Alignment for the PRONAOS Submillimeter segmented telescope.

I.Ristorcelli[1], G.Recouvreur[2], M.Giard[1], B.Leriche[2], M.Gheudin[3], G.Beaudin[3], P.Encrenaz[3], F.Buisson[4], J.M.Lamarre[2], G.Serra[1].

1- Centre d'Etudes Spatiales des Rayonnements, BP 4346, F-31055 Toulouse Cedex

2- Institut d'Astrophysique Spatiale, Université Paris XI, Bâtiment 121, F-91405 Orsay Cedex.

3- DEMIRM-Observatoire de Meudon, 5 Place Jules Janssen, 92195 Meudon Cedex.

4- Centre National d'Etudes Spatiales, 18 av. Edouard Belin, F-31055 Toulouse Cedex.

Abstract

PRONAOS, a french balloon borne experiment devoted to Submillimeter Astronomy, consisting of a stabilized gondola, a telescope, a multiband photometer and a heterodyne spectrometer, is developped in collaboration between CNRS and the french space agency, CNES, to prepare the future space programs in astrophysics. Observations in this part of the spectrum requires low atmospheric water vapor and oxygen molecule emission, so that the telescope fly under a 1 000 000m^3 balloon at an altitude of ≈37km. First flight should occur in September 1994 from the USA, using a multiband photometer; the second flight is scheduled in 1995 with an heterodyne spectrometer. The telescope is a Cassegrain type, of a weight less than 250kg, with a 2m diameter primary mirror divided into 6 panels made of carbon fiber (core with a honeycomb structure and skin) and covered by a goald coating. The whole primary mirror has a surface accuracy of 12µm rms (all defects included). The global WFE for the telescope is assessed to be lower than 43µm.

The PRONAOS telescope has raised new technological problems: how to control the image quality and how to mark out the optical axis of a wide diameter segmented telescope, when it is integrated with its focal instrument. The difficulties induced by submillimeter measurements had pushed for a solution by mean of a visible wavelength method. We have summed up in this paper the method for the panels tilts control, based on an autocollimation procedure, by mean of a visible laser which produces a real image at the telescope focus.

However, on the contrary, the piston control along the optical axis can only be realized in the submillimeter wavelengh. The method developped in that purpose is summarized in the paper. The precision reached for the final alignments of the primary mirror has been estimated to 8 arcsecond for the tilts and 7µm for the piston.

The reference for the optical axis of the payload (telescope + focal instrument) has been obtained by an original way. With the direct detection focal instrument, the method we have developped consisted into mapping the image given by a collimated beam whose axis had been refered to the star sensor in the visible range.
A similar method will be developped with the heterodyne focal instrument using another submillimetric source and a collimator with a larger diameter.

I - INTRODUCTION

The submillimeter band is one of the few regions of the electromagnetic spectrum which is still unexplored in Astronomy, because of the attenuation of the Earth's atmosphere. This spectral range is of great importance because the gas and dust of our galaxy and other galaxies, which is in processes of forming new stars, emits most of the energy precisely at these wavelengths.
Observations from a stratospheric balloon are unobstructed by the atmosphere which is opaque at submillimeter and far-infrared wavelengths, from the ground (Fig. 1). For this reason, a submillimeter balloon-borne observatory (PRONAOS) is being developed. It is scheduled to flight in 1994 and 1995 using a 1 000 000 m^3 balloon at an altitude of 37 km (Fig. 2).

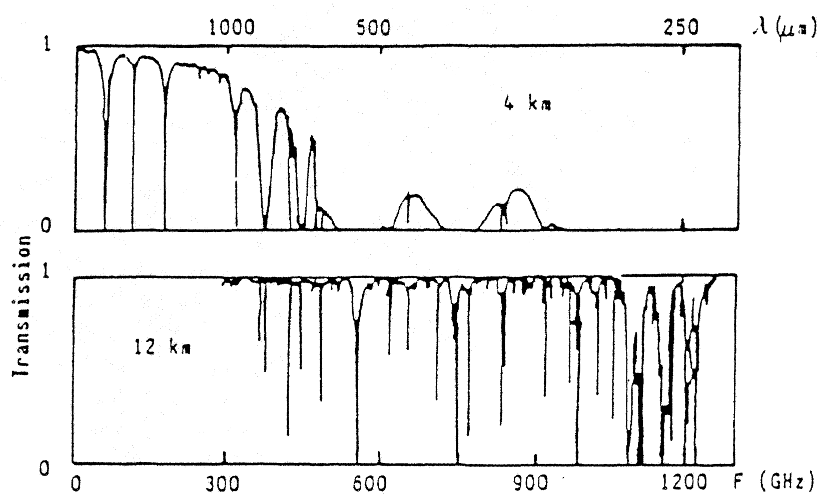


Figure 1 : Atmospheric transmission from mountain site (Hawaii) or airplane (KAO).

PRONAOS is intended to provide a facility for long duration flights (20 - 30h) for photometry and spectroscopy in the spectral region : ≈ 180 μm to 1.2 mm. The first flight will start from Fort Sumner (USA) next september ; long missions are also foreseen in the southern hemisphere.

