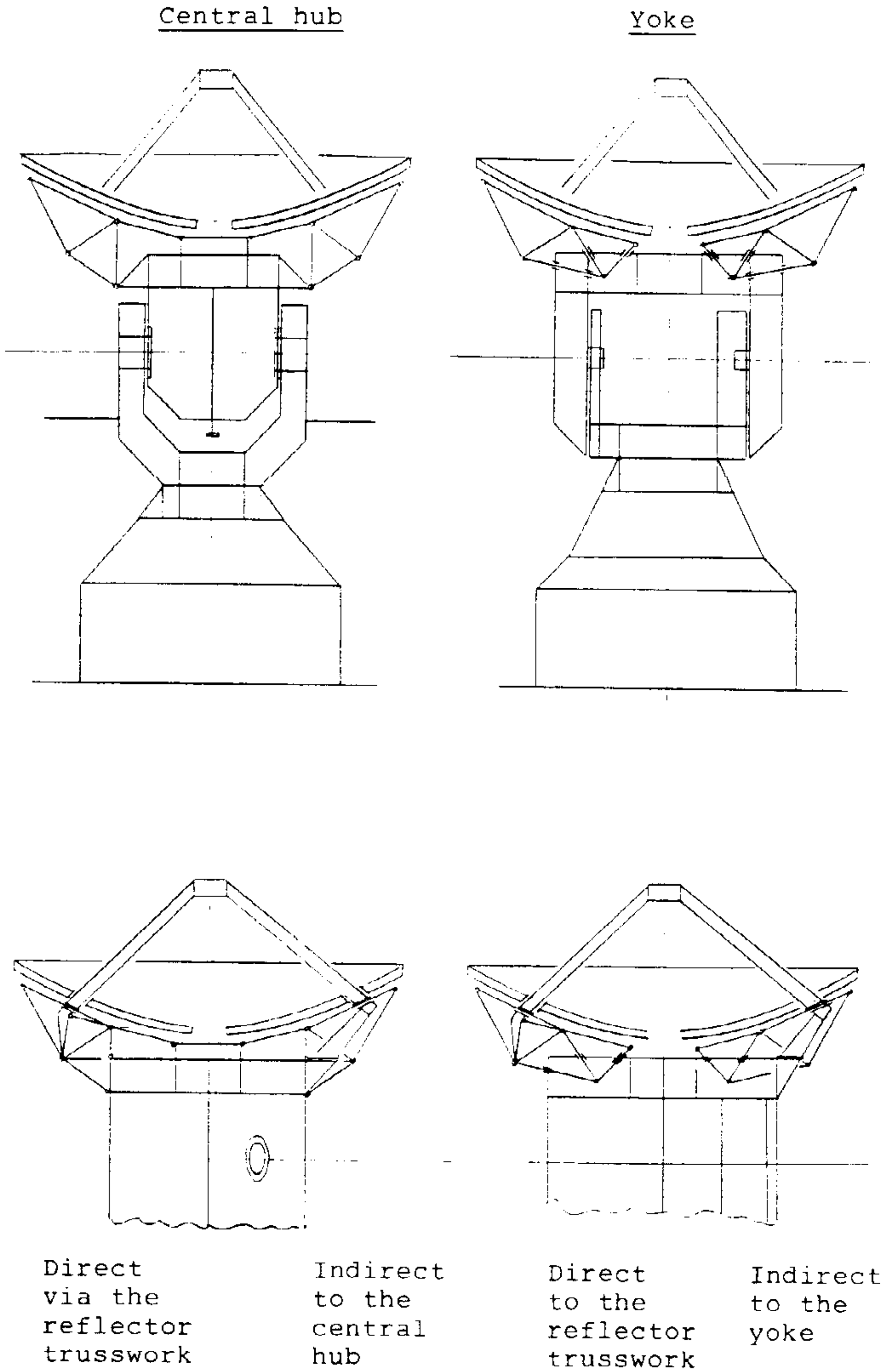


Figure 21.5 Supports for the quadrupod

Concerning the azimuth axis of the pedestal two alternatives were considered (figure 21.5)

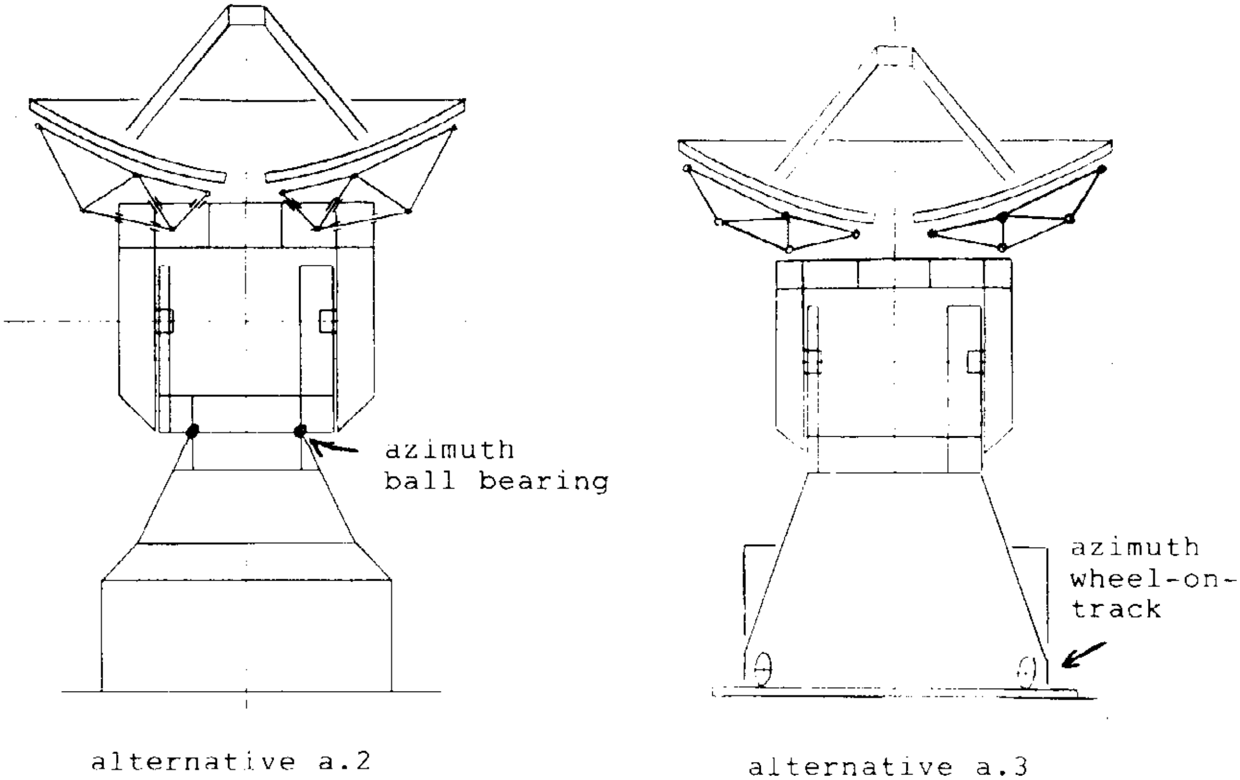


Figure 21.6 Alternatives for the azimuth axis

Both alternatives, the ball bearing in the upper part of the reflector and the wheel-on-track direct above the foundation, are compared more in detail in WP 22 000 from the operational point of view.

Telescope with offset-reflector

Because the specifications of SAO indicate, that an offset-type of reflector is not taken in mind by SAO, related telescope designs are not further investigated.

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Technical data for the structural telescope alternatives

	Alternative		
	Central Hub a.1	Yoke a.2	Wheel-on-track a.3
Reflector diameter	6 m	6 m	6 m
Type of reflector support	hub	yoke	yoke
Elevation bearings	ball bearing	ball bearing	ball bearing
Elevation drives	pinion-gear rim	pinion gear rim	pinion gear rim
Azimuth bearings	ball bearing	ball bearing	wheel-on-track
Azimuth drives	pinion-gear rim	pinion-gear rim	friction wheel
Weight	8 t	10 t	8 t
Frequency	7 Hz	6 Hz	7 Hz

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WP 22 000 Enclosure Concepts

- Design for three enclosure alternatives with special consideration of removable systems
  * Integrated reflector cover (IRC) concept
  * Astrodome concept
  * Radome concept

- Reasons for the selection of these concepts

- Technical data

Starting point for the lay out consideration for the telescopes was the assumption that it is necessary to protect the reflectors against severe weather conditions by some kind of protection. Therefore in the offer for the study some principle solutions with "classical" radoms, astrodomes and rotating buildings were sketched. During the execution of the study it was discussed and mutually agreed, that the radom solution should be abandoned - due to the unavoidable influence of the radom material on the incoming beam; and that an "open air" solution may be an optimal choice - if feasible. So at the end the following 5 alternatives were sketched and investigated.

<u>Alternative I Co-rotating building</u> (sketch on page 22.4)
derived from predecessors like the Multi-Mirror-Telescope MMT on Mr. Hopkins or the enclosure of ESO's New Technology Telescope NTT in Chile.

In this design two large Nasmyth-platforms, protected by the side-walls of the building, can easyly be arranged.

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Alternative II Independent rotating building (astrodome)

(sketch on page 22.5)

Existing example of such a lay out is NRAO's submillimeter telescope on Kitt Peak.

In this design a modified Nasmyth arrangement with the receivers on a plattform behind the elevation axis is adequate (arrangement used for IRAM's 30 m telescope on Pico Veleta, Spain).

Alternative III Integrated reflector cover

(sketch on pages 22.6 and 7)

No realized example existing.

In this design the enclosure is reduced to a reflector cover, which rotates together with the elevation part of the telescope. To reduce the size of the system a modified Nasmyth arrangement with the receivers below the elevation axis could be used.

Alternative IV Rear side cladding (sketches on page 22.8 and 9)

Derived from precedessors like IRAM's 30 m telescope on Pico Veleta, Spain and 15 m-telescopes on Plateau de Bure, France.

In this design the front surface of the reflector is always, also under severe weather conditions, exposed to the open air. The rear side of the reflector including its supporting structure is protected by a cladding. For the receivers a Coudé-type arrangement is used. Also the modified Nasmyth arrangement of Alternative III would be feasible.

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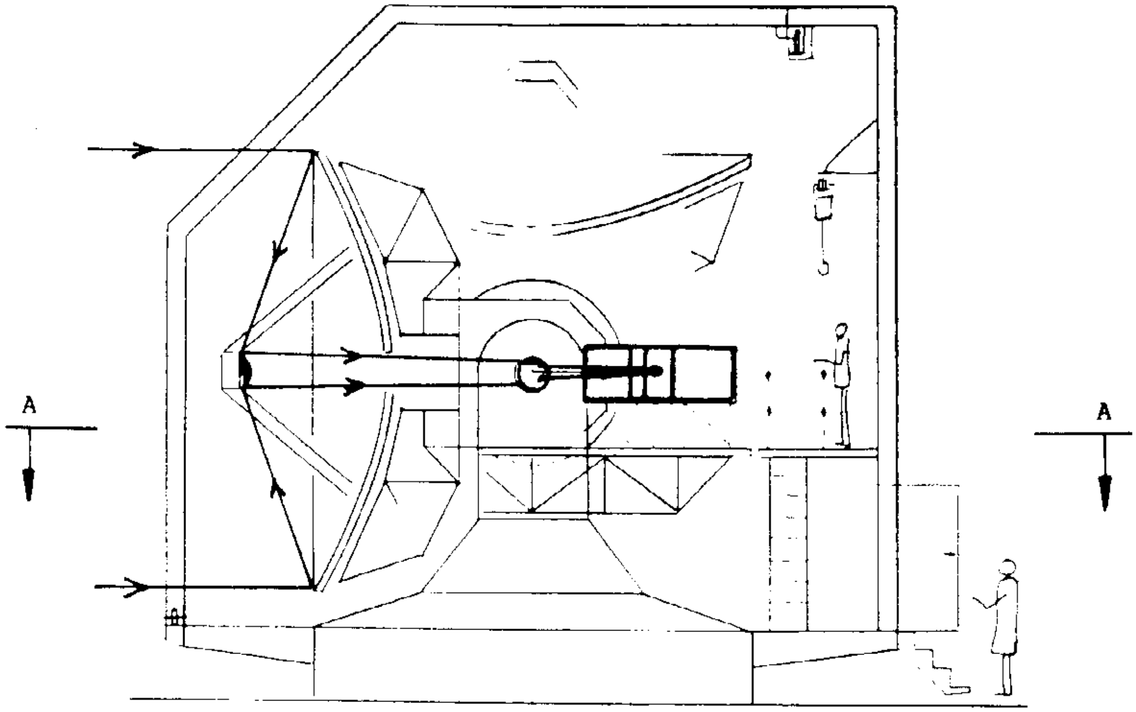
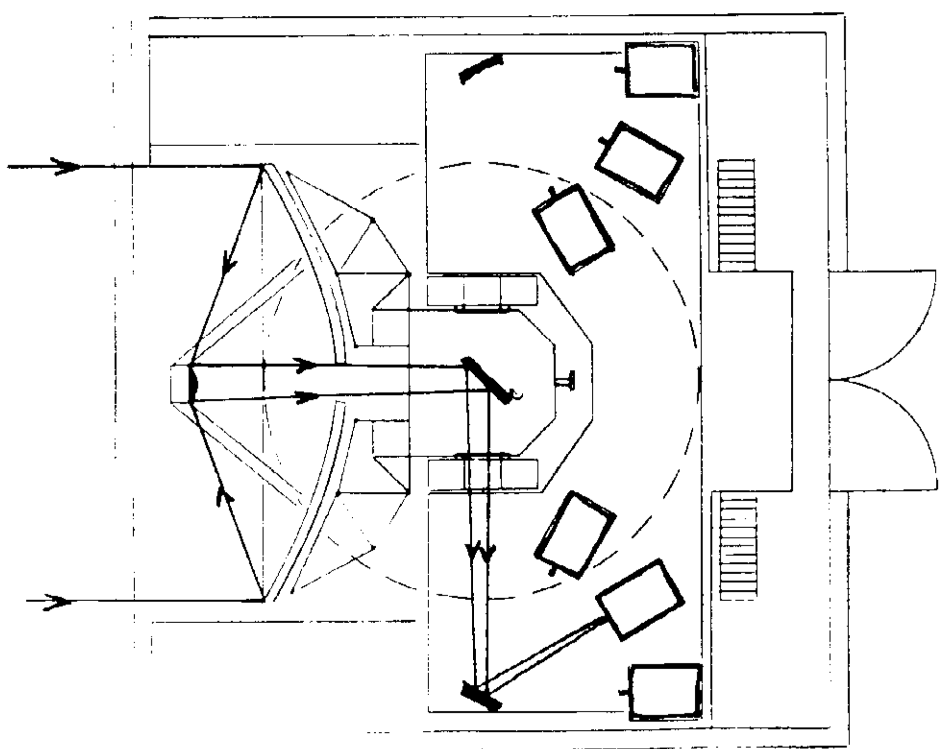
Alternative V Rear side cladding, wheel-on-track

(sketch on page 22.10)

The design is similar to alternative IV, only the realization of the azimuth axis is change from a roller bearing type to a wheel-on-track type. Thereby the restrictions for the receiver arrangements are reduced and a simplified Nasmyth arrangement similar to alternative III could be used.

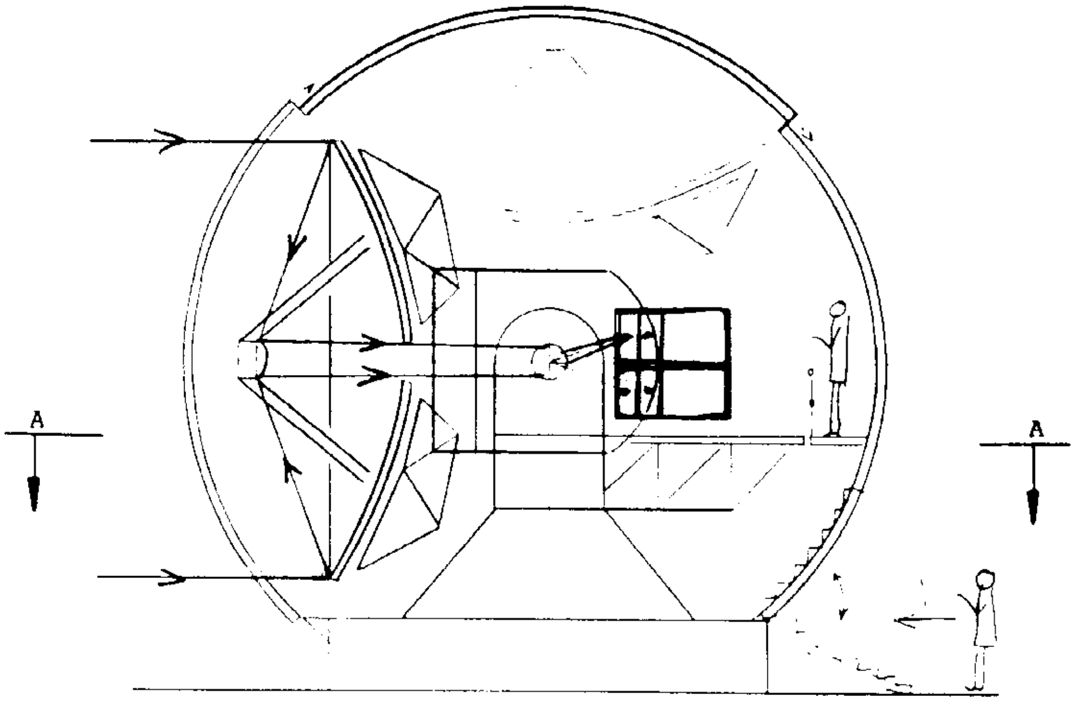
Alternative I   Co-rotating building

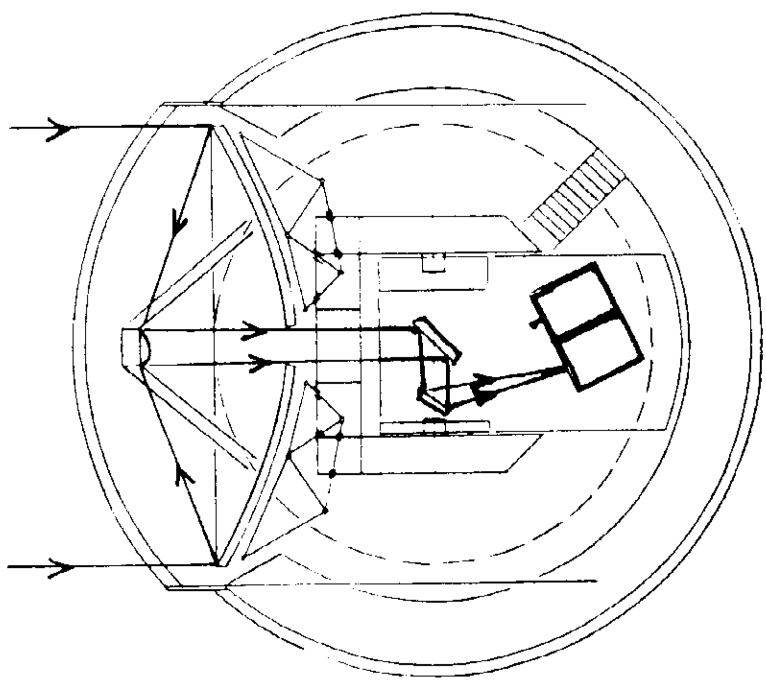




A - A

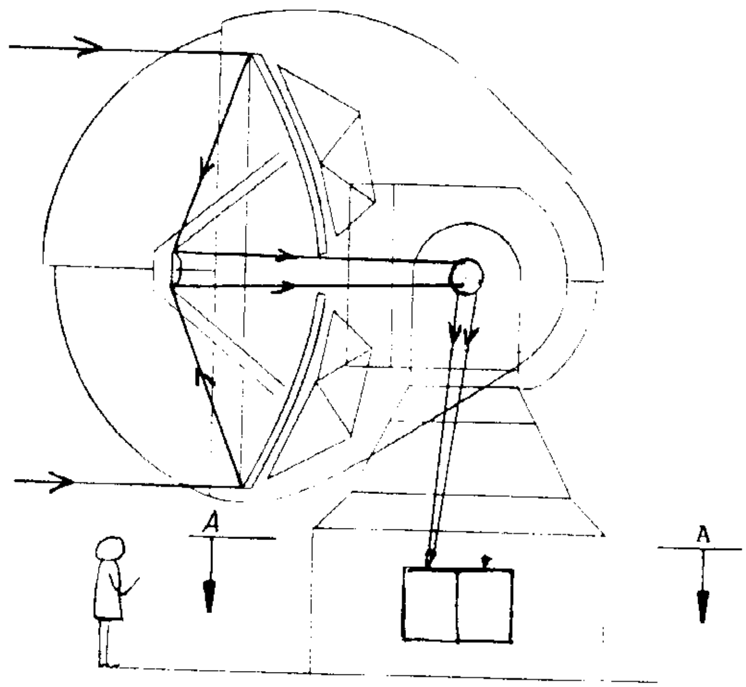
Alternative II   Independent rotating building

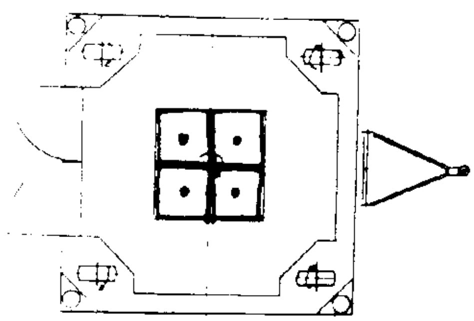




A – A

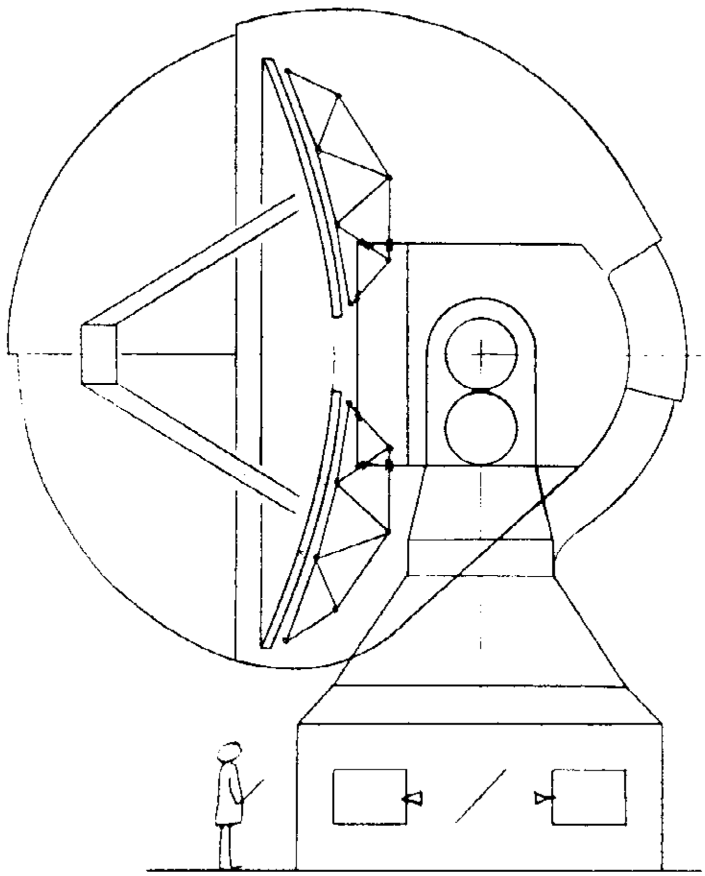
Alternative III   Integrated reflector cover



