# Cryogenic Engineering for Omega2000: Design and Performance

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## ABSTRACT

Omega2000 is a prime focus near infrared (NIR) wide-field camera for the 3.5 meter telescope at Calar Alto/Spain. Having a large field of view and an excellent optical quality, the instrument is particularly designed for survey observations. A cryogenic four lens focal reducer delivers a 15.4 x 15.4 arcminute field of view (FOV) with a pixel scale of 0.45"/pixel. The lenses are made of various optical materials, including $CaF_2$ and $BaF_2$ with diameters of up to 150 mm. They must be specially mounted to survive cooling and to follow the tight tolerances (± 0.05 mm for lens centricity and ± 30 arcsec for lens tilt) required by the optical design. For a wide range of observing applications, a filter mechanism can hold up to 17 filters of 3 inch diameter in 3 filter wheels. For exact and reproducible filter positions, a mechanical locking mechanism has been developed which also improves the cool-down performance of the filter wheels and filters. This mechanism allows a minimum distance of about 3 mm between the filter wheels. A Rockwell HAWAII-2 FPA is used to cover the wavelength range from 0.85 _m to 2.4 _m. Special care has been taken with regard to the thermal coupling of the detector. The thermal connection is made by gold layers on the fanout board and an additional spring-loaded mechanism. A warm mirror baffle system has been developed, in order to minimize the thermal background for K band observations. The camera is a focal reducer only and has no cold pupil stop.

**Keywords:** IR-Instrumentation, Cryogenic, Lens mount, Filter Wheel, Cryogenic Mechanical Design

## 1. INTRODUCTION

Infrared instrumentation at Calar Alto is essential for German and Spanish astronomy in the northern hemisphere. In recent years, the MPIA and Calar Alto have been at the forefront of development and scientific use of near infrared instrumentation. The principal instruments currently in operation are Omega Prime[2] and Omega Cass. As was the case with optical CCDs, the development of wide-field infrared cameras is limited primarily by the fabrication of large focal plane array (FPA) detectors. The Omega Prime and Cass cameras have 1k x 1k HgCdTe arrays (HAWAII-1) manufactured by the Rockwell Science Center in the USA. These were the largest available arrays of their type at the time, and the Omega Prime camera still has one of the largest fields of view (6.8 arcminutes) on a 4m class telescope in the infrared in the world. However, this is small compared to optical cameras (e.g. 33' for the Wide Field Imager on the MPG/ESO 2.2m at La Silla), and only now are larger arrays being fabricated.

The new wide-field infrared camera Omega2000 uses the even larger FPA HAWAII-2 (a 2k x 2k HgCdTe array) from Rockwell. This is the largest infrared array available. The camera will only have imaging capabilities: near infrared spectroscopy will continue to be supported at Calar Alto with Omega Cass.