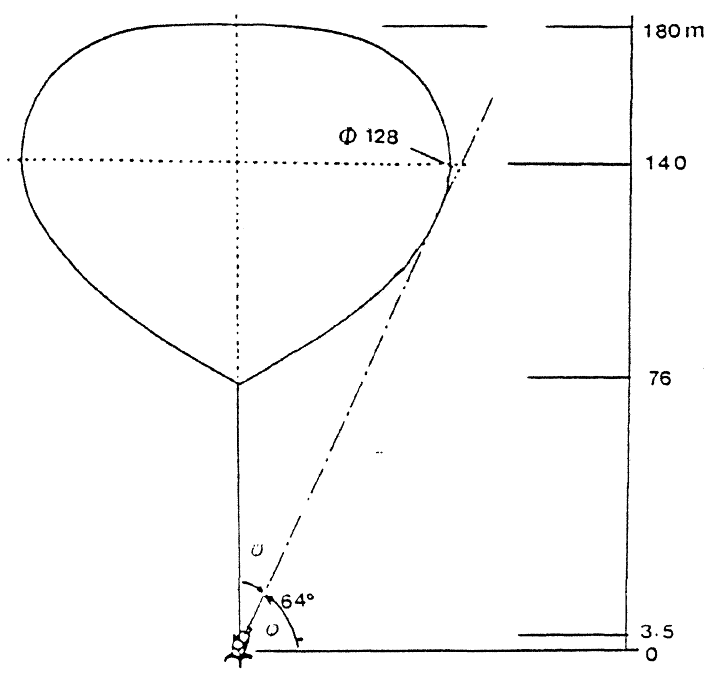
PRONAOS should also be considered as a preparatory programme for the next generation of space-borne Submm satellite contemplated by European and US agencies for the next century.

Funded mainly by the French space agency, CNES, PRONAOS is developed in close cooperation with French scientific institutes from CNRS and "Ministère de l'Enseignement Supérieur" in France, acting in this domain.

PRONAOS consists of a stabilised gondola supporting a 2 m diameter segmented telescope, associated alternately with an infrared Multiband SpectroMeter (SPM) or a high resolution submillimeter Heterodyne SpectroMeter (SMH).

- SPM will measure the Sunyaev-Zeldovitch effect in the clusters of galaxies, which permits to know their distance and their radial speed (and so the direct Hubble constant measurement) ; SPM is also dedicated to measure the thermal emission of cold dusts in the nearby galaxies which permits to know mass and space distribution of these dusts.
- SMH will be used to simultaneously detect the O_2 line and the H_2O line in the interstellar medium which permits the progress in the knowledge of the chemical processes and of the temperature and density in star formation regions.

The system Balloon-Gondola is working in a very specific environment, with the following characteristics :



- *A balloon considered as fix with regard to the earth (considerable inertia for the dimensions Ø≈ 60m, M≈2800 kg.*
- *Long period "pendulations" of the gondola with regard to point A, T≈18 sec. and amplitude ≈ 5 arcminutes on roll and yaw axis.*
- *Oscillations around the center of gravity of the gondola, due to the internal disturbances, T≈ 1,5 sec. and amplitude about 5 arminutes.*
- *Rotation around point B, due to the rotation of the balloon, and of the earth, on pitch axis.*
- *Wind disturbances due to the differential speed of the wind between balloon and gondola (about 5 km/h of differential wind applied to the gondola in the worst cas) on all axis.*

Figure 2 : Flight configuration at ceiling.

II - PRONAOS GENERAL DESIGN

The PRONAOS on board instrumentation architecture consists of three parts :

- a carry away vehicle : the stabilised gondola.

The gondola vertical size is typically 7 m and its horizontal area is around 50 m^2 (Fig. 3). The on-board energy will permits a capacity of 30 kWh by a set of lithium batteries. The dry mass is 2400 kg for a total launching mass of 2800 kg, the mass of the pointed payload including the telescope, one focal-plane instrument and various equipments is approximately 500 kg.

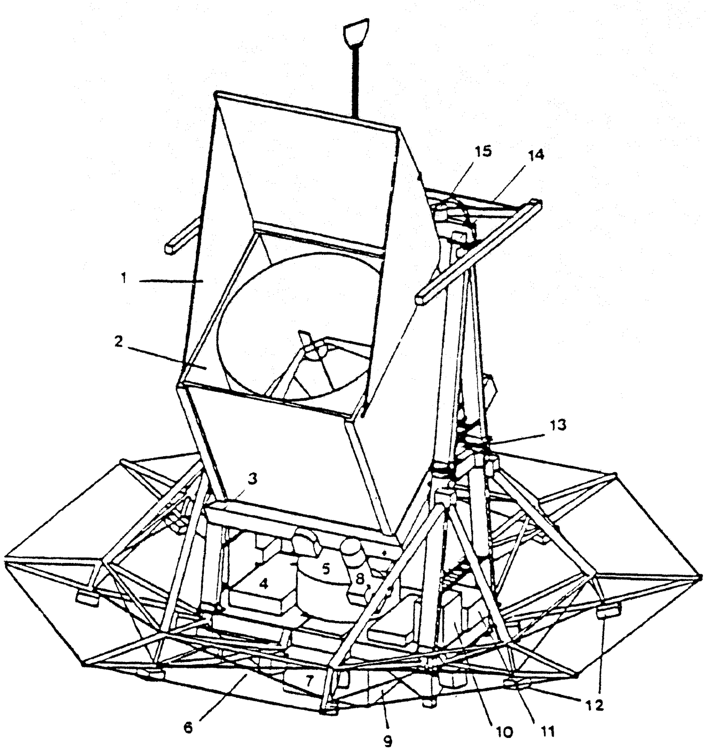
- a common facility : a submillimeter telescope.

The two meters segmented telescope with a light weight primary mirror is a Cassegrain telescope with a focal ratio F/10. The telescope is pointed (accuracy of 5 arc seconds) with a three axis system : an azimuth axis providing decoupling in rotation between the balloon and the gondola, and an elevation/cross-elevation gimbal.

- a multiband scientific payload : 2 focal plane instruments :

. A SpectroPhotoMeter (SPM) using He3 cooled bolometers, dichroïcs filters, on the field 180μm - 1.2 mm over four bands. This focal instrument is described in Lamarre et al., 1994.

. An Heterodyne SpectroMeter receiver (SMH) with high resolution $\nu/\Delta\nu \approx 2.10^6$ will operate, in the first generation, to detect simultaneously the 368 GHz and the 380 GHz lines (Beaudin et al 1993), with a next goal of operating at 557 GHz.