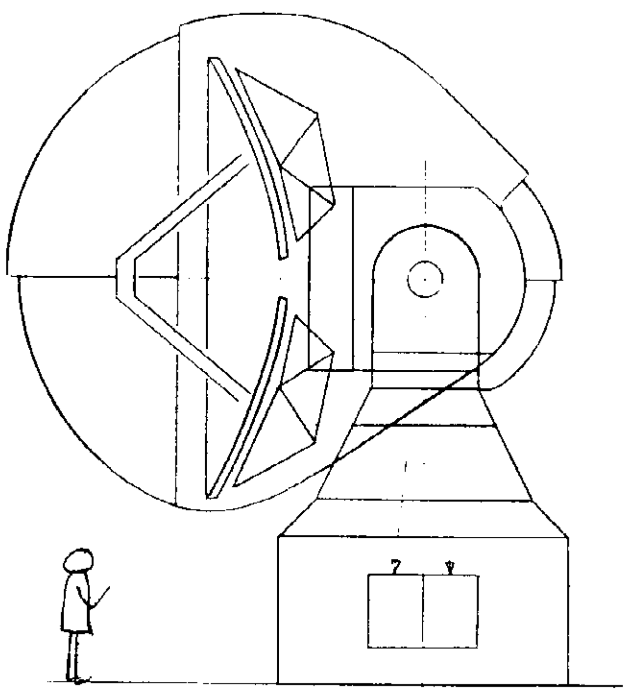


A – A

Alternative III   Enlarged

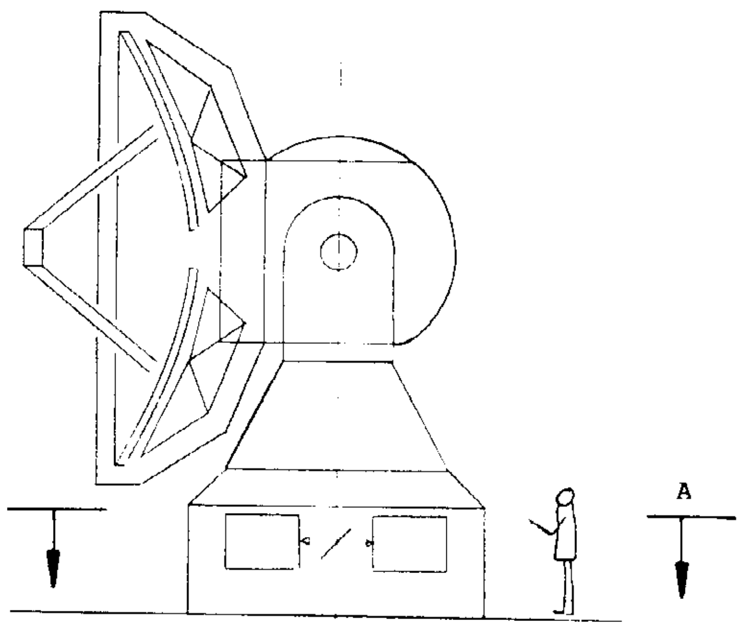


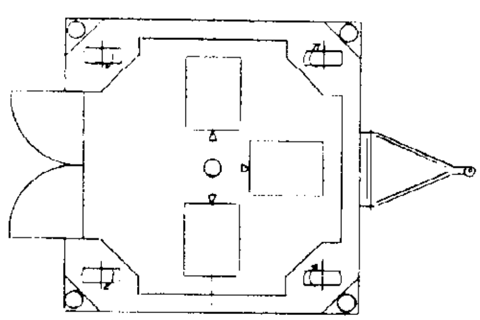
8 m



6 m

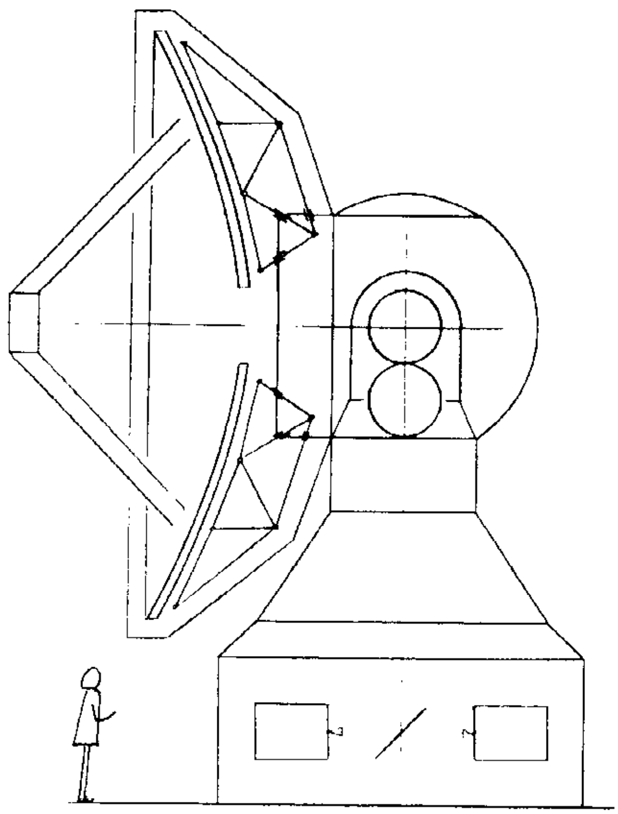
Alternative IV Rear side cladding



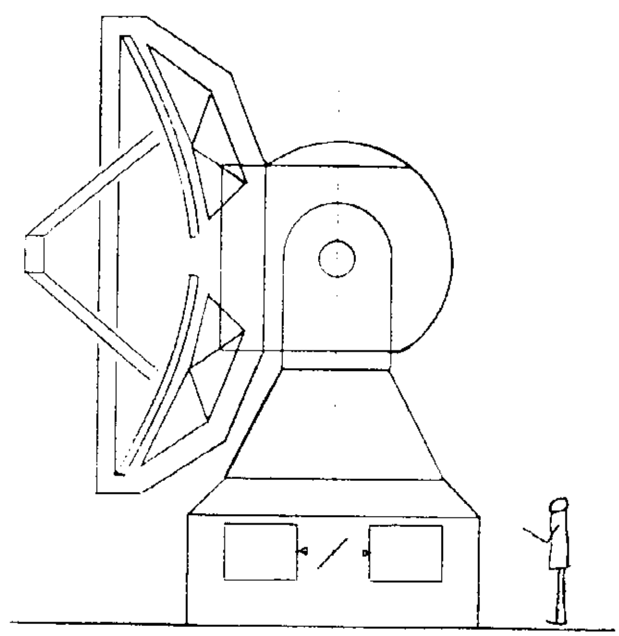


A - A

Alternative IV Enlarged

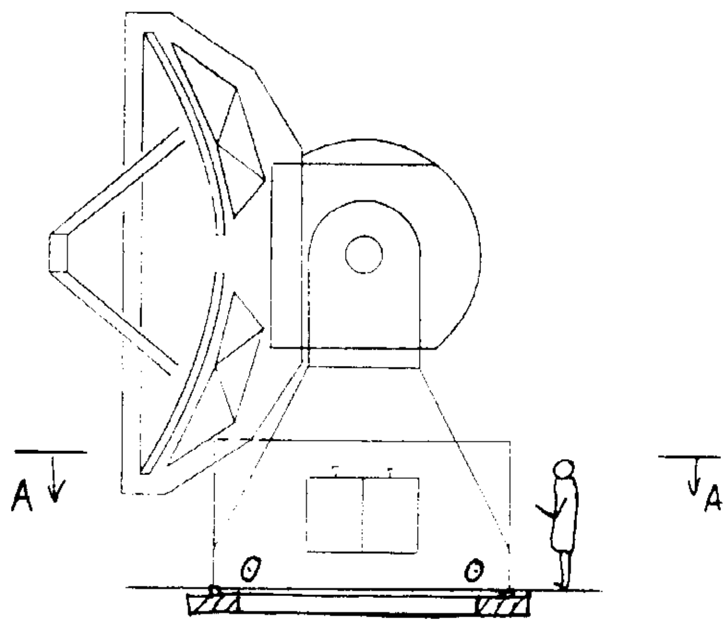


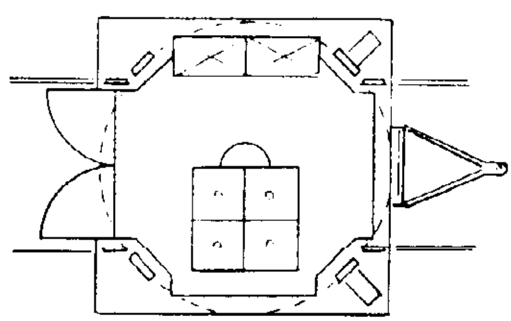
8 m



6 m

Alternative V Wheel-on-track





A - A

Comparison of the Enclosure Alternatives (and related telescope designs)

A comparison of the sketches show , that - under the restrictions of the movability of the telescopes - Alternative V, the rear side cladded telescope with wheel-on-track azimuth axis is by far the simplest (and also lightest) solution.

Main precondition for this solution is, that it must be allowed to expose the reflector front surface under all weather conditions to the open air. This question will be answered by the parallel reflector study of MAN Technologie.

A (minor) disadvantage of this solution is, that at all operating positions of the array seperate azimuth tracks must be installed. But this is compensated by the simplicity of the alidade structure for the wheel-on-track-telescope, compared with roller-bearing arrangements.

For comparison of the receiver arrangements see WP 25 200.

WP 23 000 Servo Concepts

- Design concept of a servo system

The servo system has to fulfill the following tasks:

(1) controlling the telescope movements in the two axes

(2) controlling the secondary movements in three coordinates

(3) assuring safe operation by an interlock system

(4) monitoring the status of the system

Whereas tasks (1) and (2) are described in the scientific specification of the telescope system, the design of the interlock system is governed by practical considerations and safety codes. The monitoring system (4) is introduced to have the possibility to improve the performance by knowledge of status informations during operation (see below).

The servo system should be arranged in modules:

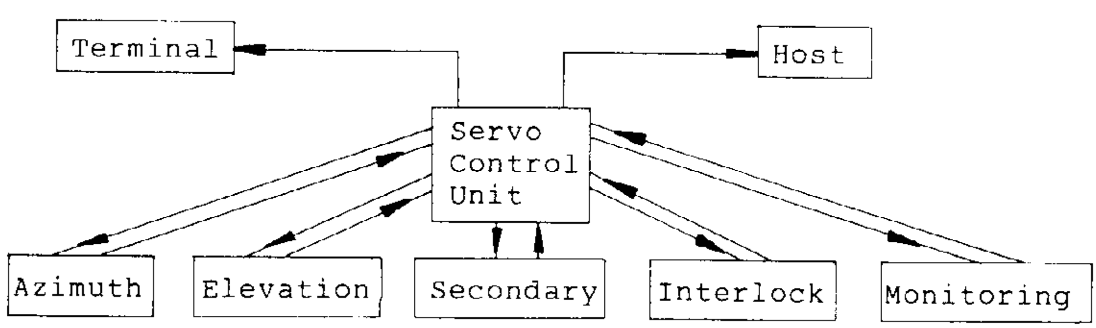


Figure 23.1 Block structure of the servo system

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The subsystems are distributed on the telescope as follows.

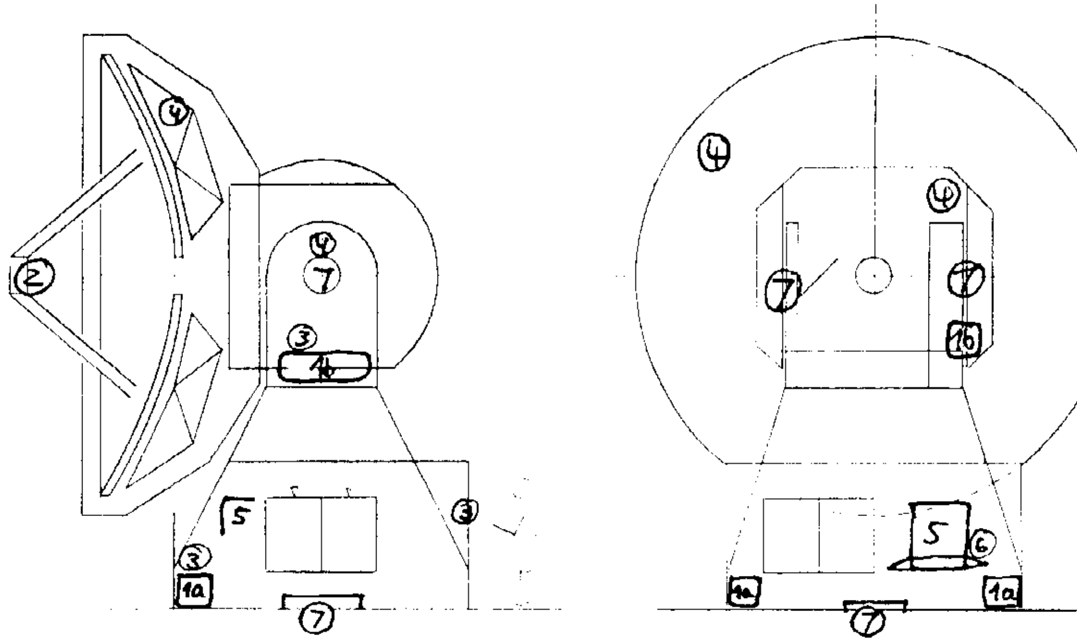

Figure 23.2   Location of the servo subsystems in the telescope

The subsystems consist of the following components

1   azimuth and elevation drives

- drive units: wheel on track (azimuth), gear rim-pinion (elevation), gear boxes, motors, tachos, brakes etc.
- position sensors: sensor coupling, sensors
- power amplifiers
- axis controller (located in 5)

2   secondary positioning mechanisms

- drive units 3 coordinates: spindles or equ., motors etc.
- position sensors (3 units)
- power amplifiers (3 units)
- coordinate controller (3 units) (located in 5)

...

(3) interlock systems
- limit switches
- stow pins
- safety keys
- safety controller

(4) monitoring system
- deformation/acceleration sensors
- temperature sensors
- monitoring controller

(5) servo control unit
- axis controllers
- coordinate controllers see (1) and (2)
- master controller
- interface devices

(6) operator terminal (for manual handling)

(7) coupling device
- interface to the host computer

The detail design of the drive units has the main influence on the achieved pointing and tracking accuracy (see special comment at the end of this WP). Standardized hardware is available for the servo control unit (figure 23.3). The design of the interlock system depends on the operation modes and conditions on site and should be detailed in the design phase. The purpose and advantages of the monitoring system are described below and mentioned in WP 52 000. The purpose of the operator terminal is to display the status of the system locally and to operate the system manually in operation mode "Manual Control". The purpose of the coupling device is to get physically the connection to the host computer in the operator building.

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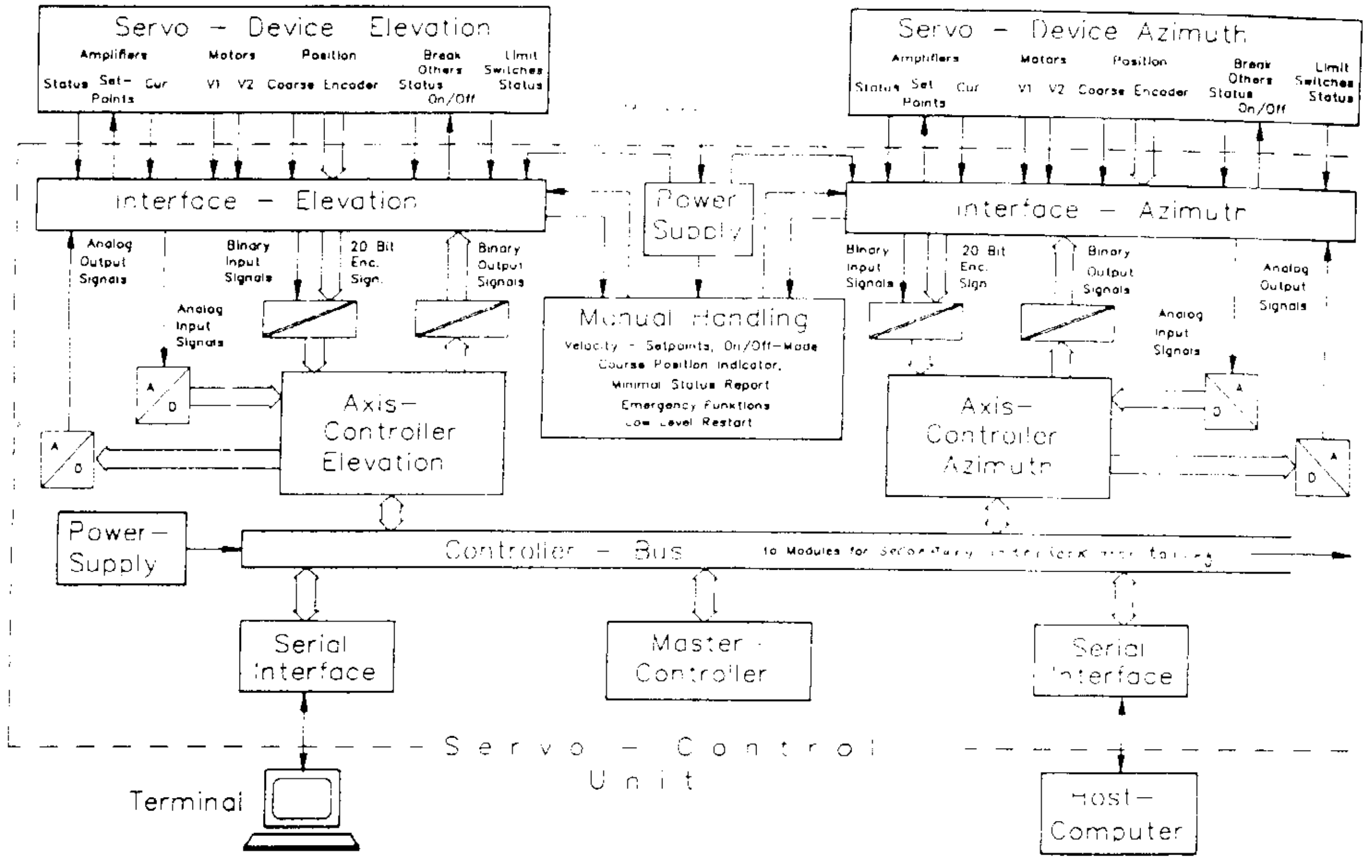

Figure 23.3 Block structure of a standardized servo control unit for the telescope drives

In each axis as basic structure of the control loops a "cascade" controller should be used (figure 23.4).
The cascade controller consists of a position, speed and motor current loop which are connected sequencely to form the cascade. Speed and current loop have PT structure, the position loop P structure and are realized by the axis control computer. The controller structure may be refined by stabe controller concepts or time-domain control models.

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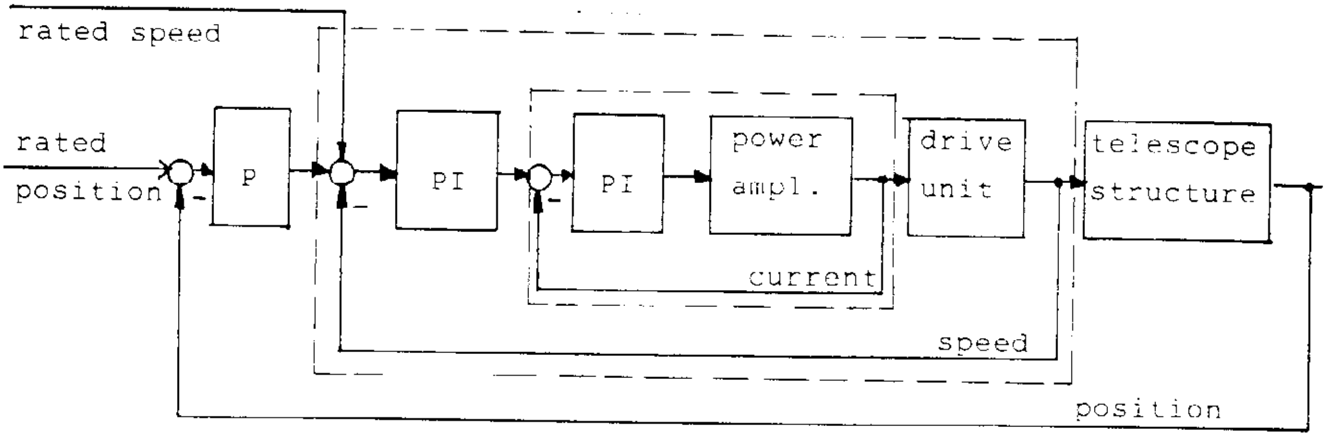

Figure 23.4 Principle structure of the cascade controller for the telescope axis

The principle components in the control loops are:

- the telescope structure
- the actuators: two gear boxes with attached motors and power amplifiers
- the sensors: position sensor, motor speed sensor (tacho), motor current sensor
- the controllers: realized digitally by the axis computer with attached C/D-converters

Inputs to the control loops are the rated positions and speeds, given by the master controller.

Disturbancies on the telescope structure are wind, temperature, friction, backlash etc.

...

- Preliminary selection of actuators and sensors

Actuators

In each telescope axis two drive units will be arranged as actuators. Each drive unit consists of a gear box with attached motor (example in figure 23.6). For the free standing telescope as sketched in figure 23.2 the gear boxes act in elevation by pinions on a gear rim, in azimuth via wheels on the azimuth track. As gear boxes schould be used planetary gears with high stiffness. The two gear boxes of each axis are biased to prevent backlash. The bias torques with special characteristics are controlled by the axis computer (figur 23.6).

Standard DC torque motors can be used (Inland,Magnedyn). Alternatively modern brushless DC-motors which are cheap and easy to set up (Balder) should be checked.

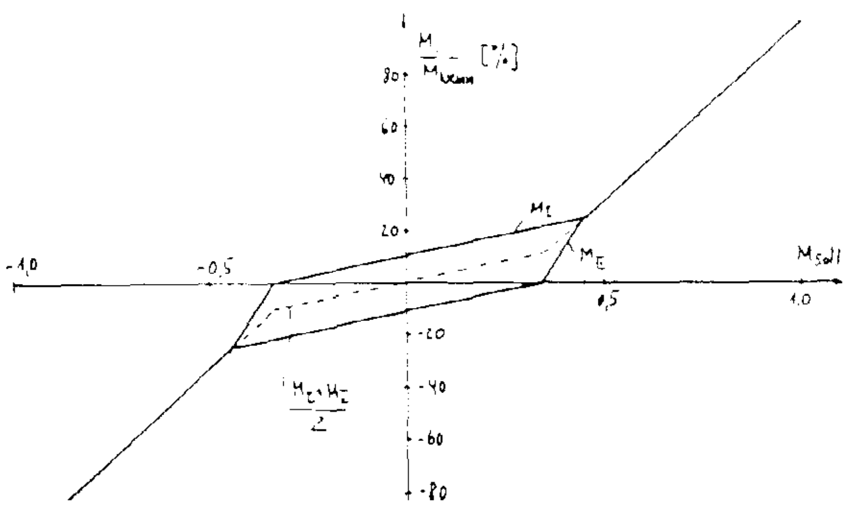

Figure 23.5 Bias torque characteristic for the anti-backlash system

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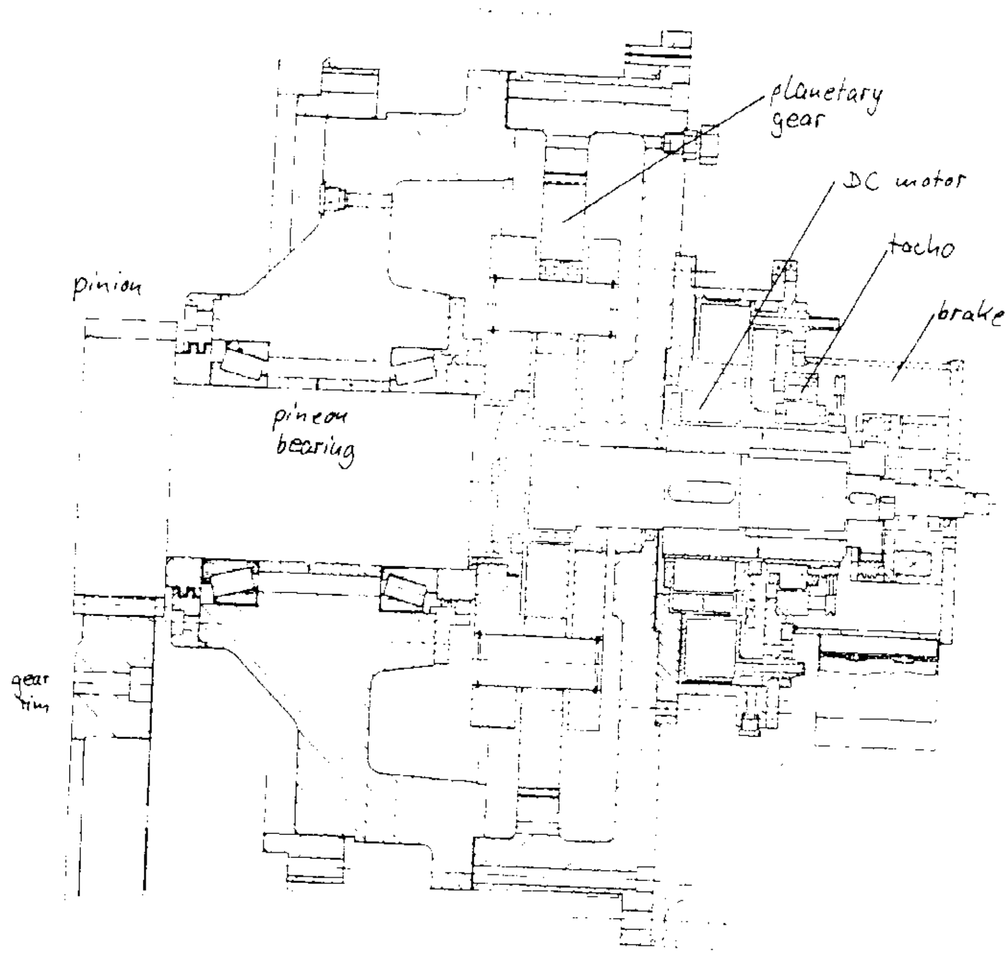

Figure 23.6 Example of a drive unit with DC motor. Special design features are applied to optimize the stiffness

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Sensors

Standard 21 bit absolute optical encoders should be used as position sensors (Itek, Heidenhain).

- Comments on the interfaces to the mechanical system and achievable accuracies

The optimal tuning between the mechanical and the servo system is of great importance for the pointing and tracking performance of the telescope. Now this can be done optimally for the mechanical as well as the servo system in a modern computer simulator. Therefore the complete mechanical system is modelized (figure 23.7). The structural components (stiffness,

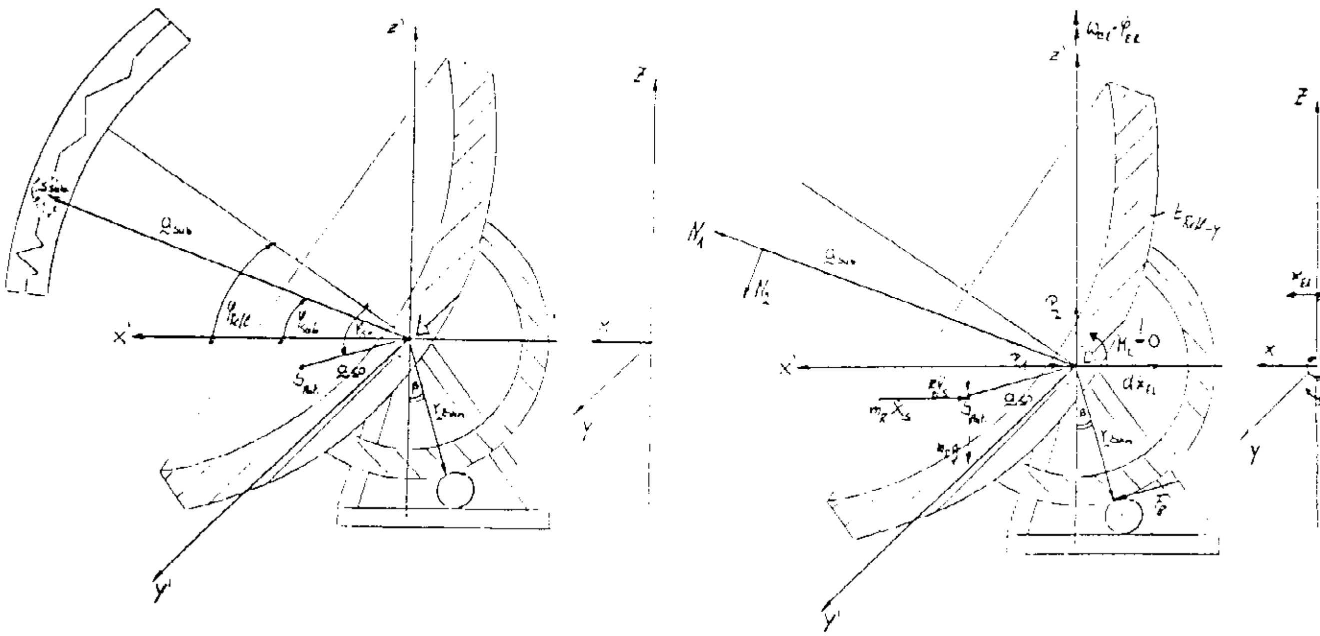

Figure 23.7 Mechanical model of a telescope (principle only)

masses, structural damping) and also the mechanical characteristics of the bearings and drives (stiffness, friction, backlash etc.) are introduced and transformed in the simulation model (figure 23.8). Also a verification of mechanical components is possible by harware-in-the-loop-simulation.