1 - Telescope shutter
2 - Telescope
3 - Two-axis pointing gimbal
4 - TM/TC box
5 - Equipments box
6 - TM/TC antenna
7 - Beacon
8 - Star tracker
9 - Main shock absorber
10 - Li batteries
11 - Energy distribution box
12 - Shock absorber
13 - Inflatable floater
14 - Passive swing damper
15 - GPS antenna

Figure 3 : PRONAOS gondola

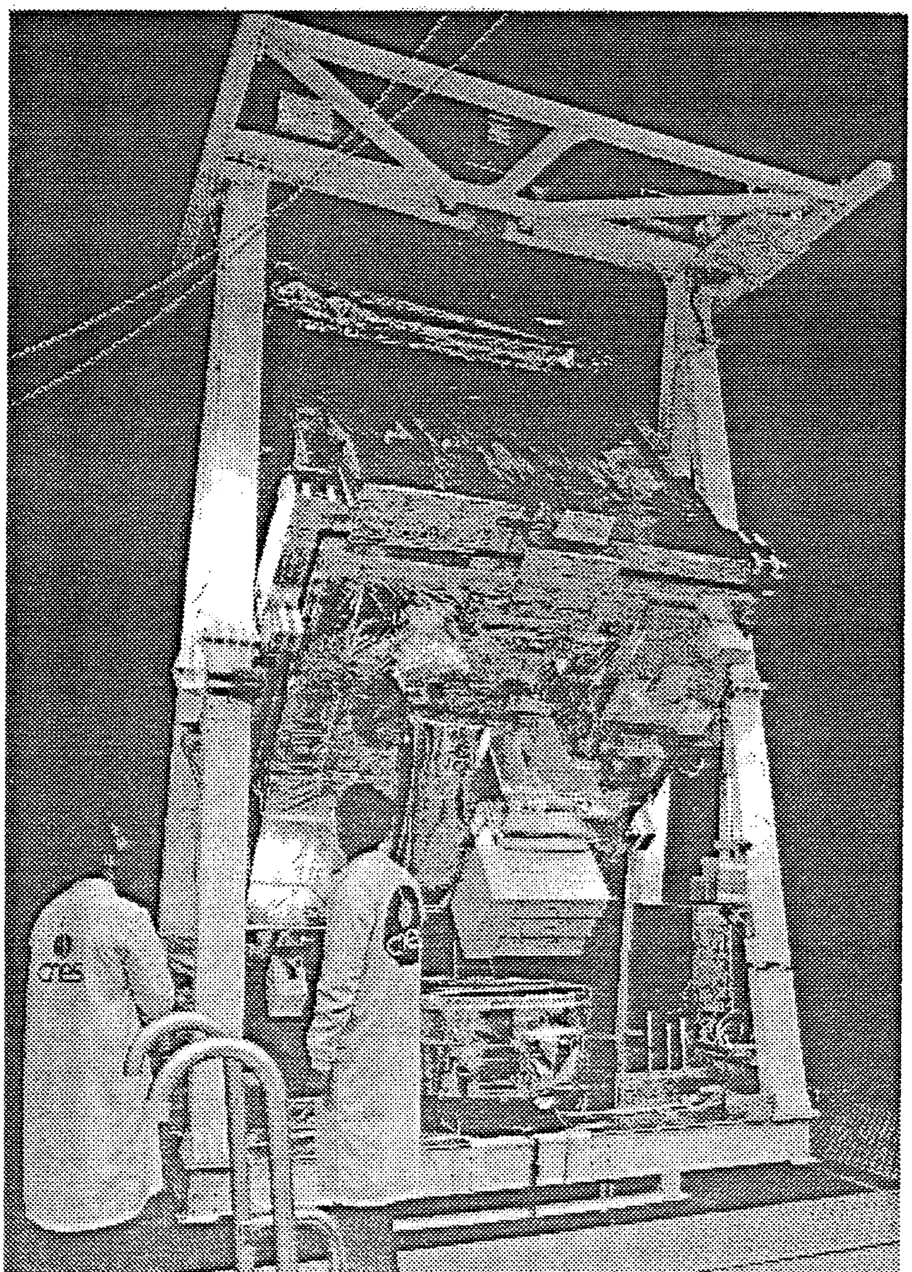


Figure 3' : PRONAOS - gondola, Telescope, SPM

III - PRONAOS TELESCOPE DESCRIPTION

In the frame of that project, CNES gave to MATRA-SPACE in Toulouse, the responsibility for the design, the development and the fabrication of the telescope ; its is pointed with an accuracy and a stability of 5 arcsecond RMS by the gondola stabilisation equipment and by a stellar sensor. It will collect the energy towards the focal instrument. A detailed description of the telescope is given in Buisson and Duran, 1990. In the following, we intend to summarize the main specifications of the telescope its design and innovative aspects and to describe its measurement procedures.

III.1. General specifications

Optical Design

The telescope design results from a compromise between on one hand the scientific requirements asking for a collecting area as large as possible and for a high spatial resolution and on the other hand the constraints concerning the height granted by the launching system and the total weight which can be launched.

The resulting optical specifications are summarized in the following table :

Type	Axi-symmetric Cassegrain
Focal length	20 m
Aperture ratio	F/10
Secondary focal length	2818.2 mm
Primary Secondary distance	1528.2 mm
Primary mirror - focal length - diameter - central hole diameter	 1778.8 mm 2045 mm 255 ± 5 mm
Secondary mirror - focal length - diameter - reflecting central cone	 275.1 mm 273 mm ϕ 50 mm, h = 4 mm
Reflectivity efficiency	> 0.97

Telescope optical characteristics

Requirements concerning image quality are issued from the value wished for radiometric energy concentration in the focal plane of the integrated telescope considering various points of the field and the spectral domain of work. It is translated into :

- requirements concerning the r.m.s. wave front error which must be better than 43μm.
- requirement concerning geometrical concentration of light beams that is i) 80 % of energy in a circle of diameter smaller than 17mm, ii) 90 % of energy in a circle of diameter smaller than 19 mm.

The image quality requirements and its relations with the main specified characteristics will be discussed later in this paper.

Mechanical design

The mechanical design must optimize the following constraints : i) stability under gravity and thermal variations, ii) rigidity (no global eigen mode lower than 20 Hz), iii) resistance to shock at landing (10g), iv) interface with two different focal instruments, v) mounting of several equipments (star tracker, inertial block, electronics) necessary to the pointing system. The total mass is 250 kg.

Thermo-emissive characteristics

Because all the instrumental variations of the emitting flux induce parasitic signals, the part of the telescope such as the mirrors, the inner sides of the baffle or the structure supporting the secondary mirror (which are either in the beam of the main lobe or close to that beam and so could intercept the secondary lobes created by diffraction) must have very faint submillimetre emissivity. For the same reason, their temperature must remain as stable as possible.

III.2. Main features of the telescope design

The telescope is made up of the following main parts (see Fig. 4)

- a basic box manufactured in CFRP honeycomb, supporting the reference plate, the secondary structure, the quadripod and assuring the interface firstly with the gondola pointing system and secondly with the focal instrument,
- the secondary structure made from carbon lattice which provides the frame for the Sun baffle as well as for the thermal protection. This structure is ended by an active cover whose functions are : i) to protect the mirrors from dust and light during integration and launching, when it is closed and ii) to protect the internal part of the telescope from solar light when it is open (during most of the day part of the flight),

- the jack mechanism for opening/closing the cover,
- the active primary mirror and its 6 panels,
- the fixed secondary mirror,
- the structure carrying the secondary mirror, in carbon fibre,
- the electronics boxes and harness required for the command of the primary mirror, the thermal control, and the command of the cover.

An inner sub-mm baffle manufactured with aluminised mylar (in reverse side) minimize the emitted submm radiation and maximize the thermal infrared coupling allowing to optimize the thermal homogeneity inside the telescope.

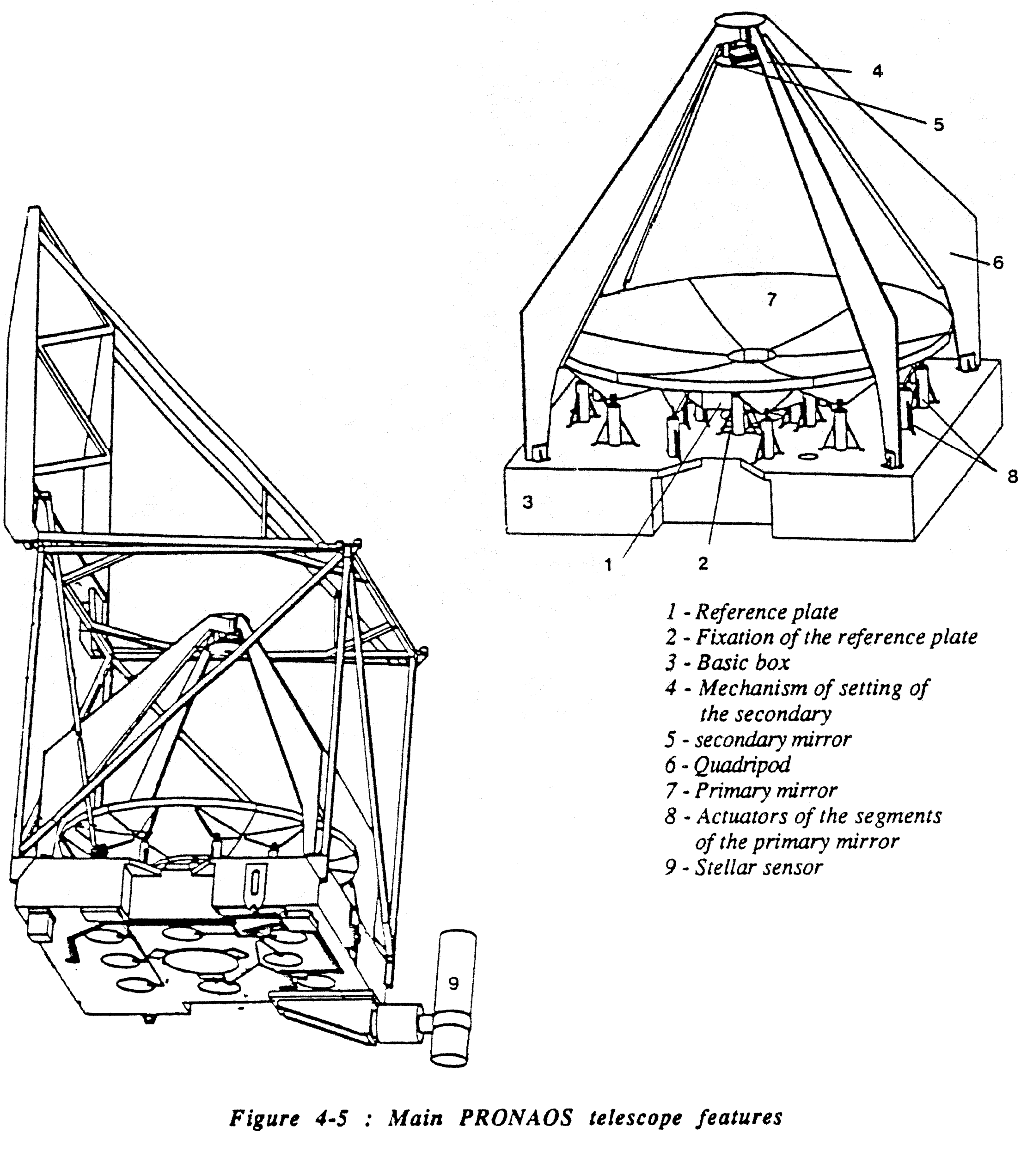


Figure 4-5 : Main PRONAOS telescope features

III.3. The semi-active primary mirror

Main reflector configuration

The primary mirror (Fig. 5) consists of six identical panels each being positioned in respect with a central reference plate by means of a servo-controlled loop using capacitive sensors. This configuration has been selected because a single mould was sufficient to manufacture all the identical panels. The central reference plate was produced in the same composite material as the panels that is two skins in carbon fibre of M40 type separated by a core in the same material. It is fixed on the main box.