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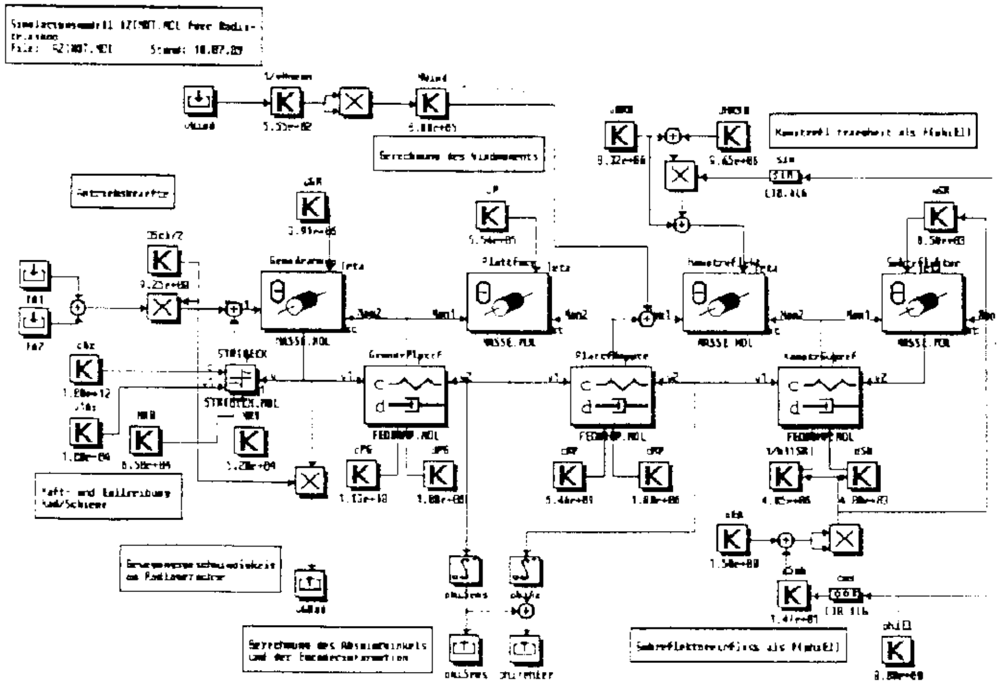

Figure 23.8 Computer model of the telescope mechanics (example)

The controller structure can be modelled also for the computer simulation (figure 23.9). The two models can be combined to the overall system, using the two models of figure 23.8 and 23.9 as substructures (figur 23.10). The control performance can be simulated and optimized (figur 23.11 and 23.12) under different disturbances.

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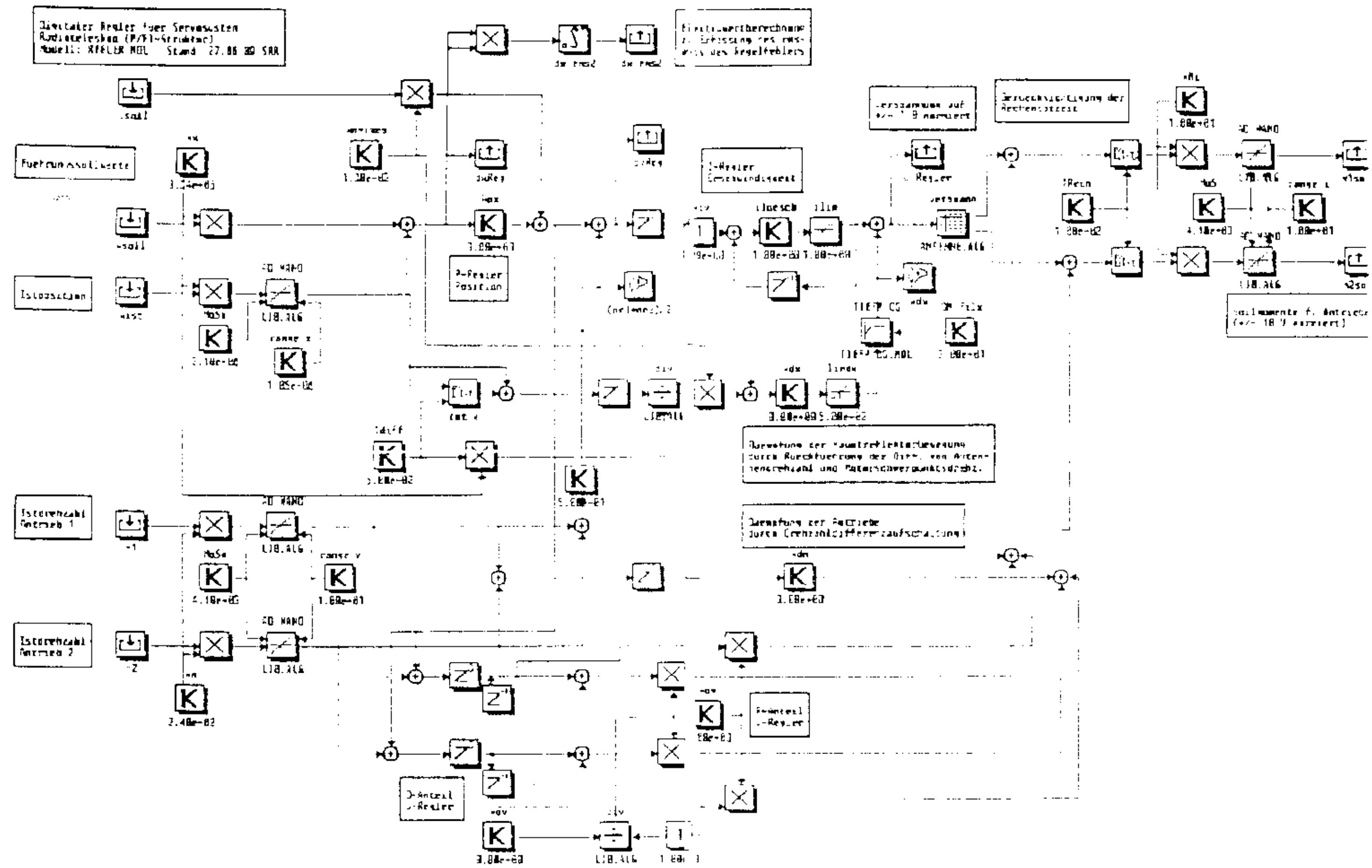
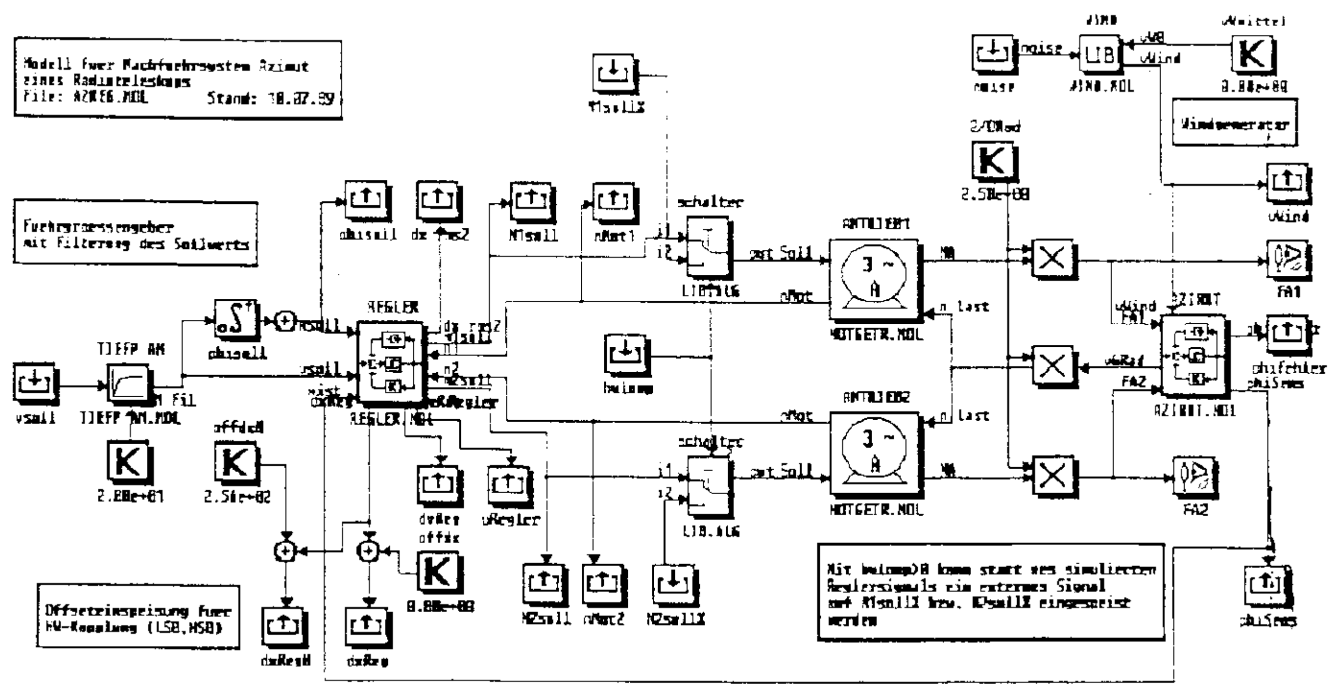


Figure 23.9 Computer model of an axis controller



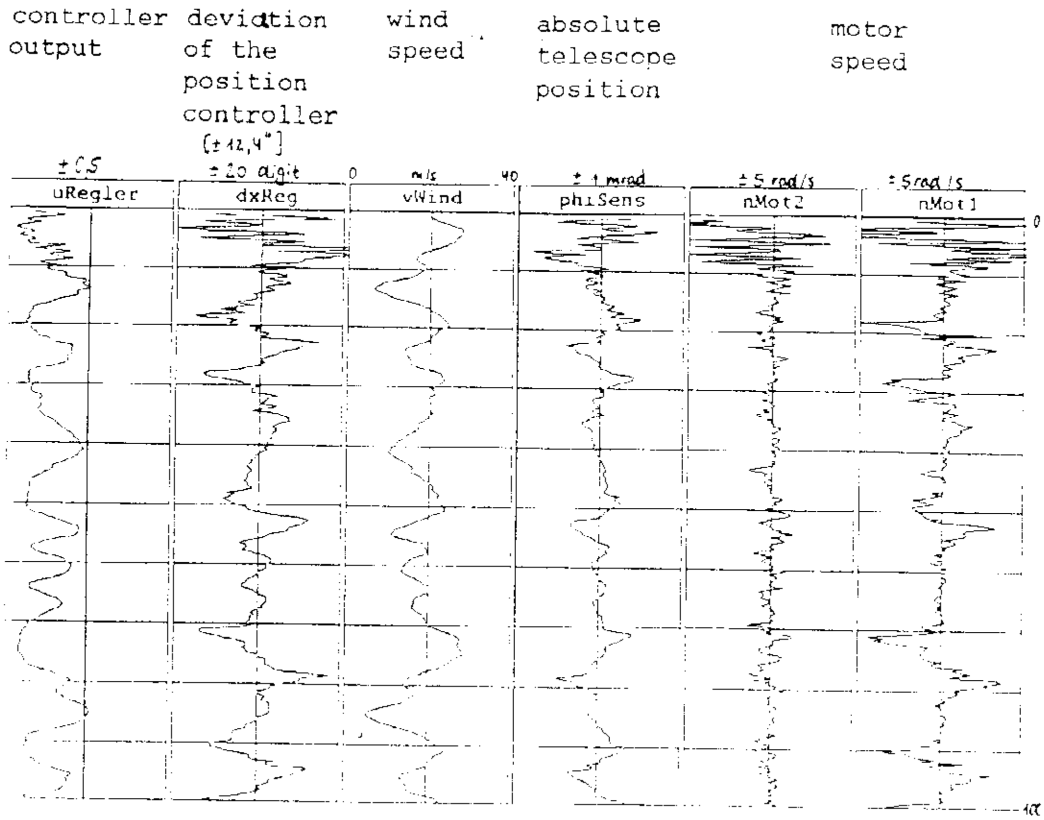


Figure 23.11 Computer simulation of wind gusts on the telescope (example)

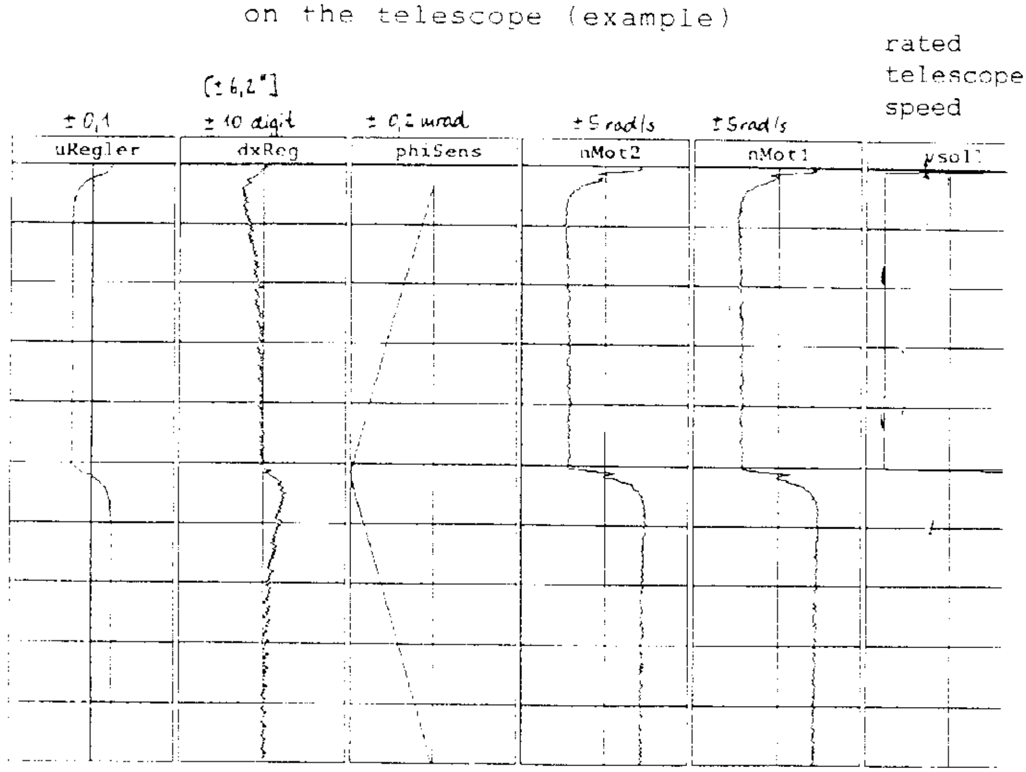


Figure 23.12 Computer simulation of a step function in the rated position (example)

- Comment on active control of constant and low frequent wind effects

In WP 30 000 is analysed, that the quasistatic and low frequent wind effects have a large in fluence on the pointing accuracy and that a compensation of these effects would increase drastically the pointing performance of the telescope under higher operational wind speeds.

Also in WP 40 000 it is argumented, that a monitoring of the temperatures in the pedestal and (may be) in the reflector system and compensating its influences by a pointing model as part of the control system would improve drastically the pointing performance during higher outside temperature changes.

Both active compensation system should consist of a status sensing system and a pointing error evaluator.

The status sensing system should be

- for the wind gust compensator 2 inclinometers on the two elevation bearing arms (minimum) and motor current sensors in both axis

- for the temperatur deformation compensator 12 temperature sensors (minimum, 8 on the reflector, 4 on the pedestal)

The pointing error evaluator is a software algorithm who transforms the measurements of the sensors in correction values for the rated telescope axis position. The algorithm could be developed from a FEM-analysis of the telescope

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structure combined with the standard pointing model formulas. The development of this algorithm could be done in the definitionsphase. Thogether with the development of this algorithm the position of the status sensors should be defined and optimized. The final correction parameters in this algorithm should be aligned during the commissioning phase of the telescope.

The feed back of the evaluated correction data for the axis positions must be faster done than the time constants of the effects, e. g. for the temperatures in the range of 10 minutes, for the wind effects in the range of 1 to 5 sec., which should be feasible using modern microcomputers.

WP 24 000 Technical Availability

- Comparison of the technological state of the art
- Comparison of availability, reliability and maintainability of the subsystems

For the reflector system - as studied in the special reflector study of MAN Technologie - very special product-development efforts are necessary, to reach the high accuracies of a submillimeter telescope. For the rest of the telescope system the situation is different. It is suggested that all subsystems - mechanical systems as well as electrical and electronical systems - can be designed in such a way that state-of-the-art components are used, which lead to no additional development costs and are mostly on-the-shelf available. For the servo-system, the speed of product development is at the moment very high, and before starting the hardware phase, the use of latest state-of-the-art components for computers, sensors and actuators should be checked. For all those components standard reliability and mainteniability performances are achievable.

WP 25 000 Receiver Cabin

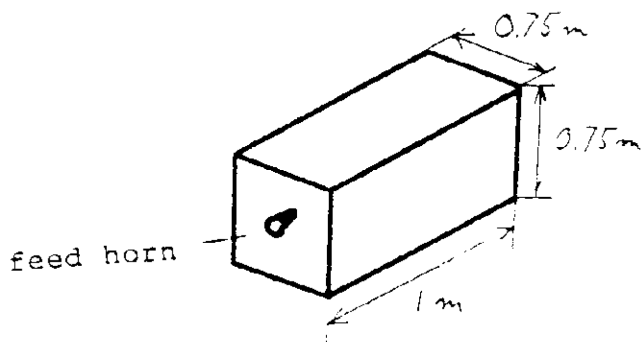
WP 25 100 Receiver Cabin general

- Configuration of the cabin
- Design of the receiver magazin
- Changing procedure of the receivers

(- Thermal conditions in the receiver cabin)

The following 4 pages were the starting point of the study work. The size and arrangement of the receiver boxis has a major inpact on the overall telescope lay out. At a later phase of the study work a further receiver boxis arrangement ("4 in a bundle") was developed, which is used in the latest telescope design and which is described in page 25.5.

As typical size of a receiver front end we assume 0.75 x 0.75 x 1 m with the feed horn in the center of the front plate:



Typical receiver front end

For changing the receiver front ends in the operation condition at the focal point of the reflector system there are two possibilities:

I Fixed focal point and changing the operational front end in the focus position by any kind of handling device (hoist, caroussel, etc.)

II Fixed receiver front ends in magazins and switching the focal point to the operation receiver by any kind of switching mirror system (e. g. rotating Nasmyth mirror etc.)

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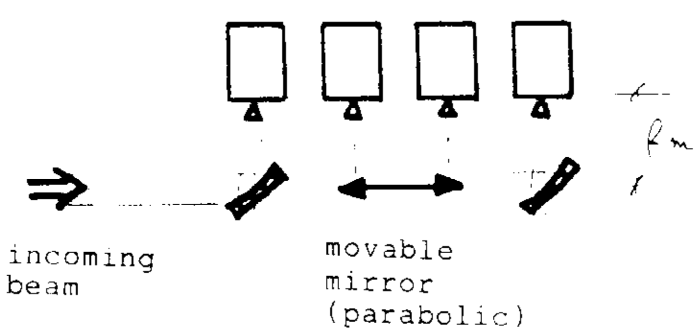
Solution I with hoist and bajonett type of fixation flange is e. g. used for the IRAM 15 m-telescopes on Plateau de Bure/ France and La Silla/Chile; solution I with a caroussel-type of changing mechanism is e. g. used for the new Cambridge 32 m-MERLIN telescope in the UK.

The system with hoist needs long changing time, the caroussel system needs large space in the region of the focal point. Both systems are assessed as not comfortable for smaller multi-receiver-telescopes and are not further investigated.

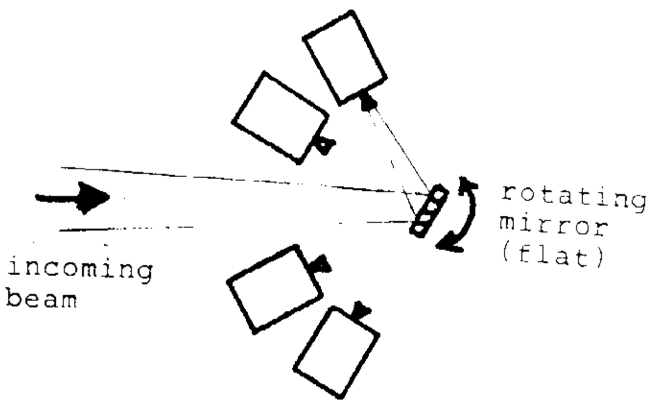
For solution II with switching mirror systems, two principle different front end arrangements are reasonable:

II a **front ends in a row**



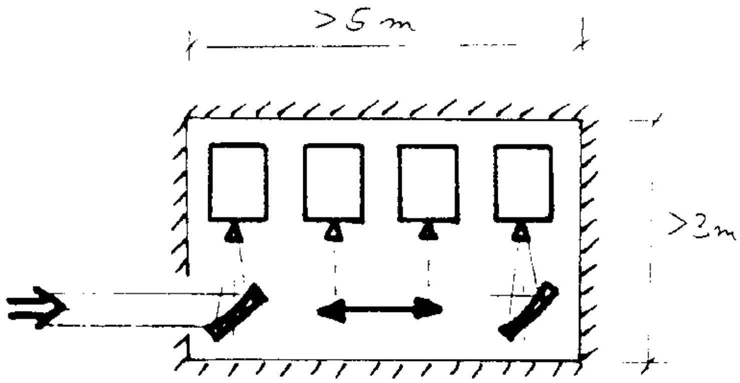
Because the distance of the individual front ends to the main mirror system changes in this arrangement, the incoming beam must be parallel and the movable mirror must be parabolic with focal length fm.

II b front ends circular



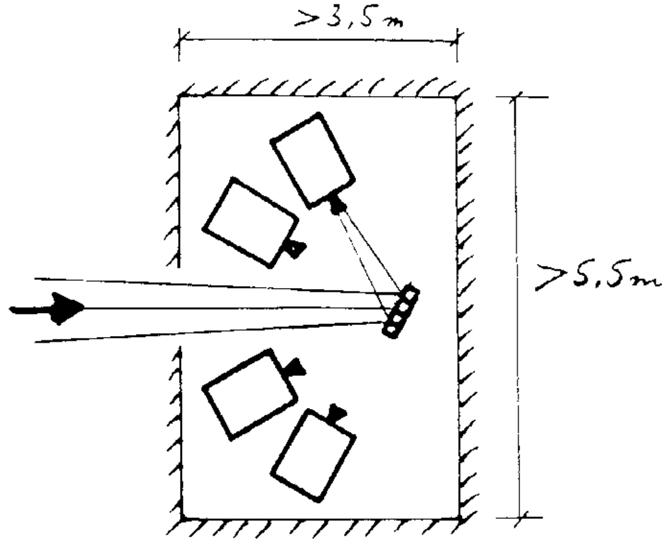
Because the distance of the individual front ends to the main mirror system is constant, the rotating mirror can be flat.

To estimate the dimensions of a receiver platform for 4 front end boxes we assume the width of the access area necessary for maintenance purposes to 0.735 m (half of the receiver width). We get the following typical platform sizes:



Solution II a

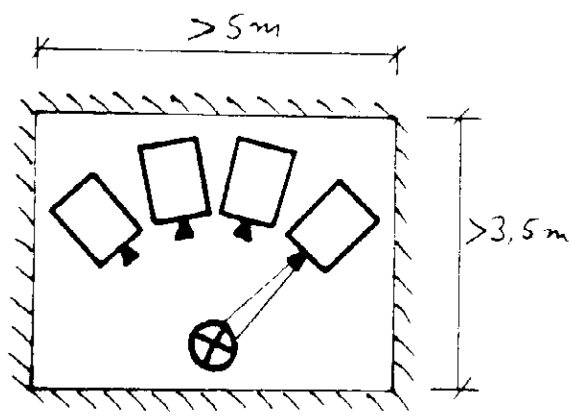
front ends in a row



Solution II b1

front ends circular,

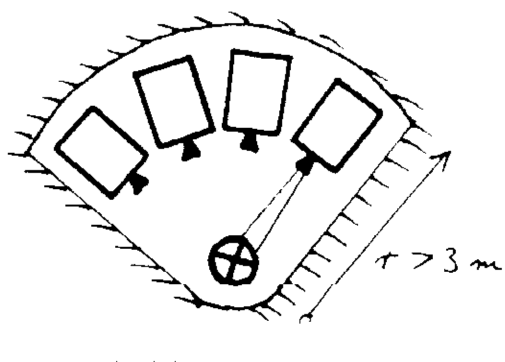
incoming beam horizontal



Solution II b2

front ends circular,

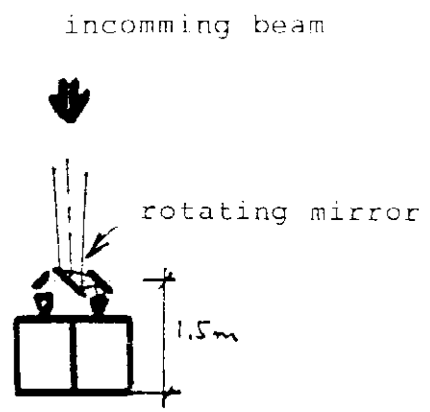
incoming beam vertical



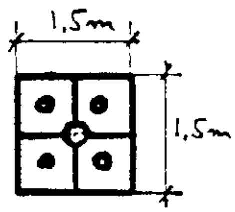
Solution IIc

Fixed receiver front ends,

4 front ends in a bundle



The switching mechanism should be part of the receiver rack.