The positioning of each segment versus the reference plate is controlled using 30 capacitive distance sensors and 18 electrical screwjacks actuators.

This servo-loop mechanism and its associated electronics represent the main contribution (23µm rms) to the global w.f.e. ("wave front error").

Panels

Their realisation was under MAN (Germany) responsibility. Eight panels (6 flight models, 1 qualification and 1 spare) were manufactured by a replica-thermique technique from one mould in zerodur glass, on a structure of honeycomb and skins in carbon fibre.

The process includes an injection of epoxy resin and a vacuum gold deposit (coating) of 0.15µm. The measured surface profile on one panel has been made using a 3D machine, for a set of points spaced by a few centimeters.

Mould

It has been manufactured by REOSC (France), in zerodur glass-ceramic. The final surface quality was reached through polishing with a computer-controlled polishing machine.

Servo-control system

- Sensors

They comprise :

- 6 intersegments sensors measuring the relative displacement of two adjacent panels
- 24 sensors (4 by panel) giving information about the panel positioning in respect to the reference plate

The system has 18 degrees of freedom; one sensor by panel is then in redundancy; it is used to improve the performance of the system and to be used as a spare model if any failure appears in one sensor.

The resolution of the sensors is 50 nm, reached by using differential capacitive sensors.

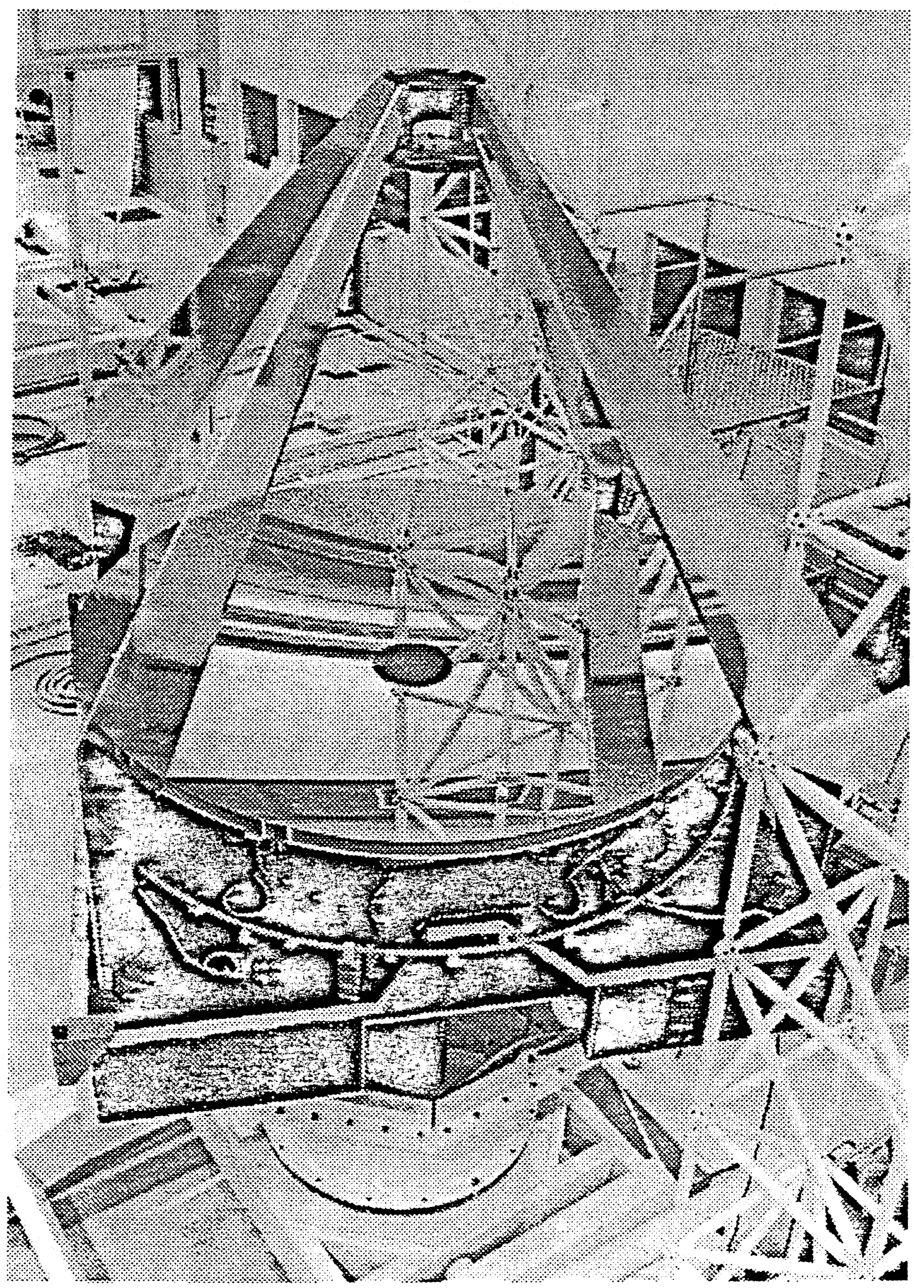


Figure 5' : PRONAOS Telescope without the baffle

- Actuators

Three actuators are dedicated to the maintaining of each panel in position according to 6 degrees of freedom. They are constituted by electrical screwjacks whose resolution is $0.1\mu m$.