This arrangement was developed in a later phase of the study work and selected for the latest telescope lay out.

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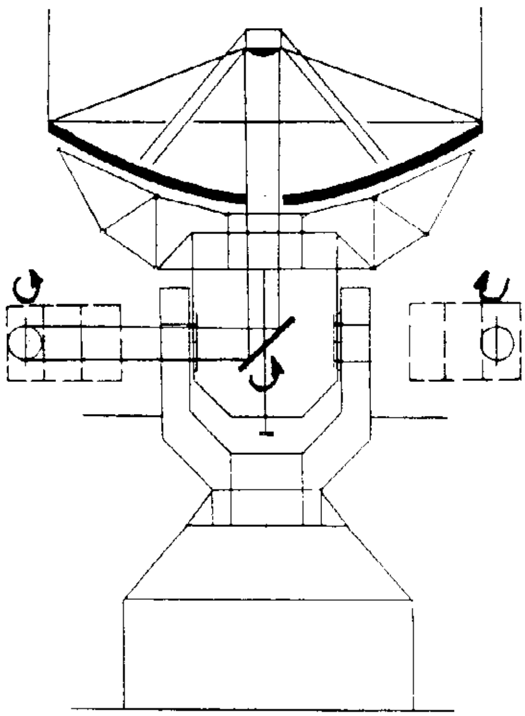
WP 25 000 Receiver Cabin

WP 25 200 Comparison of reflector and receiver arrangements

Before starting with the investigations of achievable accuracies for the different telescope lay outs (which are described in WP 22 000), the operational performance and special the accessability of the front ends should be checked. The comparison of the sketches on pages 252.2-6 shows, that the Nasmyth arrangement with the receiver cabin below the elevation axis and the switching mechanism integrated in the front end rack has by far the simplest reflecting mirror system. The interfaces between the telescope system and the receiver rack system are most clearly defined and the front ends are adequate accessible for installation and maintenance. Therefore this alternative is recommended.

Classical Nasmyth



System lay out see page 22.3

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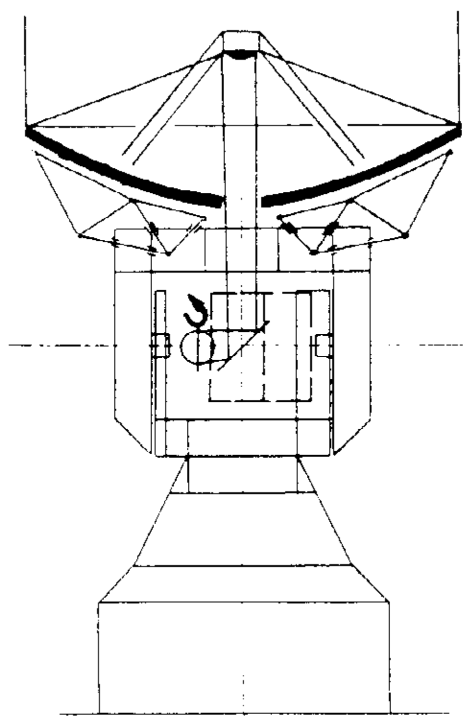
Modified Nasmyth

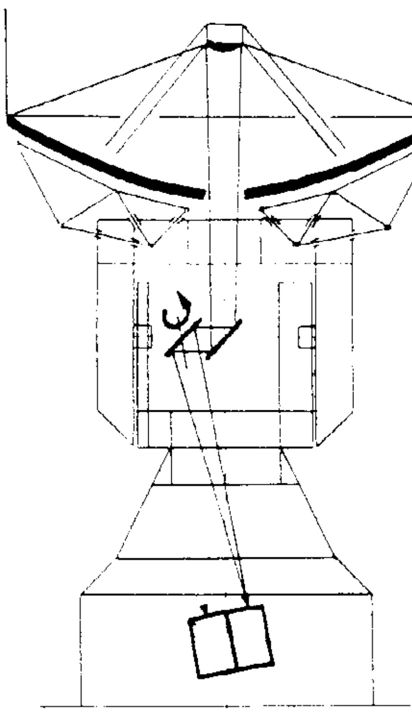
Receiver behind the elevation axis



System lay out see page 22.4

Modified Nasmyth

Receivers below the azimuth axis



System lay out see page 22.5

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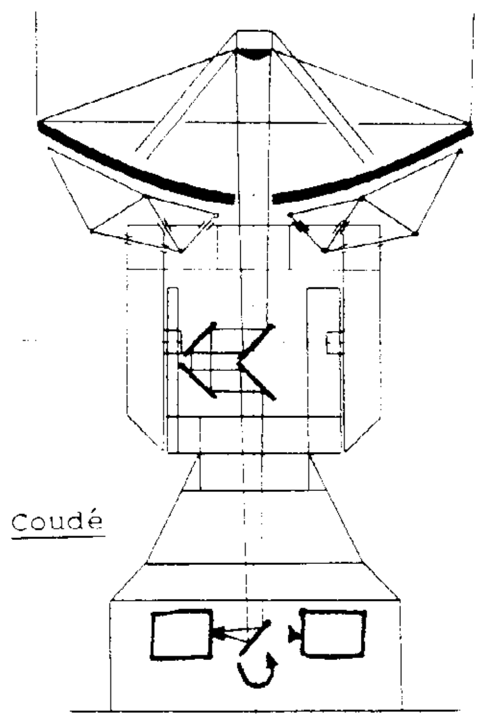
Coudé-type arrangement

Receivers fixed in any direction



System lay out see page 22.7

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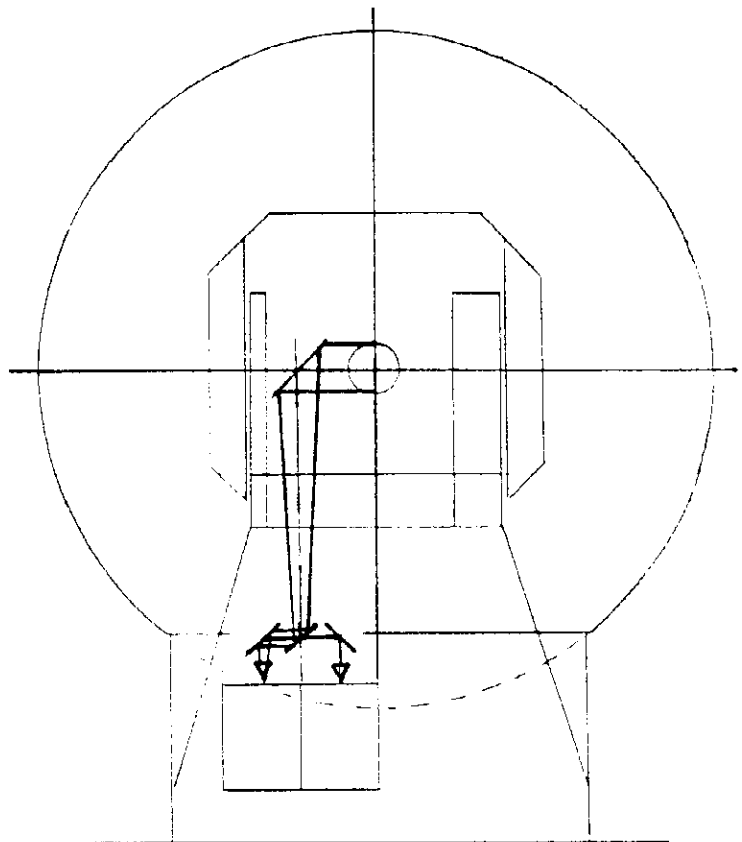
Modified Nasmyth

Receivers below elevation axis

Switching mechanism part of the receiver rack



System lay out see page 22.9

Recommended Solution

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WP 26 000 Transport System

- Design for transport system
- Comments to different solutions

Basic criteria for the lay out of the transportation system is, to move the telescopes between the different operating positions as easy and simple as possible. Therefore a system with an own active drive unit in each telescope, as e. g. realized for IRAM's 15 m telescopes, was abandoned.

The first solution considered (alternative 1 on page 26.2) was to move the telescope on a paved road by a tractor. For this solution the telescopes should be equiped with four extendable and steerable wheels on tires. The wheels must have a load capacity of 3 - 4 to, which is for a tire a high value and makes a diameter of 0.7 - 0.8 m necessary.

A simpler solution (alternative 2 on page 26.3) is to move the telescope by steel wheels on rails. In this lay out no steering mechanism for the wheels is necessary and the diameter of the wheels can be smaller than for wheels on tires. The lay out can easily be combined with the azimuth track of the wheel-on-track telescope design. A disadvantage is that between the operation positions of the telescope an extended rail system - additionally to the road for the tractor - is necessary. But this is compensated by the simplicity of the wheels itself in the telescope.

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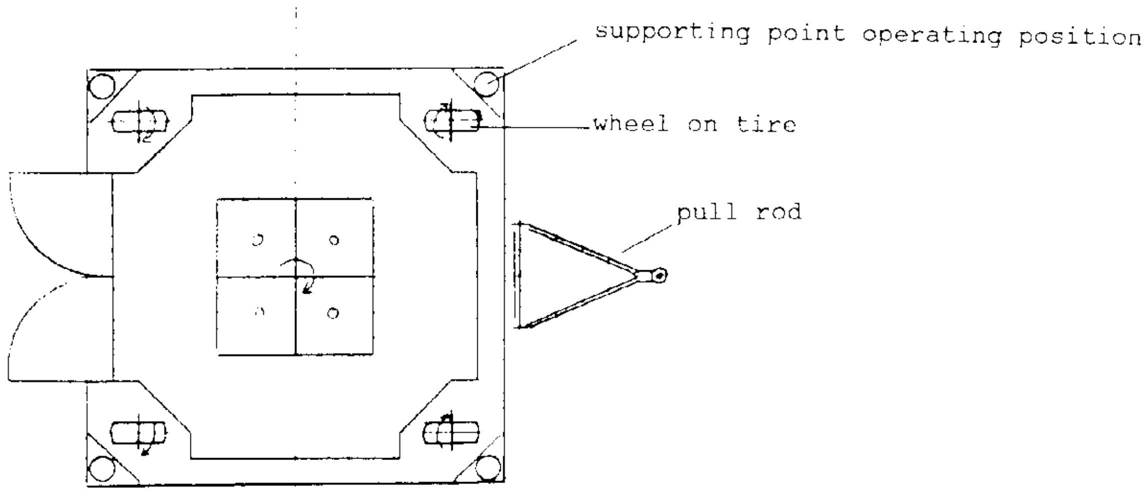
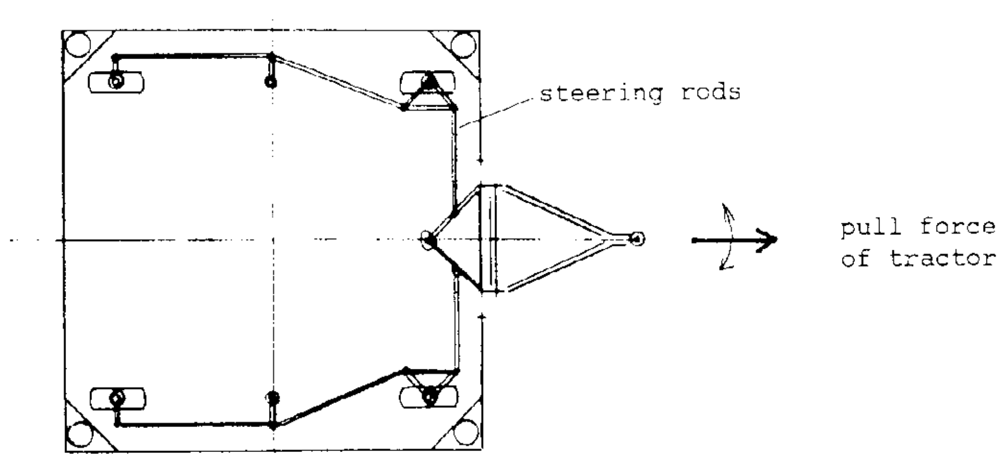
Alternative 1

Movement on rubber tires by a tractor

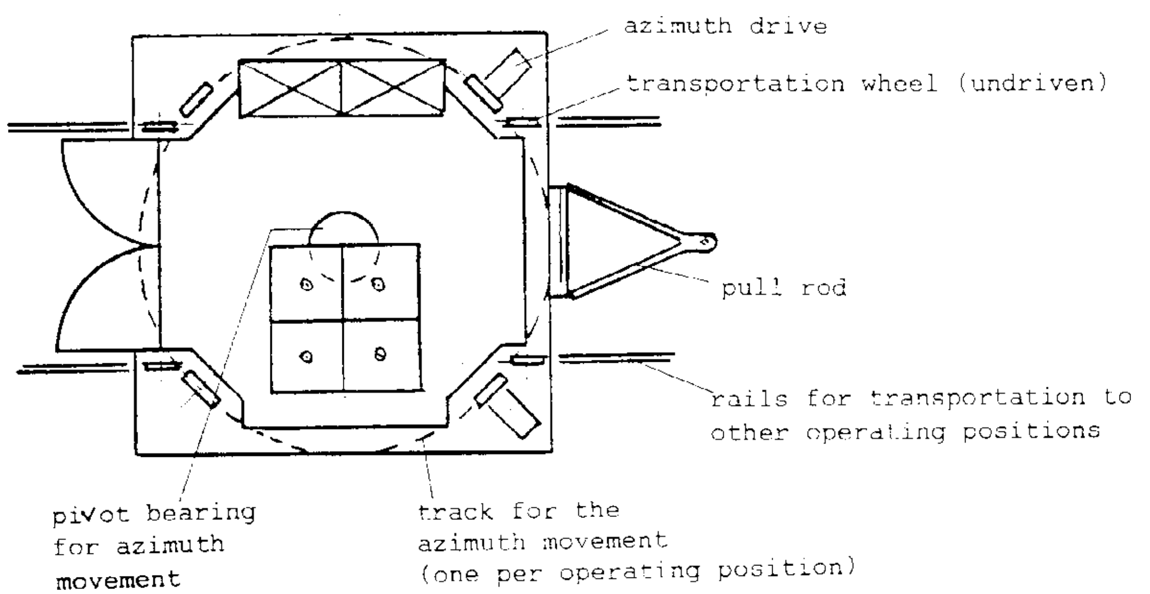


Steering system



Alternative 2

Movement on a rail system by a tractor



WP 27 000 Assembly Concept

- Discussion of preassembly and commissioning at a conveniant site.

For the first telescope unit it should be prefered, to preassemble it completely in the workshop including the reflector system and the servo and test it as a prototyp. After testing it could be disassembled, shipped and re-assembled on-site. The commissioning period on-site would than be very short. For the following units a preassembling and testing is only necessary on the subsystem level and not for the whole.

- Concept to reach an easy assembly and re-assembly

To reach an easy disassembly and transportation the main mechanical subsystems should be transported as intergrated units and not further subdivided. These units are (figure 27.1) the pedestal itself, the four azimuth drive units and the center unit in azimuth. All other parts - mainly the cladding system and all the equipment in the receiver room, should be transported in standardized containers. The pedestal will be the only piece with larger dimensions and its transportability should be specially checked after the site is decided.

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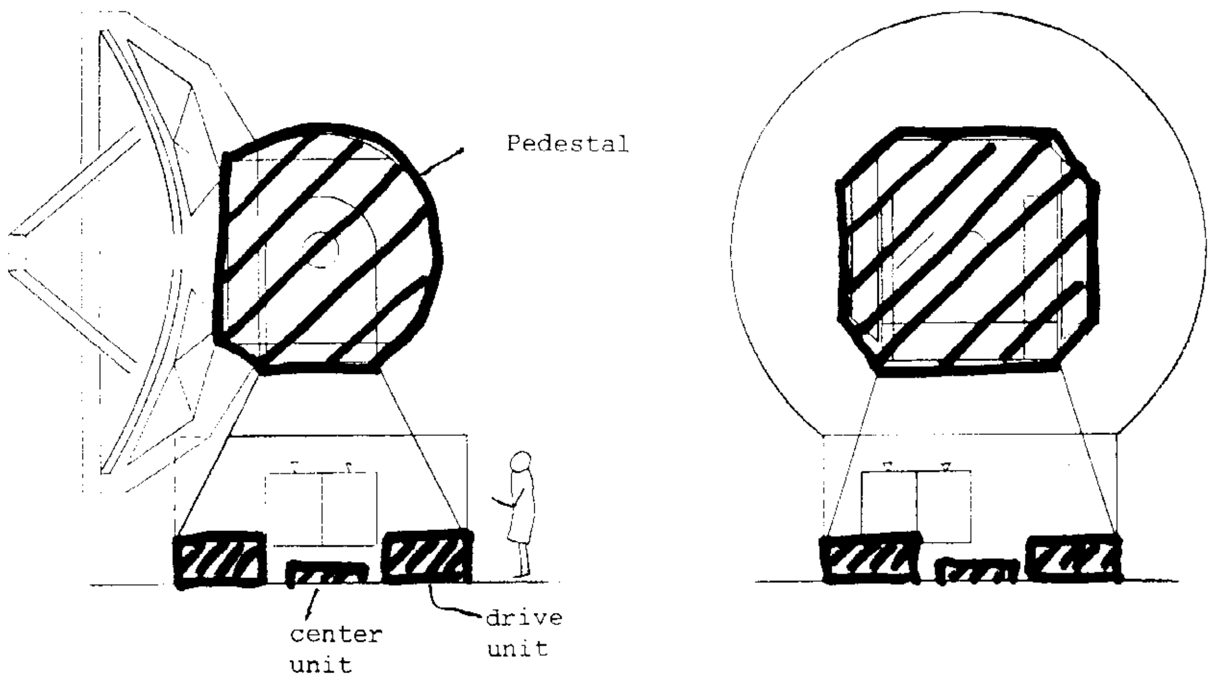

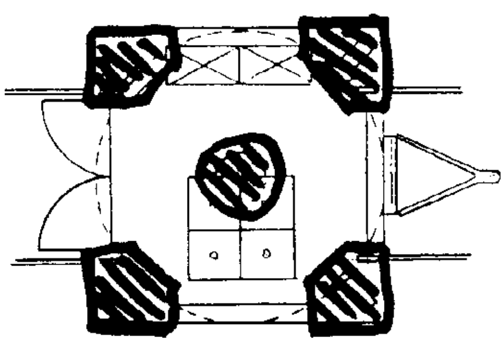

Figure 27.1

Telescope units, which should be preassembled and transportabled as a whole to the final telescope site.

WP 31 000 Wind Loads

- General comments on wind influences on telescopes and enclosures

The "wind study" has the purpose to investigate the influence of this environmental effect on the telescope and its performance, and to give - if necessary - indications for special measures which must be taken into account to get an optimal system.

The influence of wind effects on telescopes could be divided in two components

1. the low frequent, quasi-statical wind effects which mainly influence the overall reflector accuracy under operational wind speeds and the stability of the telescope structure under survival wind conditions, and

2. wind gusts in the range of the natural frequencies of the telescope structure, which influence the pointing and tracking accuracy under operational wind conditions.

The distribution, size and frequencies of the wind forces are determined by the shape of the telescope and its enclosure, by the wind speed and the angle of attack of the wind. The wind flow has also influence on the thermal balance and stability of the telescope system (see WP 40 000).

The problems with wind influences can be tackled by three different methods:

1. protecting the telescope by wind shields or enclosures

2. designing the telescope outer shape as well as its supporting structure in a way that it compensates passively the wind influences

3. control the wind influences by active compensation systems.

- Preliminary estimate of wind loads
- Definition of possible wind tunnel tests

For quasi-statical wind loads on parabolic telescope structures a lot of wind tunnel test results are reported, which allow a very confident estimate of the quasi-static wind influences on the accuracy. Also a serious theory on the estimation of wind gust influences is available (see WP 32 000 and 33 000).

For closed spherical or rectangular enclosures the wind load distribution for checking the overall structural stability under survival wind speeds can be evaluated by the adequate building codes.

For wind loads on the telescope in an open enclosure under operational wind speeds the situation is much more difficult. The enclosure may-depending on the size and shape of the opening as well as the angle of attack of the wind-partly protect the telescope structure against wind effects; but also the edge of the wind slit can enforce vortexes which increase in special wind directions the wind forces. In extrem situations the enforced vortexes can have the same frequencies as the natural frequencies of the structure in a way that resonance occures. For a detailed evaluation of the wind effects and optimization of the wind shielding of an enclosed telescope therefore wind tunnel tests should be foreseen and without those tests only rough estimates could be given by previous experience.

...

Quasi-statical find forces

For a free standing, rear-side cladded parabolic telescope structure the wind pressures on the structure are distributed as follows:

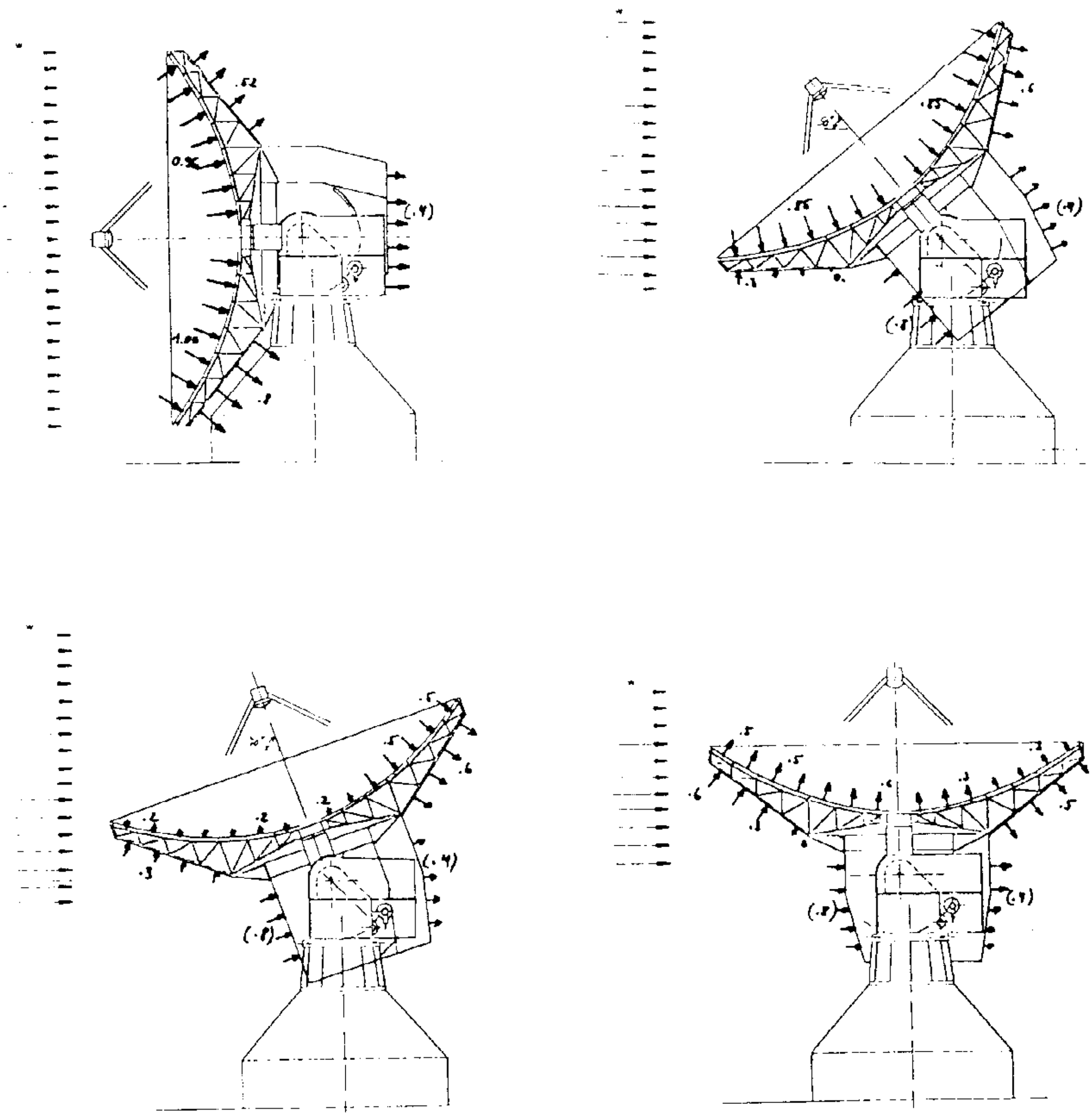

Figure 31.1 Principle wind pressure effects on a

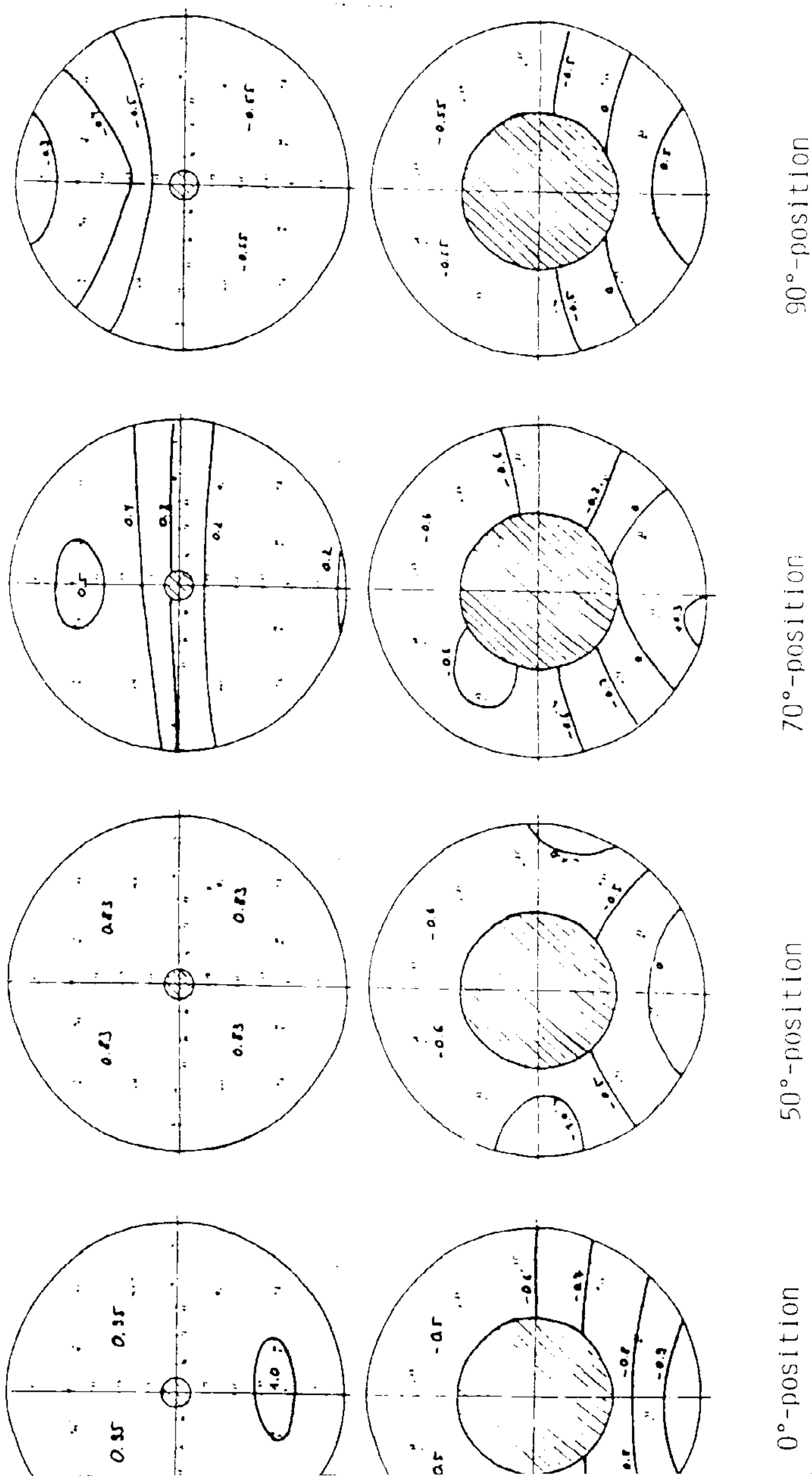

Figure 31.2 Wind load coefficients on a free standing, rear side cladded telescope
Wind from the front

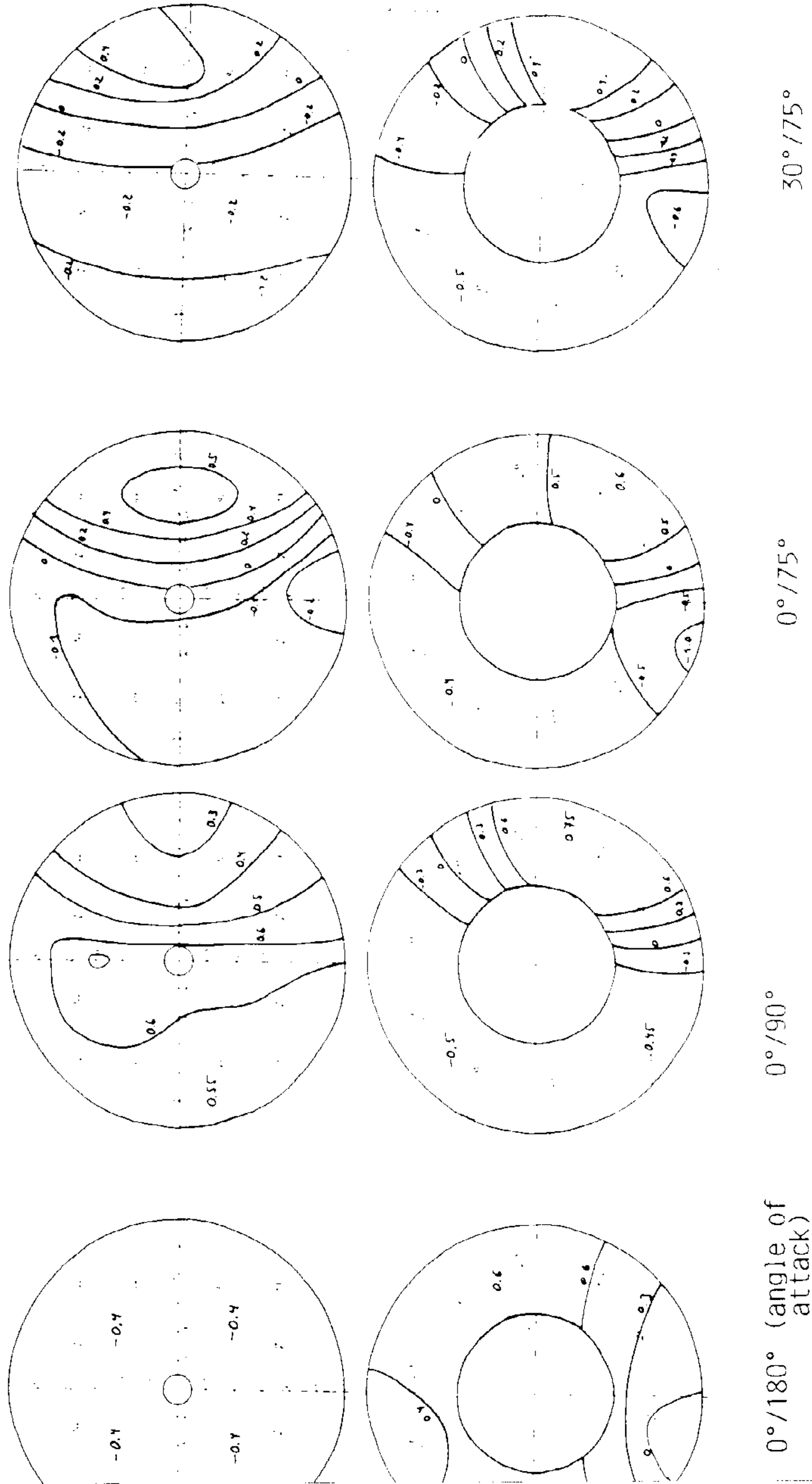

Figure 31.3 Wind load coefficients on a free standing, rear side cladded telescope
Wind from the side

Wind gusts

The effect of wind gusts can be described by standardized ("Davenport") gust spectra which give the energy content of the gusts as a function of the gust frequency.

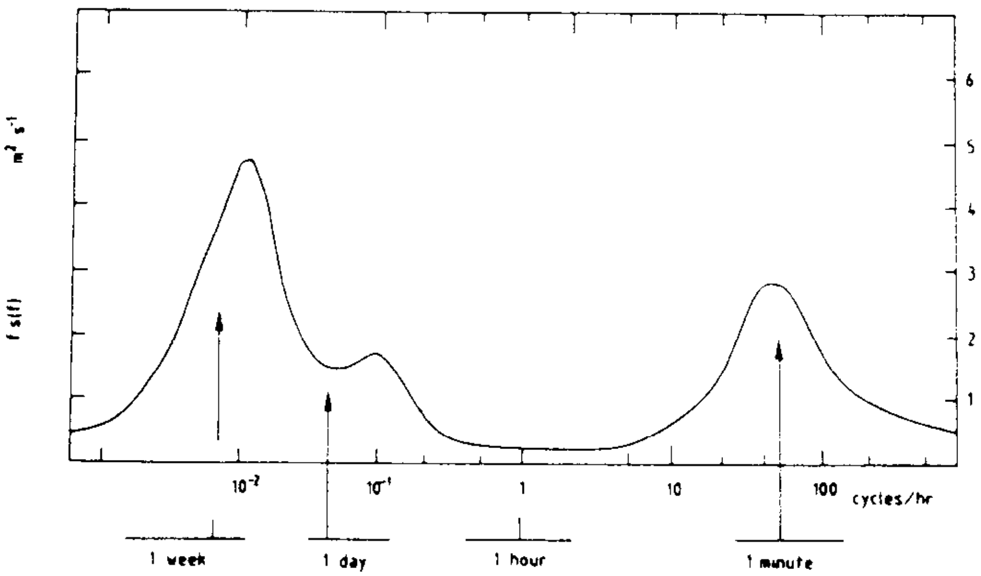

Figure 31.5 Typical power spectral density of the wind gusts in the athmosphere

For applying the gust spectra on a wind exposed structure an aerodynamical transfer function should be used which takes into a account the size and shape of the structure in correlation to the diameter of the gust and as a function of the gust frequency. For the aerodynamical transfer function estimates are available in the literature (see WP 33 000).

The gust spectra itself may be influenced by the surrounding environment. Especially a telescope site on top of a mountain may change the spectra and should be taken into a account in laber phases of the telescope design.

WP 32 000 **Estimates of Wind Effects on the Reflector Accuracy**

- Comment on overall wind effects of the reflector

Figure 32.1 shows a typical distribution of the wind influence on the reflector accuracy of free standing telescopes.

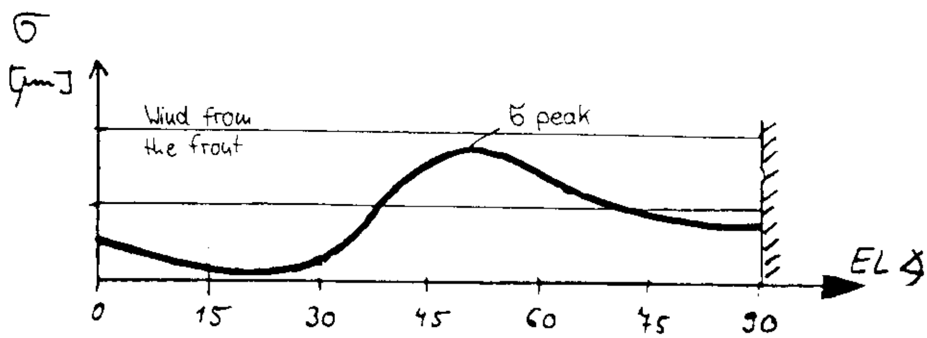

Figure 32.1 Typical reflector accuracy under wind load for a free standing, rear side cladded telescope
σ peak see figure 32.2

The figure is given for wind from the front in all possible elevation angles. Similar figures can be drawn for other angles of attack of the wind. The peak value in the figure above is related to the situation, where the reflector acts like an air plan wing (see WP 31 000) and will not be exceeded in other wind directions and elevation positions. The figures are attained by detailed computer analysis of similar reflectors as the proposed SAO telescopes. In later design phases of the telescopes they should be verified by similar calculations for the final chosen design.

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From figure 32.2 we get the following estimate for the influence of the wind loads on the reflector surface accuracy as a function of the reflector diameter and wind speed.

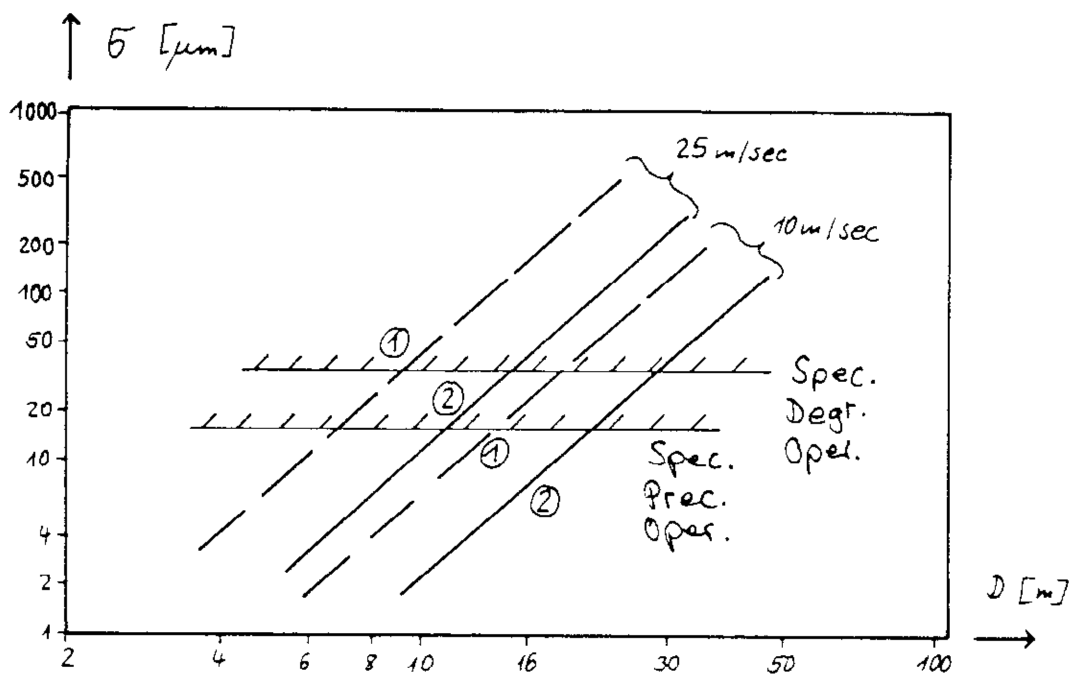

Figure 32.2 Reflector accuracy under wind loads for free standing rear side cladded telescope reflectors

In the diagramm (1) means the RMS value of the reflector deformations under the worst case angle of attack conditions ("Air plane wing" case).

(2) means the Root Summed Square (RSS) value of all possible elevation positions and angles of attack summed over the whole operational range.

...

The estimate is only valid for congruent light weight reflector designs. For other types of reflectors the accuracy level may change.

The envisaged accuracy under quasi statical wind loads as given in figure 32.2 seems adequate to the SAO-requirements for telescope diameters up to 8 m.

For telescopes in an enclosure by adequate design of the wind shielding measures the magnitude of the RSS values (summed over the whole operational range) could be further reduced. If for the enclosed reflector other typs of special flow conditions-similar to the "air plane wing" effect of the free standing telescope-occur, which would lead to other large worst case deformations, depends from the details of the enclosure and slit design and could only be checked in wind tunnel tests.

33 000 Estimate of Wind Effects on the Pointing and Tracking Accuracy

- Estimate of natural frequencies of the telescope alternatives

An estimate of the natural frequencies of all telescope and enclosure alternatives is given in WP 51 000. For the free-standing 6 m telescope with rear side cladding we assume the lowest natural frequency as larger than 6 Hz.

- Establishing of applicable wind turbulance spectra

A survey of wind turbulence spectra taken into account for the evaluation of the wind influence is given in figure 33.1. Curve (1) shows the upper part of the Davenport spectrum. Typically and important from the principle is that the peak - which gives the most powerfull wind gusts - is in a frequency range of 1 minute, whereas the energy content of gusts above 1 second is very low. This means that wind gusts, which can get in resonance with the structural eigenfrequencies - which are all above 6 Hz - have little power and therefore little influence on the telescope (see later).

Curve (2) gives a typical power spectrum in the slit of an open enclosure (example derived from wind tunnel tests). The building shifts the peak of the spectrum to higher frequencies. Also it induces a second peak, which is introduced by vortex excitement at the slit edge. Both effects have a negative influence on the telescope behaviour. Positive is that the maximal values of the peaks are reduced in a way

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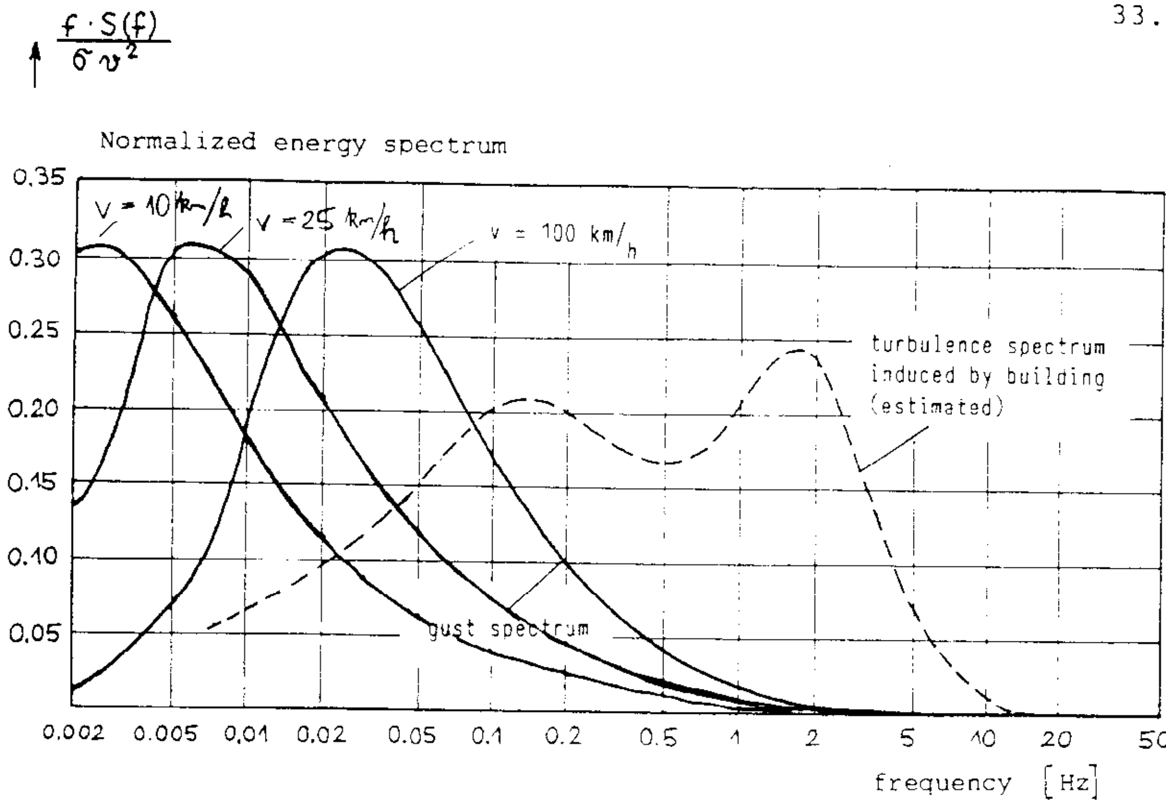

Figure 33.1 Normalized energy spectrum of the athmospheric wind

that the overall energy content of the spectrum in the slit is smaller than the free spectrum. This reduction of the energy content could be enlarged by additional measures like permeable wind screens or similar devices.

Explanations:

f	=	frequency
$S(f)$	=	energy spectrum
v	=	wind speed (5 sec)
$\bar{v}$	=	mean wind speed (10 min)
σ_v	=	standard deviation of the wind speed

Page 33.4

$S_\delta(f)$	=	spectrum of the systems response
$I = \frac{\sigma_v}{\bar{v}}$	=	rurbulence intensity
δ	=	characteristical deformation (eg. pointing error)
$\bar{\delta}$	=	mean (quasistatical) system response, related to mean wind speed

...

- Evaluation of the pointing and tracking accuracy by the response spectrum method

For evaluating the overall pointing and tracking performance we use the energy spectra of above and calculate the response of the telescope structure by its mechanical transfer function. The mechanical transfer fundtion is dominated by the natural frequencies of the structure:

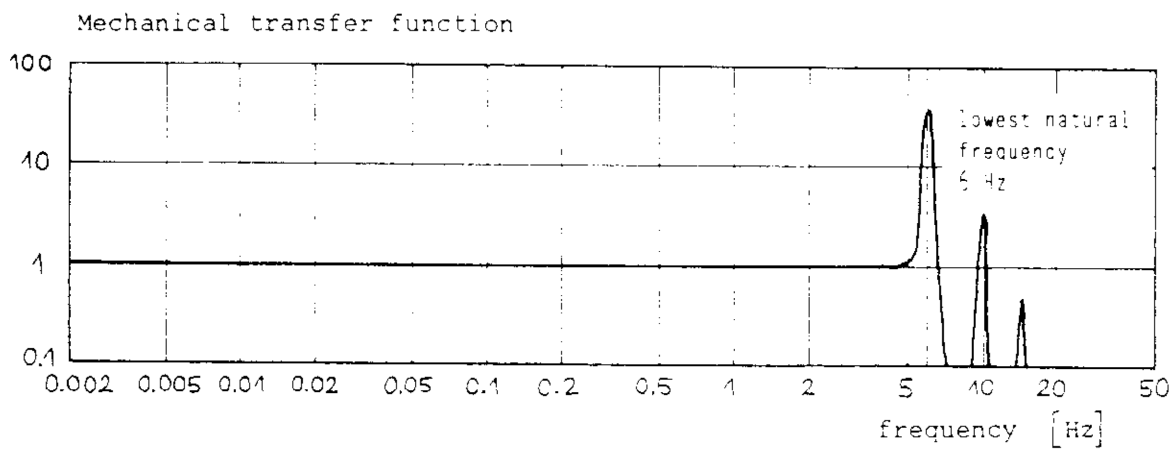

Figure 33.2 Mechanical transfer function of a 6 m telescope with the lowest natural frequency at 6 Hz

Combining the transfer function of figure 33.2 with the gust spectra of figure 33.1 gives the system response spectra as shown in figure 33.3.

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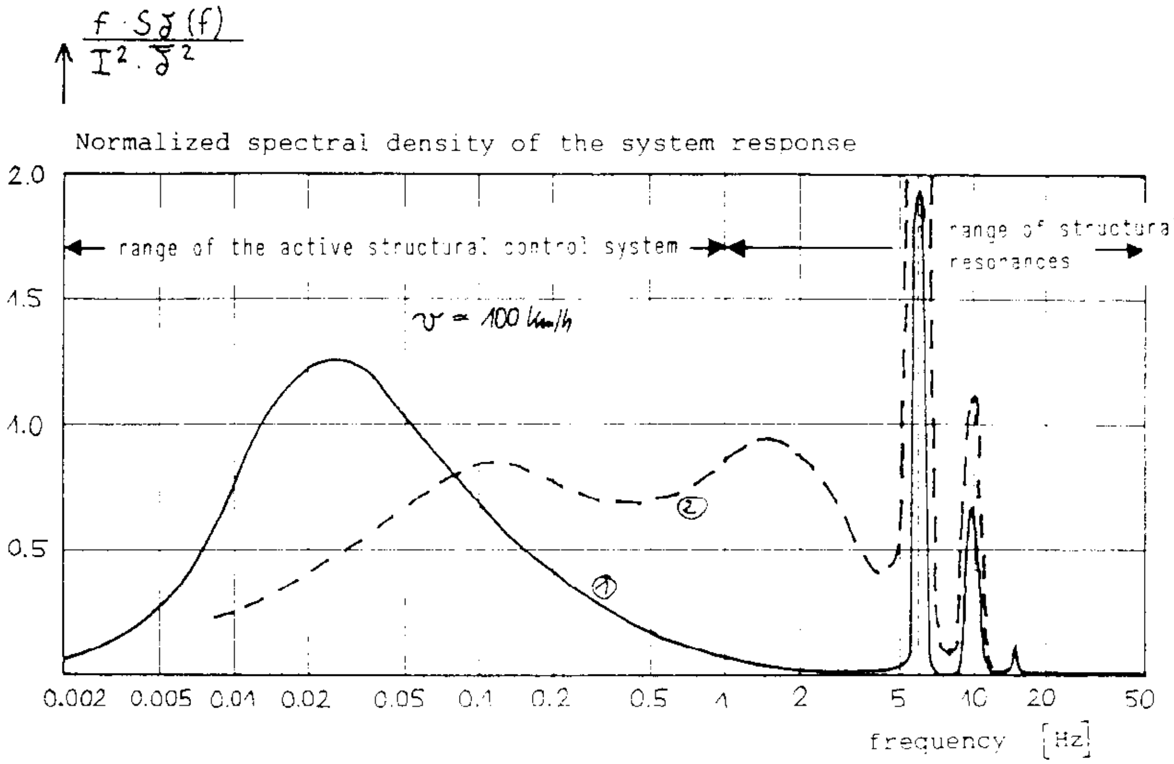

Figure 33.3 Spectral density of the telescope structural response

(1) Freestanding 6 m-telescope

(2) 6 m-telescope in an enclosure (estimated, principle effect)

In the response spectrum for the free standing telescope the peak influences of the gusts are completely separated from the resonance effects of the structure (1) , whereas for the enclosed telescope there is an overlapping zone of both effects (2) . This may be avoidable by more detail design wind shielding measures like special wind screens, but can only evaluated by wind tunnel tests.

From the response spectra of figure 33.3 the overall pointing accuracy can be evaluated by integration of the system response over the frequencies, which results in figure 33.4.