- Electronic

It realizes the control loop at a rate of 150 Hz. It is composed of 3 parts :

- an analogic electronic which generates pulses towards the leads and acquires the signal issued by the sensors,
- a numeric electronic which processes those data and converts them into commands. That electronic is based on a 80C86. The implementation of the algorithm of process of the necessary matrix (18.30) is made by software. That same computer assures other functions such exchanges with the gondola data processing system including TM/TC communications through a high speed serial data line,
- a power electronics which realizes the command of the screwjacks.

IV - TELESCOPE CONTROL ALIGNMENT PROCEDURES

The segmented primary mirror has been tuned by MATRA using a specific procedure derived from Hartman method combined by a rotation of the whole mirror respectively to its symmetry axis. Made in the visible range, these operations control, with a sufficient accuracy, the positioning of each panel in rotation. But the positioning in translation along the telescope optical axis has been made in the first stage by means of direct metrology.
After the delivery of the whole telescope by MATRA-MARCONI SPACE to the scientific team, the main problem to resolve was to control : i) the positioning of each panel belonging to the main reflector, ii) the relative positioning of the two telescope mirrors, each respectively to the other, and in respect to the nominal focal plane location. This positioning had to be controlled regarding the image quality specification.

IV-1. Specifications and spectral range for alignment

Each panel of the primary mirror presents 3 degrees of freedom:

- β, about the Y axis,

- 2 tilts:

- φ, about the Z axis,

- 1 translation, called "piston": Tx, along the optical axis.

The specifications for the image quality of the Pronaos telescope have been described as the following. The ratios of 80% and 90% of the encircled energy must be contained respectively into 17 and 19mm diameter values in the focal plane. These values are coherent with a requirement on the root mean square of the wave front error value (WFE_{rms}) equal to 43μm (all telescope). An allocation of a WFE_{rms} =9μm has been given to the primary mirror.

Using a ray-tracing modelling and the Strelh criterion, Safa (1991) has shown that such specifications were equivalent to the following panel alignement tolerances:

- β_{max}=5.2 arcsecond
- φ_{max} =2.2 arcsecond
- Tx= 7μm.

Moreover, those modellings have pointed out a drastic dependance of the image quality on the wavelenght range of the incident radiation field. This is due to the spatial frequency of the surface defaults: it corresponds to $\lambda/15$ in the submillimeter and 24λ in the visible. In consequence, the visible image energy distribution is limited by the diffusion, while it is diffraction limited in the submillimeter range.
In particular, this implies that a misalignment of a panel will induce different aberration effects in the visible and in the Submm range. Using its modelling, Safa (1992) has shown that the diffusion image (visible) is not modified within a wide range of translation misalignment; on the contrary, this can degrade considerably the diffraction image quality, because of interference effects.

In consequence, the panels piston alignment must be achieved in the Submm range. It has been necessary to developpe a new method for the piston control, able to satisfy both the image quality specifications and feasability criterions with a view to operate the defined procedures on the launching site.

On the contrary, the modelling for the alignment of the panels tilts shows that it can be obtained in the visible wavelengh. Since the development of an experiment in the visible is much less constrained in the visible than in the Submm we have decided to proceed in two stages: first, we have achieved the tilts alignments in the visible range, and then completed with the piston alignement.
The following two sections summarize this method which has been described in detail by Ristorcelli et al. 1994.

IV-2 Tilts alignment

Principle: we use an autocollimation process in the visible range. The objectives are to analyse the diffusion image associated with each panel in the focal plane and to get it centered on the focus position by mean of its tilts movement (β, φ).

- Mounting description: a schematic view of the autocollimation mounting is given in fig.6. We use an helium-neon laser source operating at λ=622nm. The source hole (Ø=200μm), placed at the focus distance, is enlighted by the laser beam passed through an objective. The beam is then partially separated (~50%) by a beam splitter. The collimated beam, reflected by a plan mirror (Ø=800mm), gives a diffusing image in the focal plane of the telescope, which is visualised by mean of a frosted glass. The image acquisition is made using a CCD camera. We can then analyse the image associated with a given panel. A special software allows to determine the barycenter position, from which we deduce the deviation from the nominal focus point. Each panel is then tilted in consequence, by mean of its actuators and in respect to the nominal optical axis.

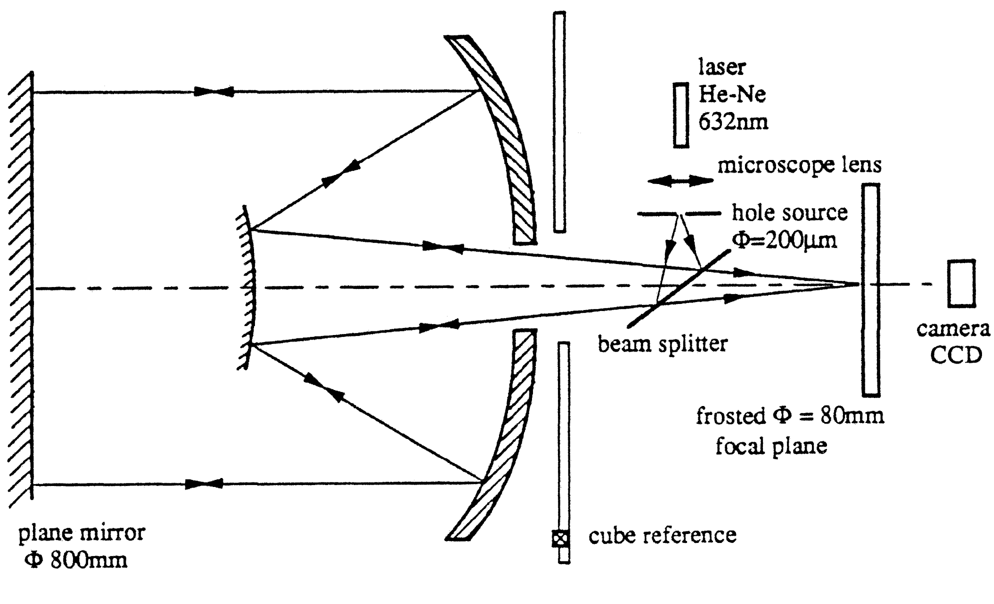


Figure 6: Autocollimation schema

The nominal optical axis of the telescope has been defined by Matra-Marconi-Space and is given by a mirror cube fixed on the basic box of the telescope (see figure 6).