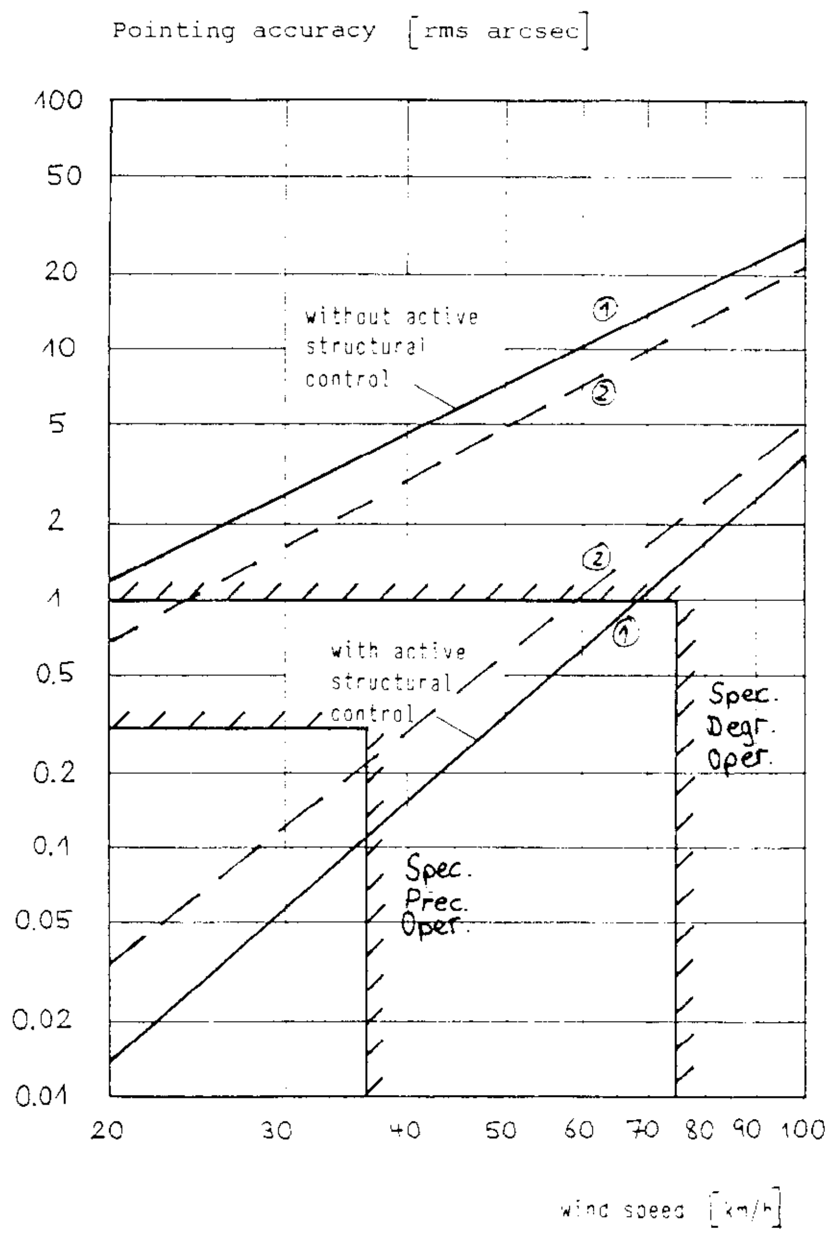

Figure 33.4

Pointing accuracy of a 6 m telescope under wind gusts

(1) Free standing telescope

(2) Telescope in an enclosure

Figure 33.4 shows that without active control devices the pointing error of a free standing telescope - taking into account all frequencies including the low frequent gusts with high energy content - is rather high. For an enclosed telescope with additional screening devices the pointing error will be reduced, but will be still in the range of the SAO specifications.

...

The situation is reversed by compensating the low frequent effects with the servo system ("active structural control"). From the points of frequencies which must be tackled and the bandwidth of adequate servo systems this is not any problem and the related low frequent gust loads could be handled like the quasi-statical wind loads mentioned above. But prior condition for the function of such a system is the adequate design of the sensors and their supports for the axis controllers of the telescope. They must be distributed and applied in such a way that they are able to measure the deflections which should be compensated. Details of the sensor application should be studied in the design phase of the telescopes.

To conclude the comments on the pointing accuracy under wind gusts the dependency of this error of the telescope diameter is sketched in figure 33.5:

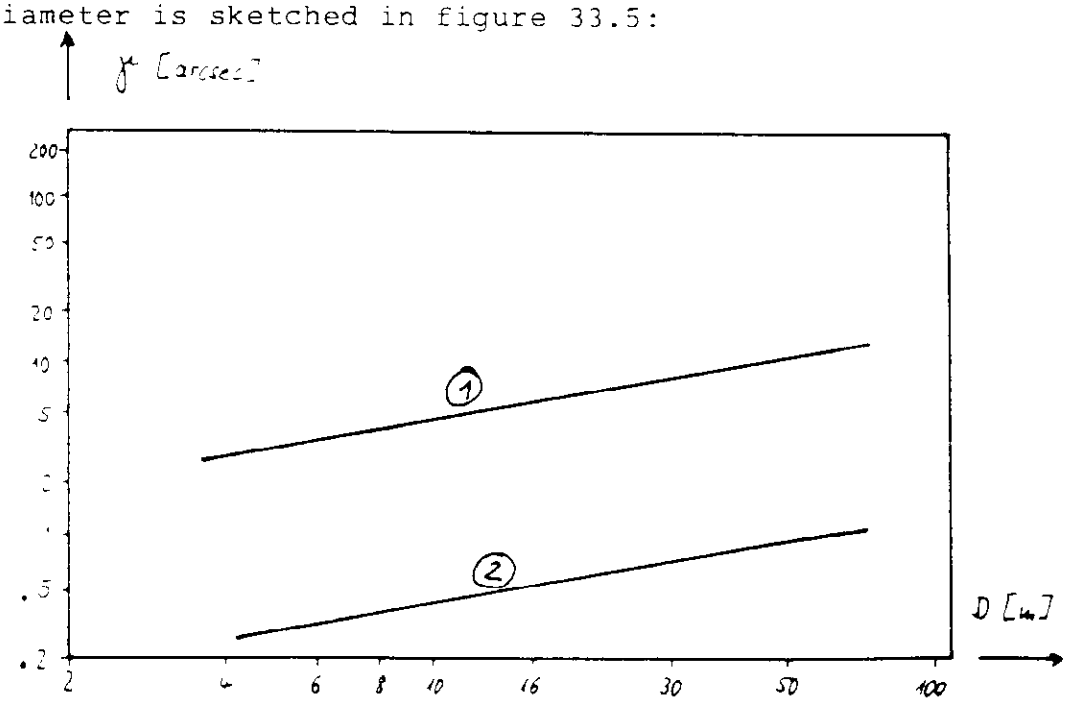

Figure 33.5
Pointing accuracy of a free standing telescope under wind gusts

1 without active structural control

2 with active structural control

It is remarkable, that the pointing error under wind gusts decreases less fast with the telescope diameter than the reflector deformation error (eg. figure 32.2 or 42.4). The reason for this fact is, that the correlation diameter of the gust bubbles, which are related to the frequency at the peak of the power spectrum (figure 33.1) are more of the size of a smaller telescope than a larger one; in other words: that a large reflector integrates and compensates the effect of the small gust bubbles over its surface purely by its size. This is only partly compensated by the advantage of the high natural frequencies of the smaller telescopes.

Therefore - compared with the other environmental influences - a smaller telescope is relatively more endangered to pointing errors under wind gusts than a larger one.

WP 41 000 Temperature Loads

- General comments on temperature influences on telescopes and enclosures

The "Thermal study" has the purpose to investigate the influence of temperature effects on the telescope and its performance, and to give - if necessary - indicatons for special measures which must be taken into account to get an optical system.

Temperature changes have influences on two different parts of the telescope system. They change the surface accuracy of the telescope reflectors by deformation of the reflector surface panels and the reflector backup structure and they change the pointing direction by deformation of the pedestal and the foundation.

The temperature effects should be separated in temperature differences across the structure and temperature changes over the time. The general philosophy of handling the temperature effects is to allow the temperature changes with the time but to controll the temperature differences across the telescope as good as necessary. The temperature distribution across the structure is governed by the thermal balance between all subsystems.

The thermal balance of the system is depending from thermal disturbances coming from the outside environment or from internal heat sources, and from the thermal characteristics of the telescope components itself.

The thermal disturbancies are changes in the temperature of the surrounding air flow, solar radiation during the day and infrared radiation to the black sky during the night. The magnitude of the radiation effects on the structure depends from the absorption and reception characteristics of the structural surfaces. There are two principally different surface treatments in use, white TiO_2-paint or metallic blank aluminized surfaces. Whereas the white paint reflects most of the insolation, it is in the infrared "black" and cools down in a large amount during the night. On the other side the aluminized surface is "white" in the infrared and has a favourable behaviour during the night, but is not so "white" as TiO_2-paint during the day. A surface treatment which combines both advantages is up to now not available and so it should be carefully examined what parts should be painted white and what should be aluminized.

The thermal characteristics of the telescope components is described by the convective thermal time constant, which depends on the convective heat transmission behaviour on the surface and the heat capacity of the component. Light latticed structures have a high convective heat transmission coefficient and relatively low heat capacity and have therefore a short thermal time constant (minutes). Compact and insulated components have a low heat transmission coefficient and a high heat capacity and have therefore a long thermal time constant (hours up to days).

Related to the thermal design of the telescope and its subsystems there are two philosphies possible. One is to protect the system or subsystem by shielding with enclosures, radons, claddings or insulations from the surrounding environment and its disturbancies. Because the shielding prevents the surrounding air having contact with the system, the internal thermal balance must be carefully examined and may it make necessary to control artificially the temperature distribution by an air conditioning or temperature control system.

The controvers philosophy is to design the system or subsystem open and latticed to let the surrounding air going through, which has the effect that all components follow imediately the temperature changes in the environment. Whereas the shielding by an enclosure or radom is the traditional method for smaller raditelescopes and optical telescopes, open air design are used for larger radiotelescopes. Even larger optical telescopes are designed in the last time for quasi-open-air operation to get the thermal balance with the surrounding environment as quick as possible.

- Preliminary estimate of temperature loads

- Definition of temperatur load cases, thermal stability and pointing accuracy

- Thermal conditions during day and night and at portial illuminations

To estimate the temperature effects on the telescope accuracy the following load cases should be taken in mind:

(1) Temperature changes in the surrounding air

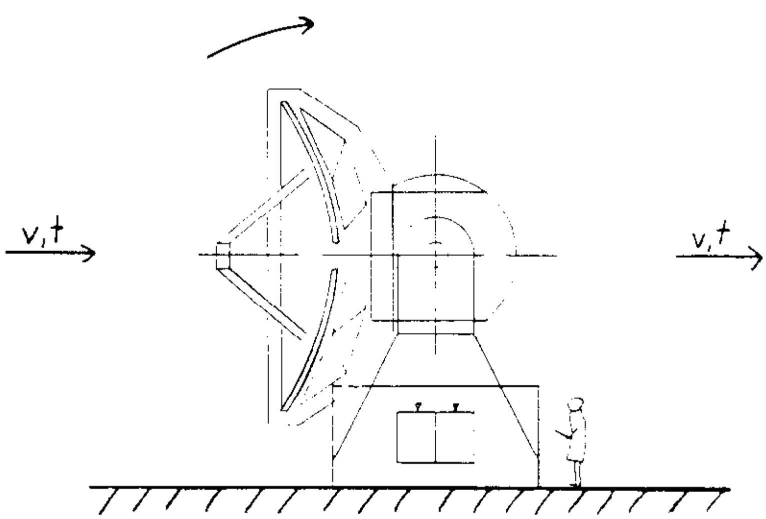

Figure 41.1

Maximal temperature difference between day and night

$$\Delta t_{max} = \pm 10°K$$

Velocity of the air flow

$$V_{air} = 1 \div 10 \text{ m/sec}$$ (Prescision operation[1])

1) Larger velocities (up to 25 m/sec for normal operation) improve the thermal balance.

The convective heat transmission coefficients related to the shape of the cladded telescope will be in the range of:

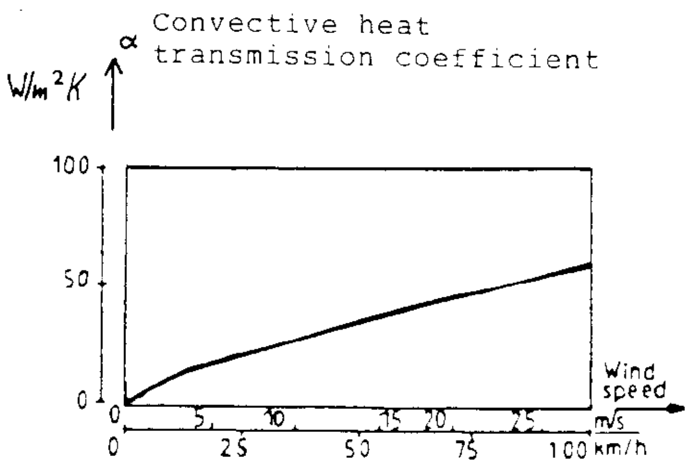

Figure 41.2

② Radiation during the day

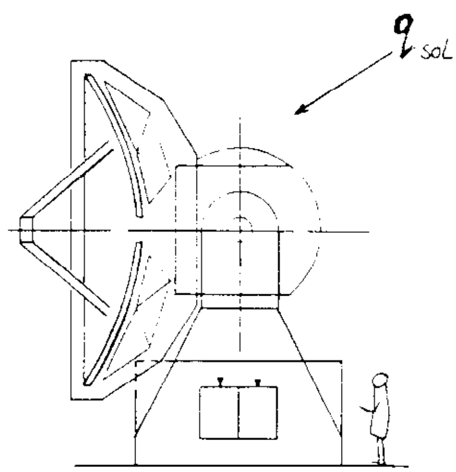

Figure 41.3

Maximal insolation coefficient

$q_{sol} \leq 1200\ W/m^2$ [1)]

(3) Radiation during the night

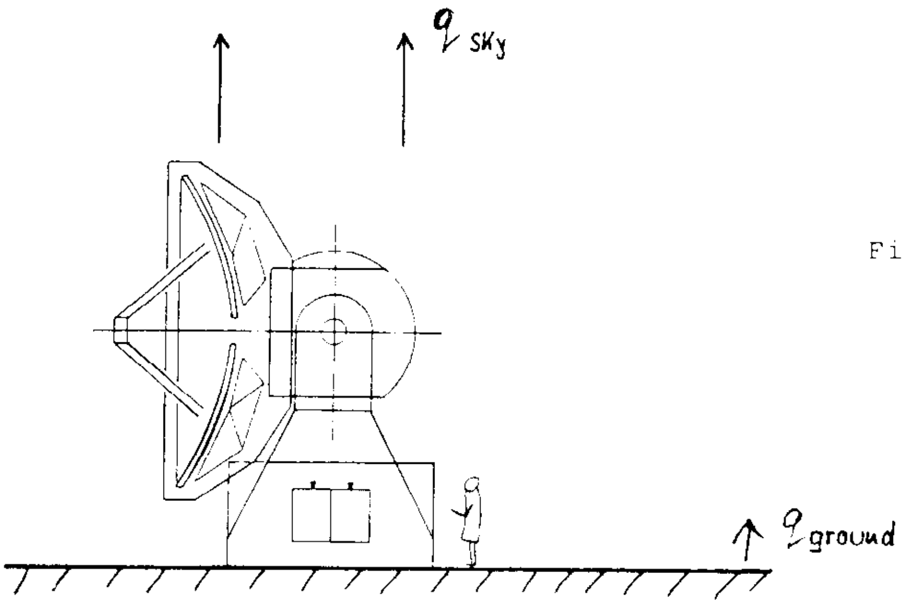

Figure 41.4

Maximal infrared radiation to the sky
(black surface)

$$q_{sky} \leq 400 \text{ W/m}^2 \quad ^{1)}$$

Background radiation of the surrounding ground

$$q_{ground} \sim 300 \pm 100 \text{ W/m}^2$$

1) Radiation coefficient of the black body $5.77 \cdot 10^{-8}$ Watt/m²K^4

- Definition of possible active or passive temperature control systems

From the standpoint of thermal balance and passive control of the temperature across the telescope an latticed structure in the open air combined with adequate treatment of the surfaces is optimal to adapt under operational weather conditions as fast as possible the temperatures of the surrounding environment. On the other side under severe survival weather conditions on the exposed site (presumably on top of a mountain) a protection by an enclosure or shielding is mandatory. Therefore enclosures with a large slit, which protect completely during bad weather and enable quasi-open air conditions during good weather, are the optimal solution. (All large optical telescopes of the last 10 years are designed in such a way). Nevertheless this solution has two disadvantages - to move large masses and to be expensive. That also a free standing telescope with rear side claddings could fulfill all requirements related to temperature effects will be shown below.

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There are two telescope subsystems, which should be - from the temperature point of view - completely different treated. Whereas the reflector system should have in principle the outside temperature, the considerations on the receivers should start with room temperatures for the cabin. Because the outside temperatures are mostly lower than the room temperatures, the aera in the telescope where the temperature differences between receiver cabin, pedestal and reflector system occur, must be specially considered:

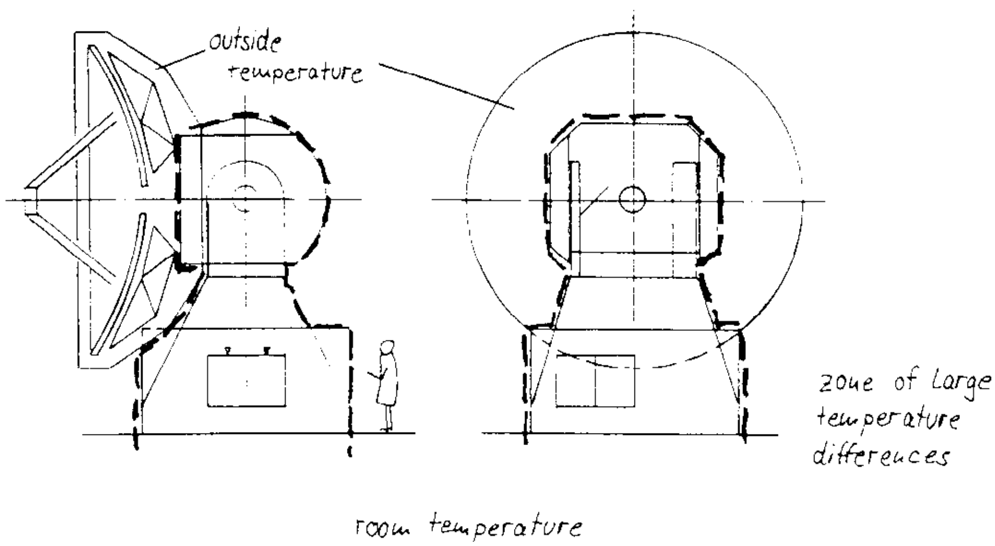

Figure 41.5 Temperature distribution in the telescope system

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Temperature balance in the reflector system

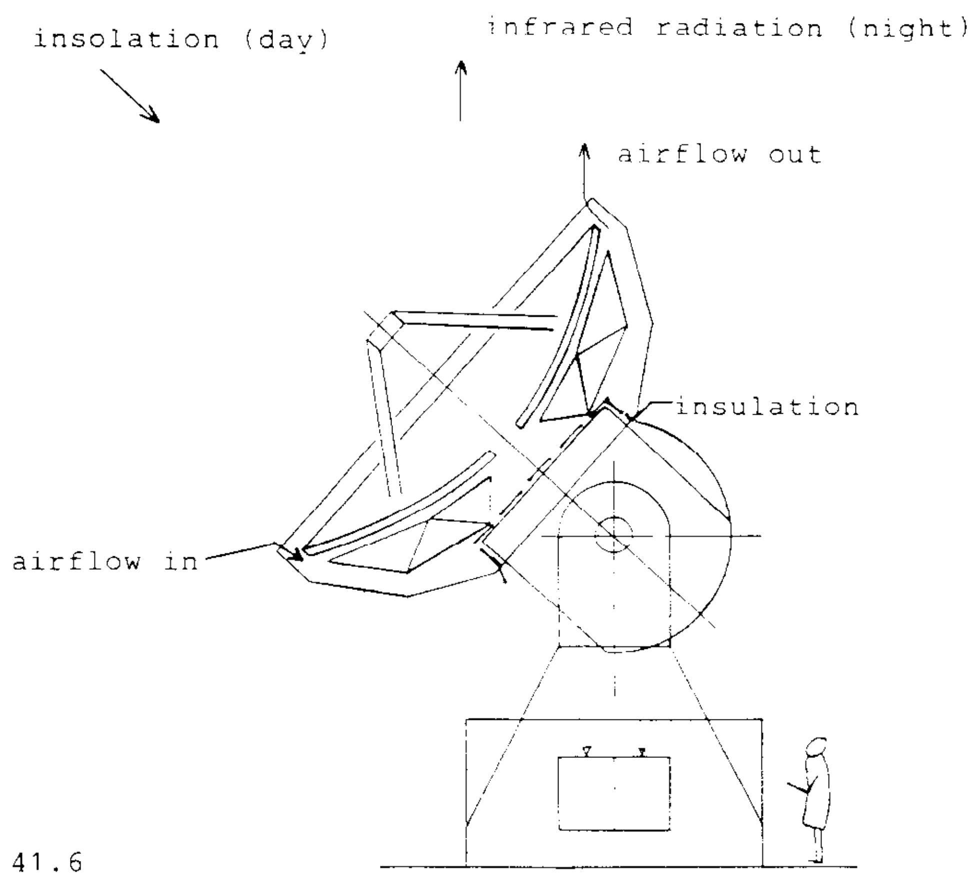

Figure 41.6

The reflector panels are - by their nature - exposed to the outside and protect the front part of the backup structure against radiation. The rear part is protected by the rear side cladding. The energy transport from the outer surface to the backup structure depends from the surface treatment and the insulation properties of the reflector panels and rear side cladding.

...

Typical emission coefficients are:

	new			aged		
	ε^{SO} 6000°C Sun	ε^{IR} 20°C Ambient	$\varepsilon^{SO}/\varepsilon^{IR}$	ε^{SO} 6000°C Sun	ε^{IR} 20°C Ambient	$\varepsilon^{SO}/\varepsilon^{IR}$
White painted	0.12	0.85	0.14	0.50	0.95	0.50
Colour painted	0.65	0.85	0.76	0.88	0.95	0.90
Bright rolled aluminium	0.25	0.08	3.1	0.40	0.20	2.0
Aluminium foil	0.05	0.03	1.7	0.15	0.05	3.0
Non-metallic black surface	0.85	0.89	1.0	0.98	0.98	1.0

A typical heat transfer coefficient of panesl and rear side cladding is

$$k_{clad} = 20 \text{ Watt/m}^2\text{K}$$

With an adequate surface treatment (aluminium foil) it is possible to get the temperature increase (during the day) or the temperature decrease (during the night) of the exposed surface areas to less then

$$\Delta t_{outside} \leq 20 \text{ K}$$

With an exposed area of A 35 m² we get the maximal energy input to the backup structure to

$$\max Q_{refl} = A \cdot k \cdot t = 14 \text{ kWatt! (worst case)}$$

...

This energy input would increase the temperature of the air around the backup structure and thereby the temperature of it itself. By sampling of the warm air in the upper parts it would result in temperature differences between the lower to the upper part of the reflector of 10 to 20 K. To avoid this effect an air circulation and exchange with the outside should be achieved. Therefore a slit at the edge of the reflector between the reflector panels and the rear side cladding should be foreseen. The slit could be protected against rain and snow by a labyrinth typ of sealing. The air flow could be realized by natural convection and the outside wind. Also a shutter in the upper part of the rear side cladding with a ventilator to enforce the air exchange may be necessary and should be examined in the design phase. With these measures an adequate thermal balance of the reflector system is possible and no additional temperature control facilities are necessary.

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Temperature balance in the cabin and pedestal

From the thermal point of view the cabin and pedestal should be seen as one integrated unit which must thermaly be tackled as a whole.

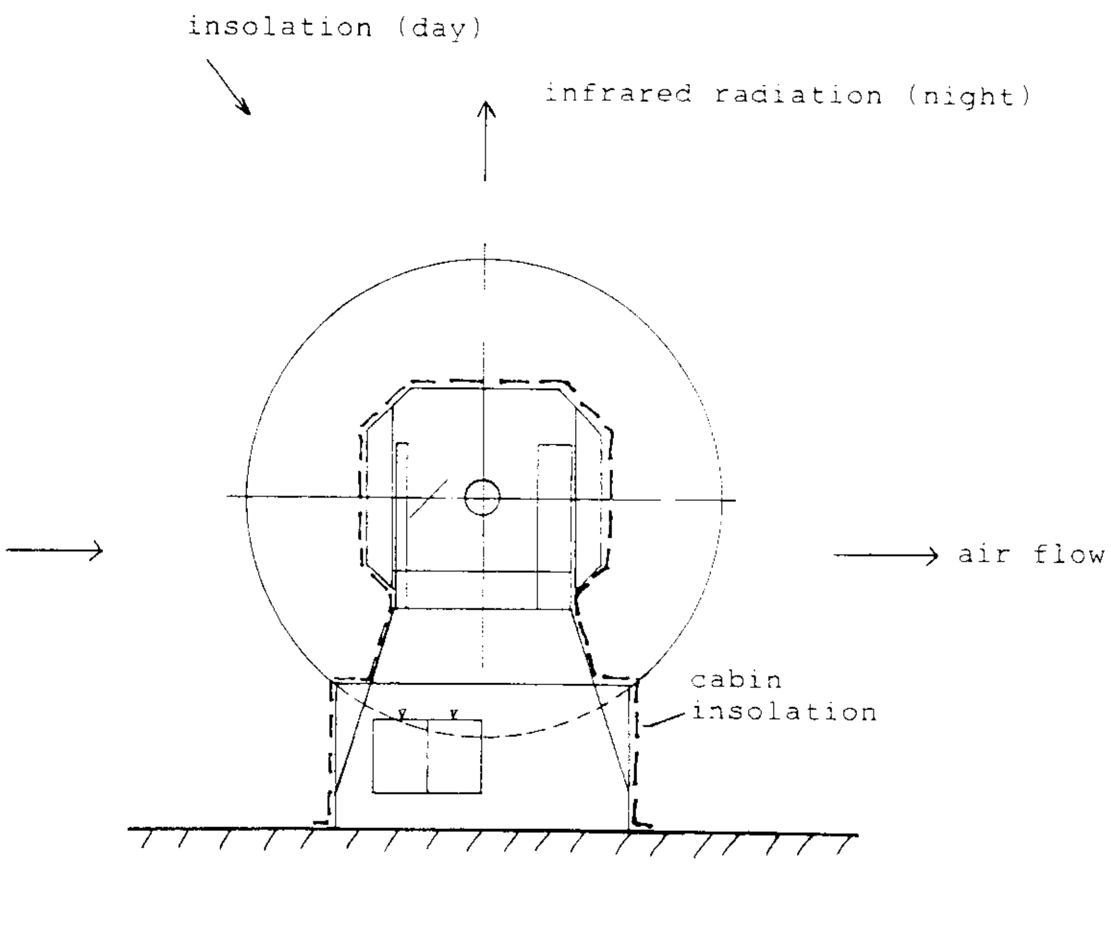


Figure 41.7

Different to the reflector system the internal thermal balance of the cabin and pedestal could not be reached by natural convention or the outside air flow. Therefore the outside cladding of the cabin and pedestal should be insulated as good as possible. Typical heat transfer coefficients of an adequate insolation (4 cm PUR-foam) are

$$k_{insul} = 1 \text{ Watt/m}^2\text{K}$$

With the same outside surface treatment as for the reflector also at the exposed surfaces the temperature increases or decreases are less than

$$\Delta t_{outside} \leq 20 \text{ K}$$

Because the exposed radiation area is less than for the reflector and the insulation is better the maximal heat input is only

$$\max Q_{cab} = A_{exp} \cdot k_{insul} \cdot t = 0{,}5 \text{ kWatt}$$

On the other side during cold nights temperature differences between the outside and the cabin of up to 40 K may be possible which result in a heat flow to the outside of

$$\min Q_{cab} = A_{outs} \cdot K_{insul} \cdot t = 3 \text{kWatt}$$

...

The energy budget of the system could be tackled with a small air conditioning system located in the cabin with a heating capacity of 3 kWatt and a cooling capacity of 0.5 kWatt. The air conditioning system should also ensure an enforced air flow through the cabin and pedestal to avoid temperature layers. By a duct system the warmer air in the upper part of the pedestal could be removed by suction and after treatment in the conditioning unit blown to the lower part of the cabin.

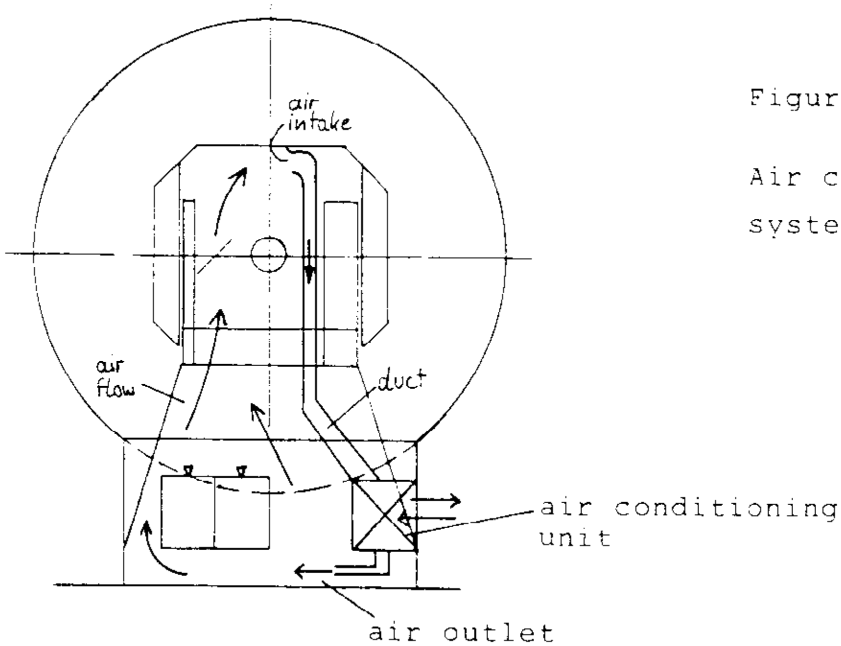


Figure 41.8

Air conditioning system

With a standard air conditioning unit a temperature uniformity in the range of 1 to 2 K could be achieved. With an improved system this value could be brought to less then 0.5K. Details should be examined in the design phase.

...

WP 42 000 Estimates of Temperature Effects on Reflector Accuracy and Pointing

- Comment on reflector deformations due to temperature loads

Temperature deformations of the reflector surface are influenced by two effects, the temperature deformations of the reflector surface panels itself and the temperature deformations of the back-up structure:

Temperature deformations of the reflector panels

The panel business is more seriously handled in the reflector study and so here only some principle comments are made.

Panel deformations due to temperature effects occur when - by radiation effects during the day (insolation) or during the night (infrared radiation to the sky) - the front panel surface accepts another temperature than the rear side surface. The magnitude of possible temperature differences depends on the reception and emission behaviour of the front and rear side surface treatment and the heat transmission behaviour of the panel and from the thermal features of the backup structure and its rear side cladding. For the panel surface treatment and heat transmission behaviour data are given in the reflector study.

If all thermal measures are done adequately as described in WP 41 000 under worst operational weather conditions maximal temperature differences between the front and rear side of 2K may occur. If the thermal deformations are not obstructed

...

by the panel supports, this results in a change of the panel curvature dependent on the thermal elongation coefficient of the panel top and bottom layer material. For a typical flat panel of 50 mm thickness we would get the following curvature radic:

$$\rho = \frac{50\ \mathrm{mm}}{2K.23.10^{-6}/K} = 1.1\ \mathrm{km} \quad \text{for aluminium}$$

$$= \quad ./. \quad = 2.1\ \mathrm{km} \quad \text{for steel}$$

$$./. \quad = 20.8\ \mathrm{km} \quad \text{for CFRP}$$

For a uniform 6 m-reflector stell with a focal length of 2.4 m this effect would result in a change of the focal length ot

$$\Delta f = 5.2\ \mathrm{mm} \quad \text{for aluminium}$$
$$= 2.7\ \mathrm{mm} \quad \text{for steel}$$
$$= 0.3\ \mathrm{mm} \quad \text{for CFRP}$$

For a segmented reflector the related deformation pattern of the surface depends on the reflector panel arrangement, the size of the panels and the arrangement and typ of panel supporting screws. Typical for the panel arrangements as suggested in WP 21 000 are deformation patterns shown in figure 42.1. In the sketches it is assumed that the panel supports are designed in such a way that they do not obstruct the thermal deformations of the panels.

...

Segmented with central monolith

Segmented all

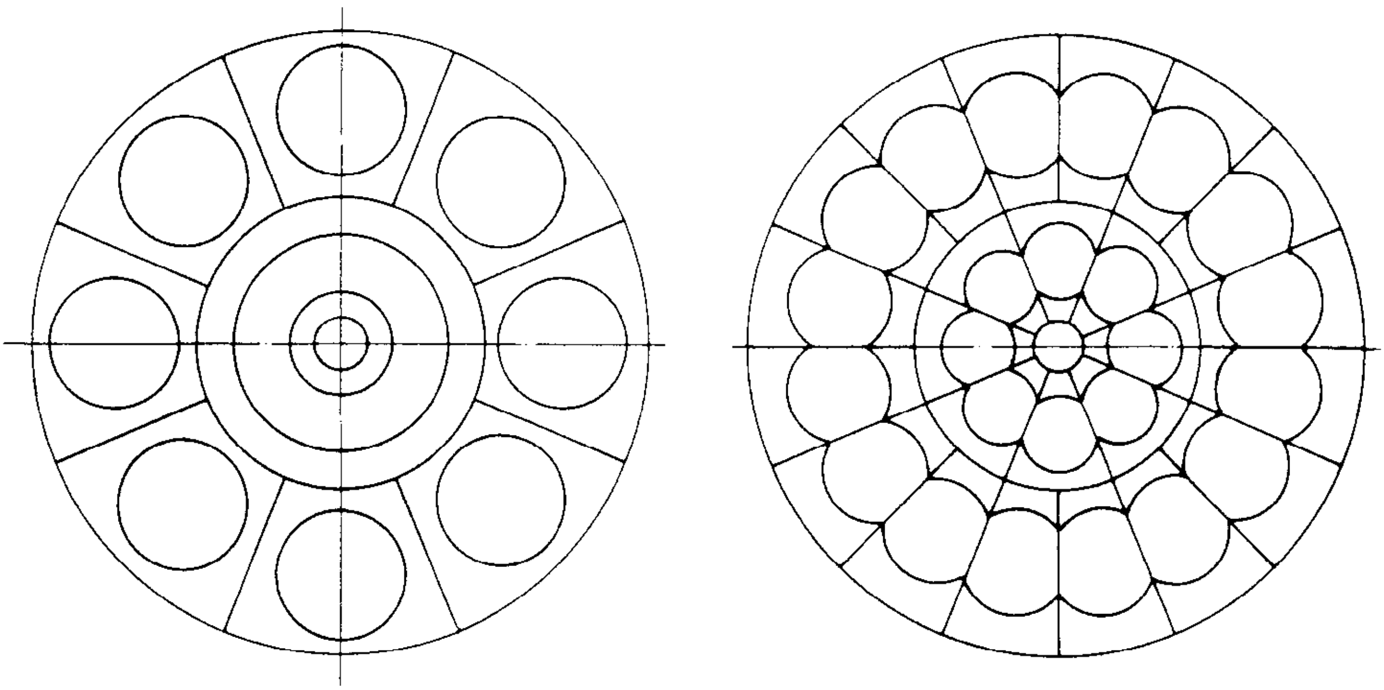


Figure 42.1 Typical deformation patterns of segmented reflector surfaces

Typical deformation values for the 2K load case mentioned above are:

size of the panel	aluminium	steel	CFRP	
0.75 m	120	66	6	peak (3σ) values in μm
0.5 m	57	30	3	
0.75 m	40	22	2	RMS (σ) values in μm
0.5 m	19	10	1	

Figure 42.2 Reflector accuracy due to panel deformations under temperature load (2K accross the panel thickness) $d = 50$ mm

by the panel supports, this results in a change of the panel curvature dependent on the thermal elongation coefficient of the panel top and bottom layer material. For a typical flat panel of 50 mm thickness we would get the following curvature radic:

$$\rho = \frac{50 \text{ mm}}{2K.23.10^{-6}/K} = 1.1 \text{ km for aluminium}$$

$$= \quad ./. \quad = 2.1 \text{ km for steel}$$

$$./. \quad = 20.8 \text{ km for CFRP}$$

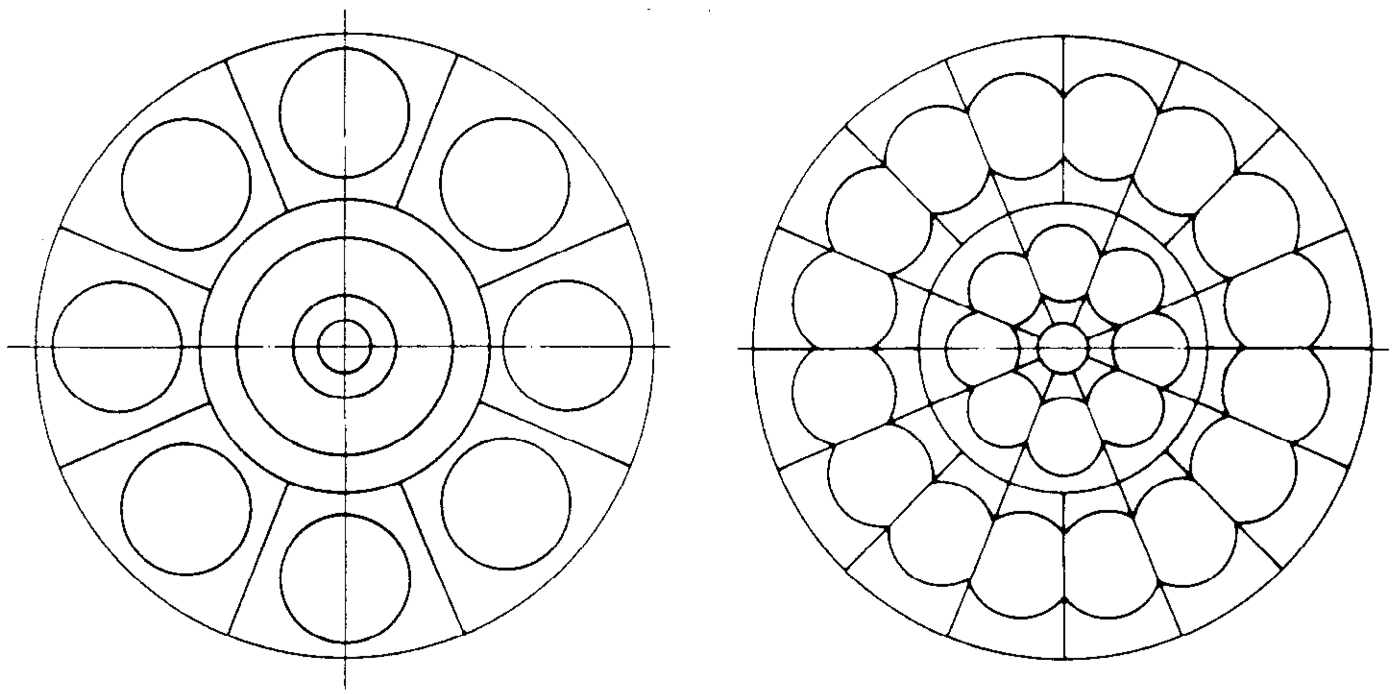
For a uniform 6 m-reflector stell with a focal length of 2.4 m this effect would result in a change of the focal length of

Δf = 5.2 mm for aluminium
= 2.7 mm for steel
= 0.3 mm for CFRP

For a segmented reflector the related deformation pattern of the surface depends on the reflector panel arrangement, the size of the panels and the arrangement and typ of panel supporting screws. Typical for the panel arrangements as suggested in WP 21 000 are deformation patterns shown in figure 42.1. In the sketches it is assumed that the panel supports are designed in such a way that they do not obstruct the thermal deformations of the panels.

...

Segmented with central monolith   Segmented all



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0.5 m	19	10	1	

Figure 42.2 Reflector accuracy due to panel deformations under temperature load (2K accross the panel thickness) $d = 50$ mm

...

The deformation values given in figure 42.2 depend except the temperature difference and the material properties only on the panel size, not on the overall reflector diameter.

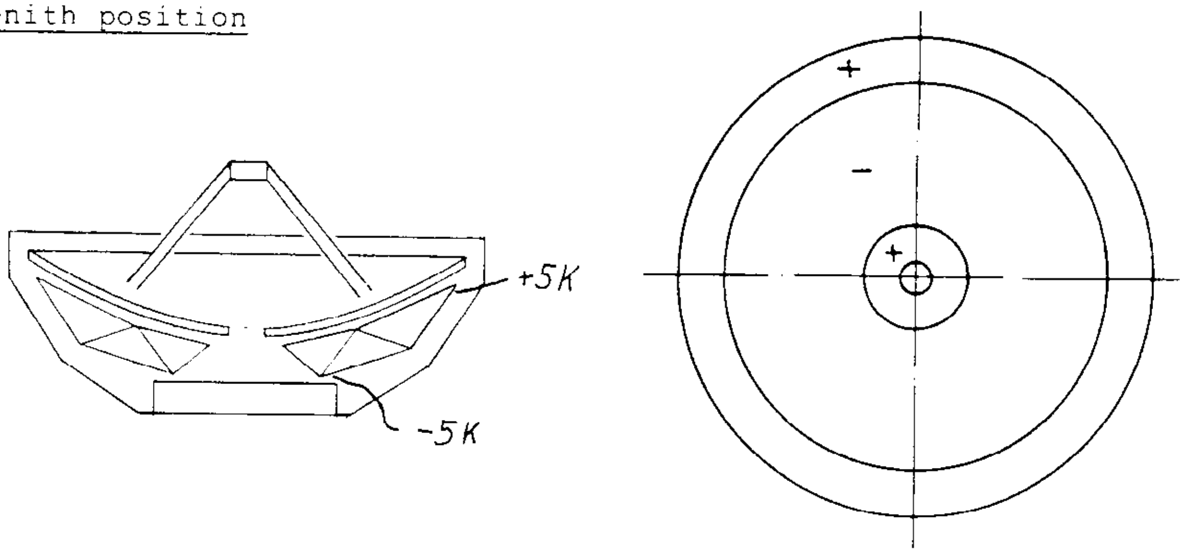
Figure 42.2 clearly indicates the advantages of the CFRP panels for a submillimeter-telescope. Aluminium panels would have no chance to come in accuracy regions, where the thermal deformations would contribute an adequate shave to the overall error budget.

Temperature deformations of the reflector backup structure

For the reflector backup structure a great variety of temperature distributions are possible. To catch the principle effects first two characteristical distributions with related characteristical deformation patterns are considered (figure 42.3). In zenith position a temperature distribution occures with warm air at the front chards of the backup structure and cold air at the rear chards during the day. In horizontal position a similar situation occures with warm air at the upper half and cold air at the lower half of the structure. During the night the reversed effect is less severe because the infrared cooling of the upper part of the panels and rear side cladding is partly compensating the sampling of warm air in the upper part of the backup structure.

...

Zenith position



Horizontal position

related deformation patterns

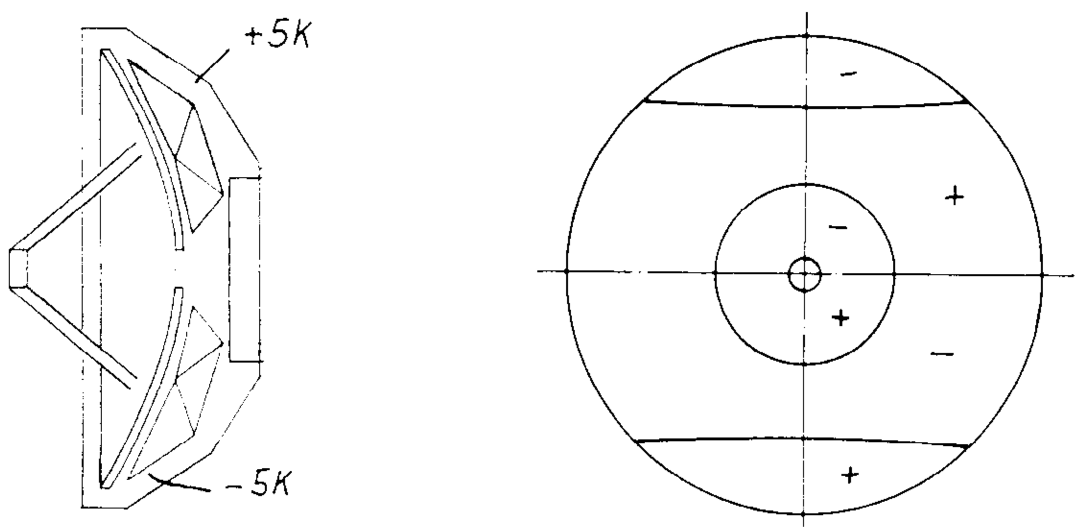


Figure 42.3 Typical temperature deformation patterns of the backup structure

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From finite element calculations as well as measurements under daytime conditions of previous designed and errected telescopes we get the following estimate for the influence of the temperature deformations of the backup structure on the surface accuracy.

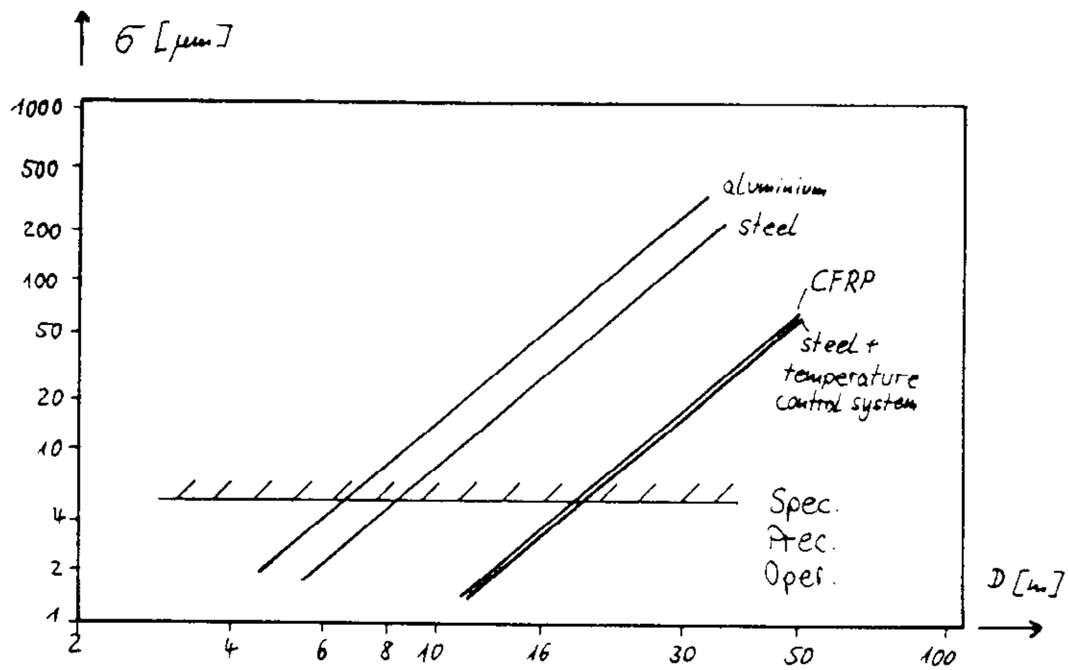

Figure 42.4 Reflector surface accuracy under temperature loads on the backup structure of free standing rear side cladded telescopes

Figure 42.4 indicates, that from the view point of temperature deformations for the backup structure of the 6 m SAO telescope a CFRP solution is not mandatory and that a steel version is sufficient.

...

- Comment on pointing effects due to temperature loads on reflector and pedestal

Influence of temperature deformations of the reflector backup structure on the pointing

The tilts of the reflector surface related to the deformations explained in figure 42.3 and evaluated in figure 42.4 are estimated in figur 42.5

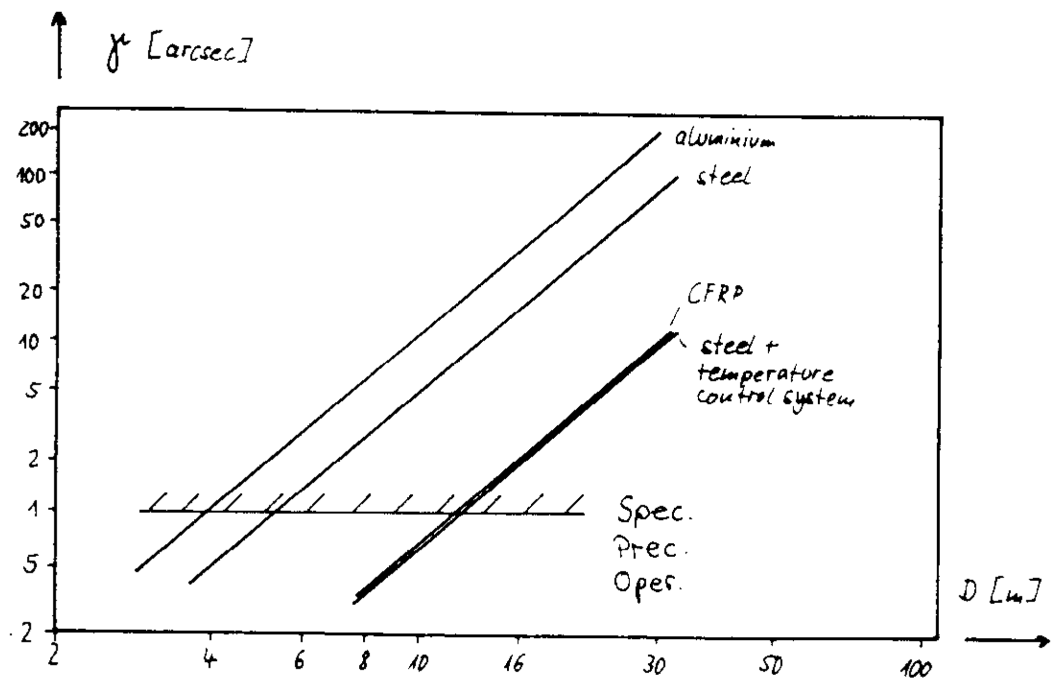

Figure 42.5 Pointing errors under temperature loads on the backup structure of free standing rear side cladded telescopes (peak values 3σ)

...

Unlike the overall surface accuracy considered above for the pointing effects the differences in temperature deformation behaviour are significent between the aluminium or steel structures and the CFRP or temperature controlled steel structure. Alu or steel should not be used without additionally temperature control facilities. If the CFRP structure is rejected as to expensive, the pointing effects due to temperature differences can be identified for a steel structure by a temperature monitoring system and easily introduced as correction factors in the final pointing model of the servo system (see WP 23 000).

Temperature deformations of the pedestal and foundation

The pedestal, which is a mostly from outer influences isolated system, can be handled different from the backup structure. Due to its function as reciver cabin it will be equiped with an air conditioning system (WP 41 000). By experience it is no problem and especially no cost increasing requirement to design the air conditioning system in such a way that a thermal homogenity of 0.5 K (3 value) it is achieved. (This should be verified by thermal calculations in the definition phase.) Such a system can redunce the effects on the pointing to less than

$$\Delta\gamma_{\text{pedestal}} \leq 0.5 \text{ arcec} \quad (3\,\sigma \text{ value})$$

Nevertheless for redundance some temperature monitoring sensors should be introduced to have , together with those at the main reflector, a complete overview on the thermal status of the telescope system during operation.

...

WP 51 000 Final Comments and Recommendations

In the sketches and tables on the following two pages a comparison of the sizes, proportions and the main structural parameters are given for the 4 alternatives, investigated at the beginning of the study work.

Later on in the study the main effort was laid on the investigation of an open air telescope, because:

- it is obvious, that the enclosed telescope lay outs are havier, in operation not more comfortable and more expensive in investment as well as maintenance
- it is feasible to fullfill all specified accuracies
- the exposed main reflector surface (the main disadvantage of the open air design) could be tolerated regarding the most severe weather influences under survival conditions.