- Precision of the tilts alignment: with the method described above, we have obtained a tilt control within a precision of 10 arcsecond.

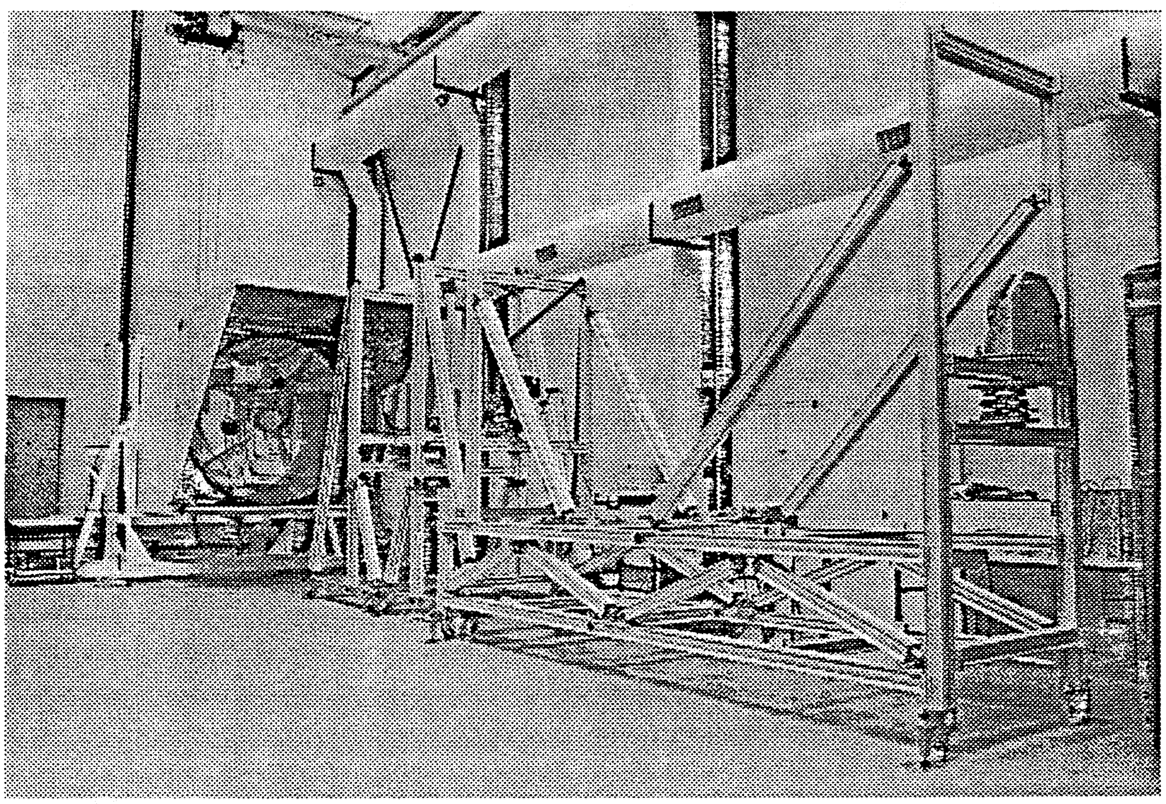


Figure 6' : PRONAOS telescope under aligment procedure

IV-3. Translation alignments:

- Principle: the objective is to analyse the distorsion of the diffraction image associated with a point source when the panel piston varies.

Let's consider a monochromatic (λ) parallel incident beam centred on an intersegment of the primary mirror. If there is a translation misalignment $\delta \neq 0$ between the two panels, then the diffraction image at the focus is altered by interferences which are function of the ratio δ/λ.

This distorsion is maximum for $\delta=\lambda/4$ and periodic with a $\Delta\delta=\lambda/2$ period. On the contrary, if we use a large wavelengh passband incident beam, then the periodicity is broken by the superposition of the different wavelenghs and the distorsion variations decrease when the widness of the wavelenght band increases. A unique piston value which gives a nominal diffraction image ($\delta=0$) is obtained when using an intermediate value of the bandwidth, located arround $\lambda/\Delta\lambda \approx 1$.

The locating of this particular position for each intersegment allows the alignment translation of the whole primary mirror.

In addition, the incident beam lights up in practice only a small surface sub-pupil of the primary mirror. An analyse of the diffraction image obtained for different radial positions of the sub-pupil on the intersegment leads to further information on the tilts alignment of the two panels.

- Mounting description

The Submm mounting that we have developped is shown in figure 7.

- Source system: we have used a high pressure mercury vapor arc lamp, which radiates both in the visible and the Submm, as a blackbody at a temperature $T \approx 1800K$. Its emission beam is then refocused by a parabololic mirror onto a hole source ($\varnothing$=1.3mm) and is modulated by mean of a chopper.

The hole source has been placed at the focus point of a collimator ($\varnothing$=200mm), in order to obtain an output parallel beam.

- The focal system: A diaphragm ($\varnothing$=10mm) is centred at the nominal focus point, in order to sample the diffraction image. The detector we have used is a silicium bolometer cooled at liquid helium temperature ($T \approx 4K$). It is located inside a dewar containing high passband wavelengh filters and a quartz lens to focus the sampled image on the detector. The electrical signal delivered by the bolometer is then analysed by a lock-in amplifier connected to the chopper.