The recommended telescope lay out is described on the last page of this work package.

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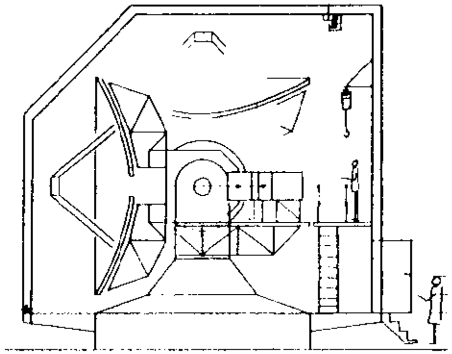
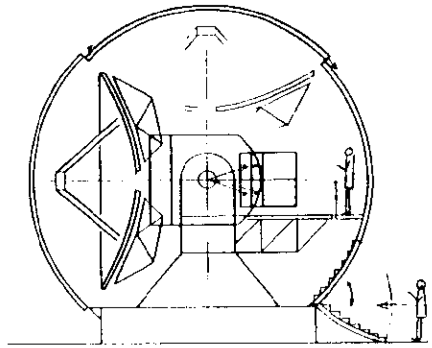
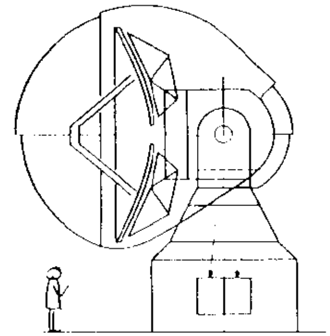
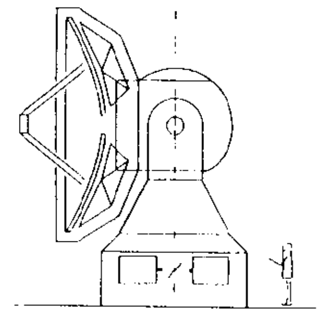
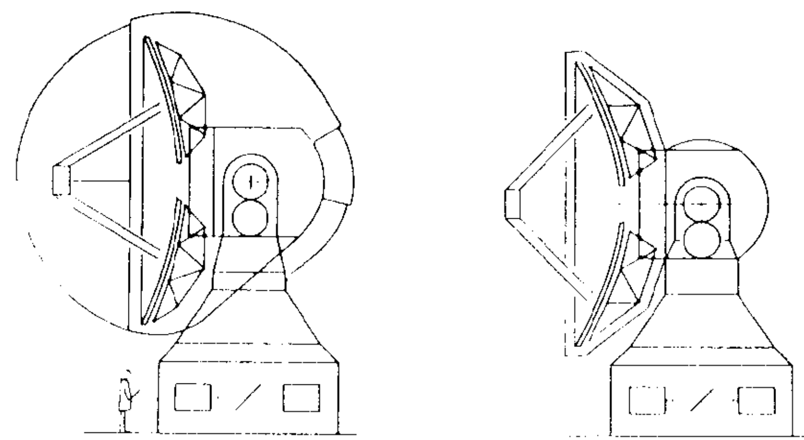





of osure	Co-rotating building	Independent rotating building	Integrated reflector cover	Rear-side cladding
her ection	all	all	all	Main reflektor + sub-reflector exposed
cal ngement	Classical Nasmyth	Modified Nasmyth (horizontal)	Modified Nasmyth (vertical)	Coudé
er of ecting Surfaces	4	4	4	7
ngement of iver Boxes	6 on 2 platforms	4 in a cube	4 in a cube	4 in a circle
of Reflector ort	Central Hub	Yoke + Whiffle trees	Yoke + Whiffle trees	Yoke + Whiffle trees
st Natural uency imated)	8 Hz	7 Hz	5 Hz	6 Hz

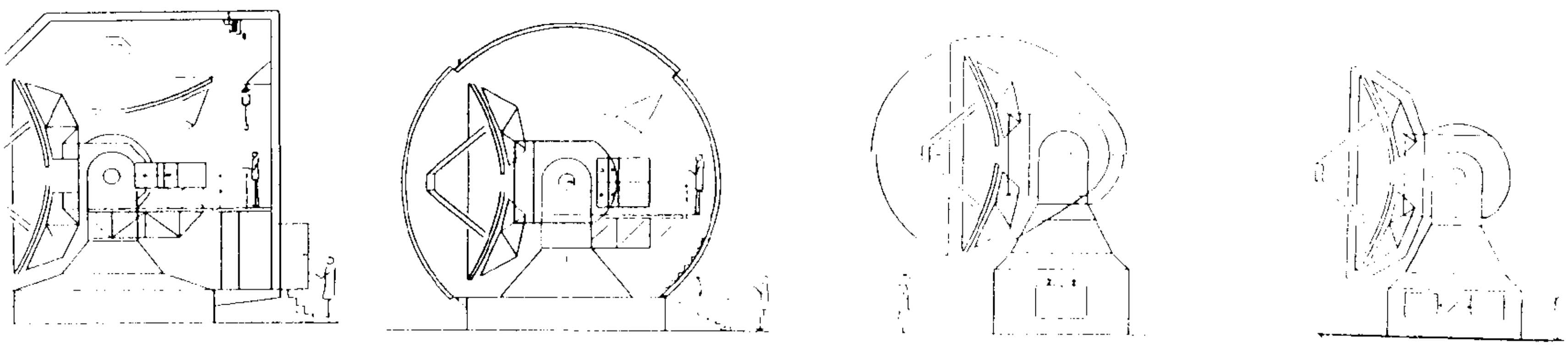
Smithsonian Astrophysical Observatory
Submillimeter-Wavelength Telescope Array

Comparison of Sizes

D = 8 m



D = 6 m



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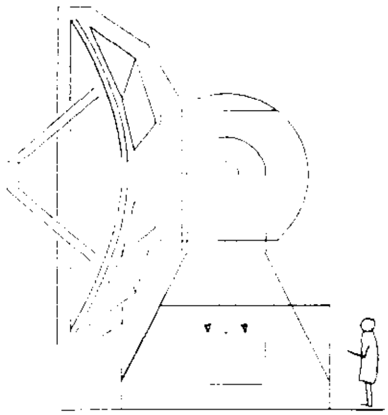
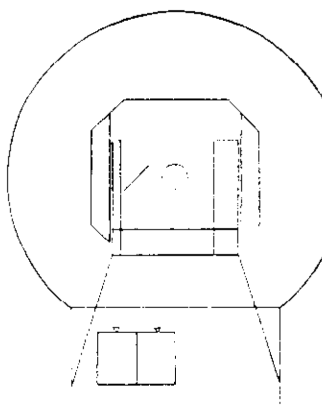
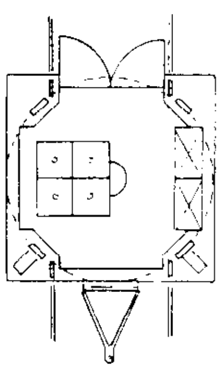
Technical Data of the Recommended Lay Out







Type of Enclosure	Rear-side cladding
Weather protection	Main reflector + subreflector exposed
Optical arrangement	Modified Nasmyth (vertical)
Number of Reflecting surfaces	4
Arrangement of Receiver boxis	4 in a bundle
Reflector Diameter	6 m
Type of Reflector support	Yoke + whiffle tree
Elevation Bearings	Ball bearing
Elevation Drives	Pinion-gear-rim
Azimuth Bearings	Wheel-on-track + pintle bearing
Azimuth Drives	Friction wheel
Transportation Systems	Wheel-on-rails, tractor
Weight	8 t
Frequency	7 HZ

...

WP 52 000 Revised list of specifications

The list of specifications given in WP 11 000 is arranged under the aspects of the operational requirements of the telescope. They cover all aspects: general data, environmental conditions, accuracies, computer control, handling and instrumentation.

To make clear what of those data are essentials for the performance of the telescope as submillimeter-facilities, all effects which contribute to the error budgets are arranged in the following tables and identified with their cause. These contributions will be measurable during the manufacturing process of the related parts or during the commissioning phase of the system itself.

Reflector error budget

(Precision operation)

Panel manufacturing		7 µm	*)
Panel alignment		7 µm	
Gravity	deformations	5 µm	
Temperatur	under operational	5 µm	
Wind	conditions	5 µm	
Subreflector total		5 µm	
Contingency		5 µm	
	total	15 µm	

*) RMS values added as RSS

...

Pointing error budget

(Precision operation)

Encoders	0,5 arcsec *)
Controller	0,3 arcsec
Wind	0,3 arcsec
Temperature	0,5 arcsec
Contingency	0.5 arcsec
	1,0 arcsec

*) 3 σ values added as RSS

Whereas the reflector errors of page 52.2 should be interpreted as absolute errors related to a best fit parabolic of the reflector surface, the above listed pointing errors should be interpreted as the non-repeatable components of the overall effects. The repeatable ones, which may be of higher magnitude, should be actively compensated by the servo system via a pointing model. To get the high accuracies, the temperature and wind deformations should be monitored as described in WP 30 000 and WP 40 000 and introduced in the pointing model procedure.

...

WP 61 000 Cost estimate Definition Study

We estimate the costs for a serious definition on study of the complete telescope system (alternative V of WP 22 000 excluding the reflector system, as described by MAN Technology) to

450.000 $

The estimate includes the following:

- Basic engineering
- Definition drawings and spezifications of 15 subsystems
- Engineering analysis of the complete system
- Workplaning and quality assurance planing
- Documentation and travels

As a result of the definition study all telescope subsystems will be defined in such depth, that the function and performance is described for each subsystem and that the costs for the realization could be estimated in an accurancy range of better than 10 %.

For the system alternatives with enclosure the costs for the Definition study would be ~ 30 % larger.

WP 62 000 Cost estimate

Design Study

We estimate the costs for a serious Design Study of the complete system (alternative V of WP 22 000 excluding the reflector system as described by MAN Technology) to

600.000 $

The estimate includes the following:

- Detail engineering
- Workshopdrawings, specification part lists for the subsystems
- Verification of the engineering anaylsis
- Documentation and travel

As a result of the design study all telescope subsystems could be procured and manufactured. The documentation will be given in such depth that the costs for the realization could be definitly calculated and fixed.

For the system alternatives with enclosure the costs for the Design Study would be ~ 30 % larger.

WP 63 000 - 66 000 Cost estimate

- Manufacturing
- Assembly
- Testing
- Operation

We estimate the costs for one telescope unit (alternative V of WP 22 000 excluding the reflector system as described by MAN Technology) to

2.000.000 $

The estimate includes the following:

- Manufacturing of all subsystems incl. servo
- Assembly of all subsystems
- Assembly, commissioning and testing on site

The estimated costs are assumed to be in an accuracy range of 20 %, supported that the scope of supply is equivalent to the systems described in this study.
No contingencies for remote sites are included.

For the system alternatives with enclosure the costs for the realization would be 20 to 40 % larger

WP 67 000 Site influence of costs

- Comments to cost driving site conditions

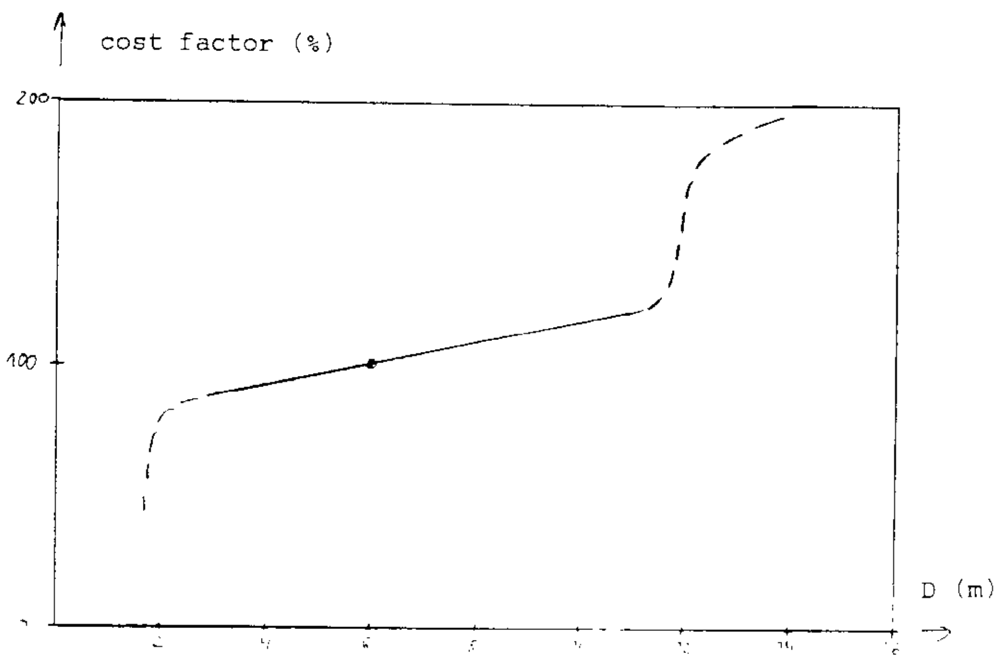
Remote sites have the following additional cost driving influences:

- accessibility (roads, assembly platforms, etc.)
- transportation of material and staff
- accommodation of staff
- industrial infrastructure and services in the vicinity (general services, repair shops, parts manufacturer, cranes etc.)
- reduced personal performance at high altitudes

Reliable estimates of the additional costs could only be made, if more details of the selected sites are known.

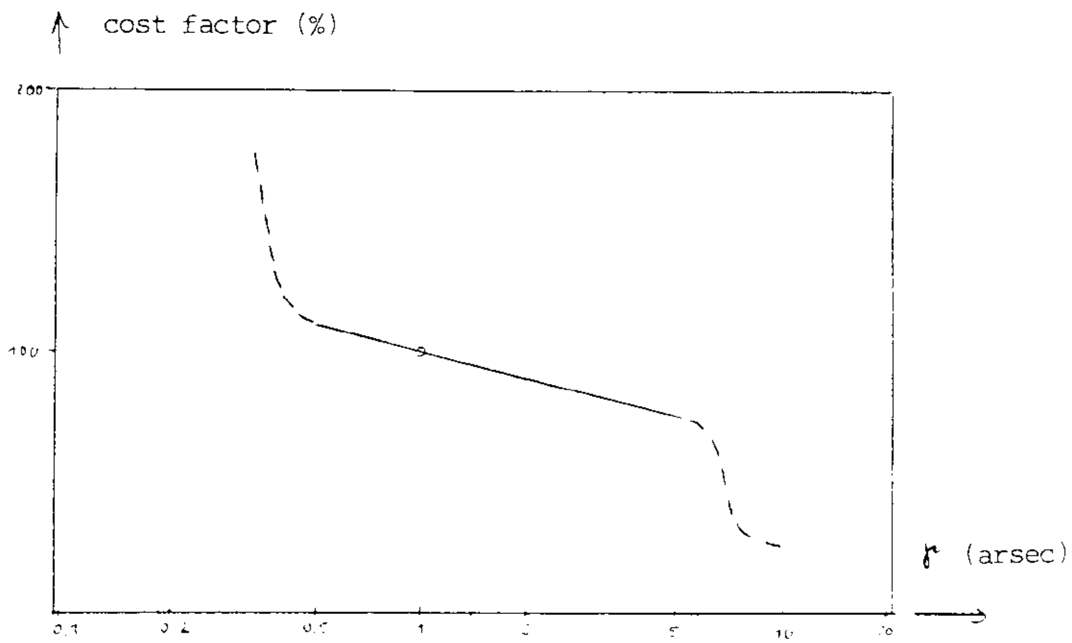
WP 68 000 Cost parameters

- aperture size



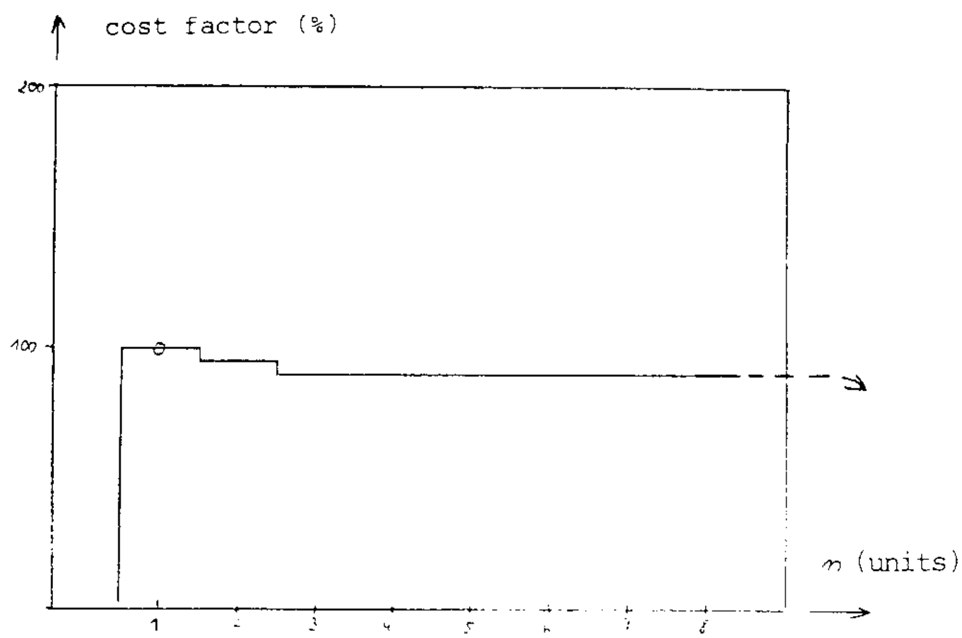
WP 68 000 Cost parameters

- precision



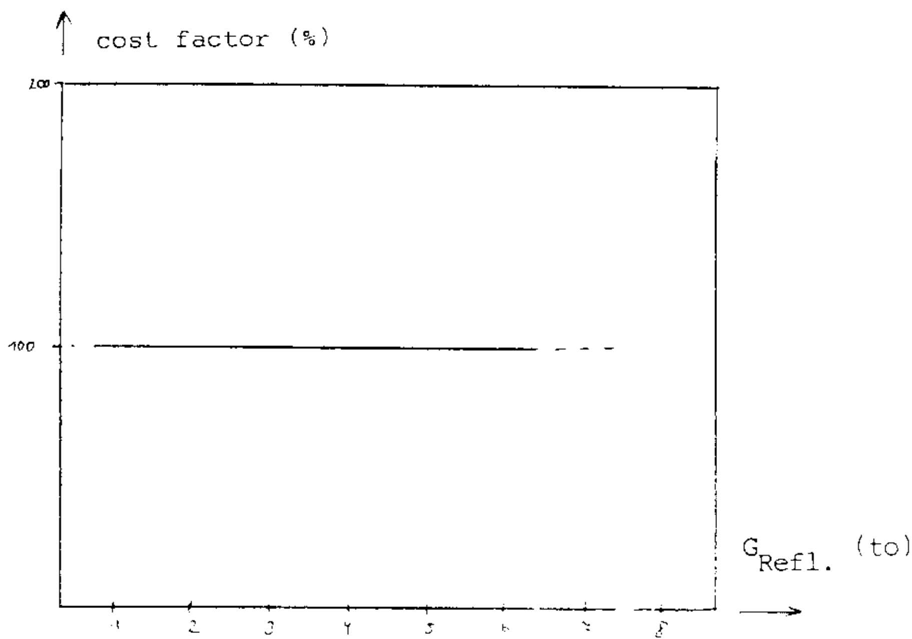
WP 68 000 Cost parameters

- quantity



WP 68 000 Costs parameters

- weight of the reflector (material)



WP 70 000 Work Sharing Possibilities

- Subsystem definitions

- List of recommended subsystem suppliers

From the procurement point of view the telescope should be divided at least in the following subsystems (excluding reflector system)

- mechanical subsystems (pedestal, drive units, center unit) consisting of
  - . steel structure
  - . machining of steel structure
  - . bearings
  - . gear boxes
  - . wheels, gear rims, stow pins, limit switch supports
  - . encoder supports
  - . preassembling of units

- motors, tachos, amplifiers

- encoders

- servo (cabling, interlock, computer software)

- secondary-, Nasmyth- unit

- claddings

- air-conditioning

- preassembling, testing of prototype

- foundations, azimuth track, rail and road system

...

- cable traces, grounding

- tractor

- final assembly, commissioning on-site

Special telescope know-how is necessary only for the suppliers of the servo system, preassembly and prototyp testing and final assembly and commissioning on-site. For the other subsytems the manufacturing-performance in the workshop and the reliability of the products should be the criterions for the choice of the suppliers.

Annex 1

Original Work Package Description

of the Study Contract

WORK PACKAGE DESCRIPTION	WP REF. NO. 10 000
WP No.	Title Project Definition
11 000	Specification - Check of specifications for telescope system and requirements for supplementary data.
12 000	Interface Definition - Definition of interfaces to subsystems and structures which are not concerning the telescope system itself (i. e. CFRP reflector, radome etc.).
13 000	Statement of Work - Setting up a work package plan and description for the definition phase.
14 000	Time Schedule - Listing of development and manufacturing steps time schedule with bar and milestone-plan for development, manufacturing, assembly and test phase.
Delivery Items	Report approx. 10 pages

WORK PACKAGE DESCRIPTION		WP REF. NO. 20 000
WP No.	Title System Design	
21 000	Telescope Concepts - Design for two telescope concepts with * rotational symmetric reflector * Offset-reflector - Reasons for the selection of these concepts - Technical data for both concepts	
22 000	Enclosure Concepts - Design for three enclosure alternatives with special consideration of removable systems * Integrated reflector cover (IRC) concept * Astrodome concept * Radome concept - Reasons for the selection of these concepts - Technical data	
23 000	Servo Concepts - Design concept of a servo system - Preliminary selection of actuators and sensors - Comments on the interfaces to the mechanical system and achievable accuracies	
24 000	Technical Availability - Comparison of the technological state of the art - Comparison of availability, reliability and maintainability of the subsystems	
Delivery Items		

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2. Issue 22.08.89

WORK PACKAGE DESCRIPTION		WP REF. NO. 20 000
WP No.	Title System Design	
25 000	Receiver Cabin - Configuration of the cabin - Design of the receiver magazin - Changing procedure of receivers - thermal conditions in the receiver cabin	
26 000	Transport System - Design for transport system - Comments to different solutions	
27 000	Assembly Concept - Discussion of preassembly and commissioning at a convenient site - Concept to reache an easy assembly and reassembly	
Delivery Items	Approx. 8 concept drawings, 1 block diagram Report approx. 20 pages	

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2. Issue 22.08.89

WORK PACKAGE DESCRIPTION	WP REF. NO. 30 000
WP No.	Title Study on Wind Effects
31 000	Wind Loads - General comments on wind influences on telescopes and enclosures - Preliminary estimate of wind loads (by know-how of previous designed and erected telescopes and in reference to literature) - Definition of possible wind tunnel tests for the definition phase (if applicable)
32 000	Estimates of Wind Effects on the Reflector Accuracy - Comment on overall wind effects of the reflector, using the results of reflector study and previous experience
33 000	Estimates of Wind Effects on the Pointing and Tracking Accuracy - Estimate of the natural frequencies of the telescope alternatives - Establishing of applicable wind turbulence spectra under telescope operating conditions for the different telescope and enclosure alternatives - Evolution of the pointing and tracking accuracy by spectra transfer methods
34 000	Conclusion on Wind Effects
Delivery Items	Report approx. 20 pages including approx. 10 figures on wind loads, wind spectra, structural response spectra, pointing and tracking accuracies

2. Issue 22.08.89

WORK PACKAGE DESCRIPTION	WP REF. NO. 40 000
WP No.	Title Study on Temperature Effects
41 000	Temperature Loads - General comments on temperature influences on telescopes and enclosures - Preliminary estimate of temperature loads (by know-how of previous designed and erected telescopes and in reference to literature) - Definition of possible active or passive temperature control systems, necessary for the different enclosure alternatives - Definition of the temperature loadcases, thermal stability and pointing accuracy - Thermal conditions during day and night and at partial illuminations
42 000	Estimates of Temperature Effects on Reflector Accuracy and Pointing - Comment on reflector deformations due to temperature loads, using the results of the reflector study and previous experience - Comment on pointing effects due to temperature loads on the reflector and pedestal
43 000	Conclusion on Temperature Effects
Delivery Items	Report approx. 15 pages (incl. approx. 8 figures on temperature loads, temperature deformations, pointing and time history

2. Issue 22.08.89

WORK PACKAGE DESCRIPTION	WP REF. NO. 50 000
WP No.	Title Comparison of the Results
51 000	Final comments and recommendations
52 000	Revised list of specifications
Delivery Items	Report approx. 10 pages

WORK PACKAGE DESCRIPTION	WP REF. NO. 60 000
WP No.	Title Cost Estimates
	Definition and Costs for:
61 000	Definition Study - engineering analysis - work planning - quality assurance planning
62 000	Design Study - detail engineering - work preparation - quality assurance
63 000	Manufacturing - jigs and tools - materials - manufacturing - quality assurance
64 000	Assembly - preassembly of one pedestal - final assembly on site - acceptance test
65 000	Testing - natural frequency - painting and tracking performance
66 000	Operation - DOC
Delivery Items	Price lists with comments

WORK PACKAGE DESCRIPTION	WP REF. NO. 60 000
WP No.	Title Cost Estimates
67 000	Site influence on costs - Comments to cost driving site conditions (MAN GHH needs detailes information about the two sites)
68 000	Cost parameters - discussion of costs of telescope mount depending on the following parameters * aperture size * precision * quantity * weight of reflector (material) - discussion of substantial jumps in costs
Delivery Items	Price lists with comments

2. Issue 22.08.89

WORK PACKAGE DESCRIPTION	WP REF. NO. 70 000
WP No.	Title Work Sharing Possibilities
70 000	Work Sharing Possibilities - Subsystem definitions - List of recommended subsystem suppliers
Delivery Items	Work Breakdown Structure List of subsystem suppliers with comments