- Measurement process: in order to obtain a cartography of the diffraction image in the focal plane, the easiest way is to move the hole source in its focal plane so that the collimated beam axis varies. For that purpose, the system source (arc lamp + mirrors + chopper + hole source) has been rigidly mounted on a motorized micro-control movement. The amplitude of the motion, the value and number of steps and the integration time have been optimized in order to cover the whole diffraction image, with a sufficient signal to noise ratio and within a reasonable time. A processor connected both with the micro-control movement and the lock-in amplifier allows a simultaneous acquisition of the signal and the source position. This leads to a cartography of the diffraction image which can then be analysed through different criteria such as its barycenter position or the energy distribution. We repeat this image analysis for a sample of piston values applied by mean of the three actuators.

- Accuracy of the method: the image distorsion is detectable by this method within ±7μm around the nominal translation position. An analyse of the diffraction images obtained for different positions of the sub-pupil along the intersegment has also allowed to improve the tilts control accuracy to ±8 arcsecond.

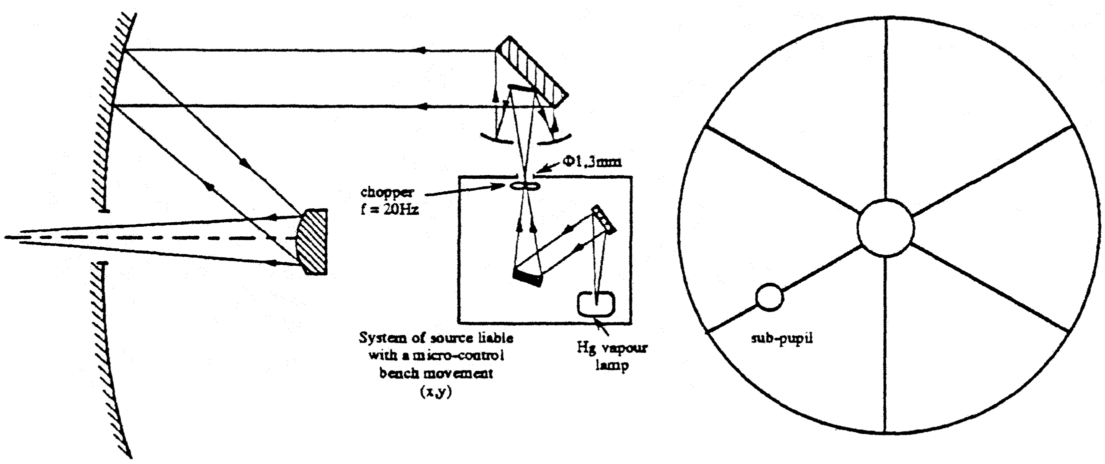


Figure 7: Mounting of the collimated beam

V- Payload alignment control

We call "payload" the integrated PRONAOS sub-system containing the telescope and one of the two focal instruments.
The payload axis may deviate from the nominal telescope axis mainly because of the optics alignment inside the focal instrument and a slight structure deformation due to the different mass configuration of this integrated system. It is important to locate the real axis of the payload nearby the nominal telescope axis, in order to avoid geometrical aberrations damaging the image quality.

The method developped and applied for SPM has been described by Ristorcelli. et al 1994. It consists in using the multiband photometer with a view to map the illumination in the focal plane when a collimated beam scans incident directions around the nominal telescope axis. The incident direction is controled using a high accuracy theodolite (±2 arcsecond).

The technological difficulty is increased with the heterodyne focal instrument SMH because the wavelengh passband of the heterodyne instrument is reduced and the use of a continuum incoherent source would lead to an insufficient signal to noise ratio. In addition, the requirement on the focal positioning in translation along the optical axis is more constrained.

The developpement of a modified method derived from the one described above is now in progress. The source used will be a line source increasing the radiated energy inside the instrumental bandwidth but the principle of the alignment procedures will remain the same. Another need will be a collimator with a larger diameter, lightening a sub-pupil with a much more larger area.

VI Conclusion

PRONAOS constitues a new step in the french ballooning. Devoted to get astrophysical results and to support new technological developments with a view to prepare future satellite Submm astronomical experiments, PRONAOS gives the opportunity to develop new subsystems methods. In particular, the alignment procedures and control, involving the telescope and the payload, need to operate using non-conventional methods.

Combining measurements respectively in the visible and in the submillimeter ranges, we reach to control the positioning of each panel of the segmented main reflector, within ±8 arcsecond in rotation (two axis) and ±7μm in translation along the nominal telescope axis. The procedures used allows to measure the angular off-axis existing between the payload and the star-sensor, with an accuracy of ±10 arcsecond. This measure will be confirmed during the first PRONAOS flight, scheduled in September 1994, with the multiband photometer SPM.

References and bibliography:

Buisson F. and Duran M., 1994, Proc. 29th Liege International Astrophysical Colloquium From Ground-Based to Space-Borne Submillimeter Astronomy, Liège, Belgium, 3-4 July 1990, ESA SP 314 (December 1990).

Lamarre J.M. et al. 1994, IR Phys. Tecno., Vol. 35, N0. 2/3, pp.277-289.

Ristorcelli I., Lamarre J.M., Giard M., Recouvreur G., Leriche B., Serra G., submitted to "Experimental Astronomy", 1994.

Safa H., Applied Optics, Vol. 31, No. 13, 1992.

Safa H., Ph. D. Thesis, 1991, CESR Toulouse, France.

Beaudin G., Deschamps A., Encrenaz P., Feautrier P., Febvre P., Gheudin M., Léridon B., Maoli R., Pernot J.C., Robert C., Ruffié : "PRONAOS" a balloon borne experiment for submillimeter radioastronomy whith a 380 GHz SIS heterodyne receiver , SPIE LASE Astronomy Instrumentation, L.A., USA, january 1993 ; 18th International conference on Infrared and Millimeter waves, University of Essex, U.K., sept. 1993.