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## 2. DEWAR DESIGN

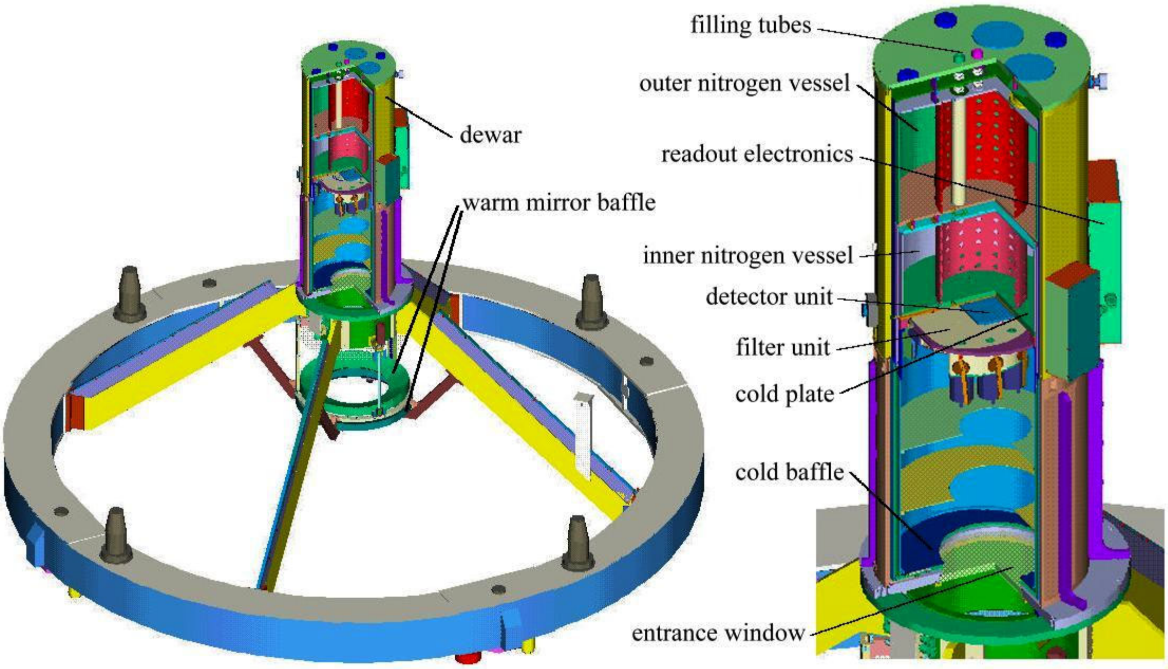



**Figure 1:** Omega2000 dewar mounted on front ring

The vacuum dewar of the Omega2000 instrument has a cylindrical shape with an outer diameter of 600 mm and a length of 1680 mm. The HAWAII-2 detector and all other inner parts are cooled by liquid nitrogen to a temperature of about 77K. To reduce the heat load on these components, three radiation shields are nested into each other (Figure 1). The large dewar entrance window is made of fused silica with a diameter of 350 mm and a thickness of 20.7 mm.

The liquid nitrogen is stored in two vessels that can be filled on the telscope through the upper side of the dewar. One of the nitrogen tanks is directly connected to the inner radiation shield and is referred to as the inner vessel in the following. Its capacity is about 47 liters. The outer vessel, with a capacity of about 72 liters, is connected to the second shield. Both nitrogen vessels are only filled half to allow a maximum tilt angle of the telescope of ± 90°, e.g. for balancing of the telescope and nitrogen filling. With both vessels filled up to half of their capacity and all cooled parts at thermal equilibrium, the dewar retains a temperature of 77 K for about 34 hours.

The cold plate is mounted at the lower end of the inner vessel which ensures that it always has the lowest temperature in the dewar. This cold plate is designed to be very rigid, since it is the basis of the detector unit. The outer shield is a passive one, since it is not thermally connected to either of the liquid nitrogen vessels. The shields and tanks are mounted on fiber reinforced epoxy parts for thermal isolation. To allow controlled radial shrinkage during cool-down and warm-up, the epoxy spacers that carry the load parallel to the dewar axis are arranged tangentially. Figure 2 shows that all axial stress (in direction of the optical axis) is taken by the top plate of the dewar (the one pointing to the sky during observations).

The axial shrinkage of the inner shield with respect to the dewar walls during cooling down to 77 K is more than 6 mm. That means that the inner parts have to be supported very flexibly in the axial direction and very stiff in the radial direction at the same time. Figure 2 shows the spacers arranged in a star-like shape, supporting the cold plate at a small distance from its center. For that reason the cold plate is split into two plates, connected by screws, with the radial spacers in-between.

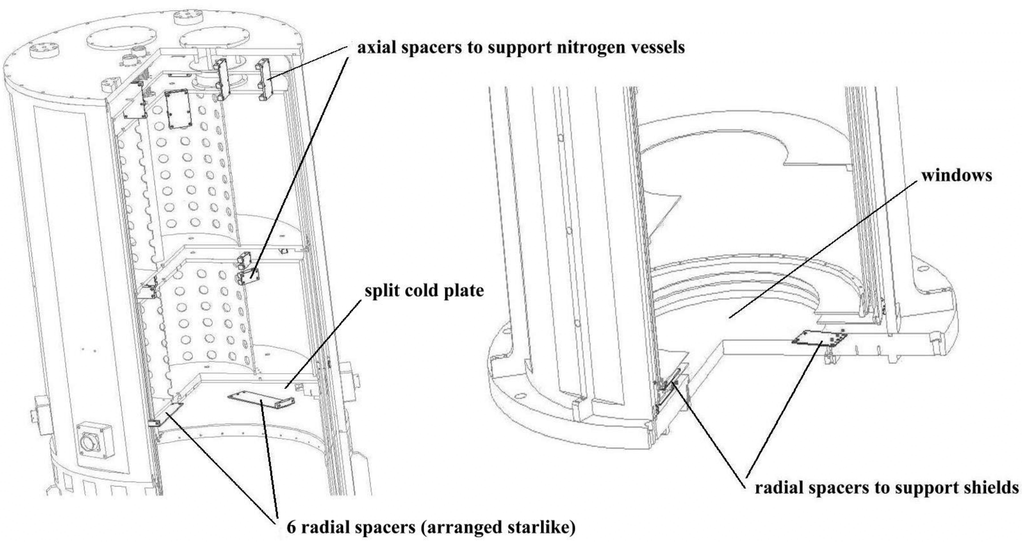



**Figure 2:** Radial and axial arrangements of spacers to support the shields, the cold plate and the nitrogen vessels

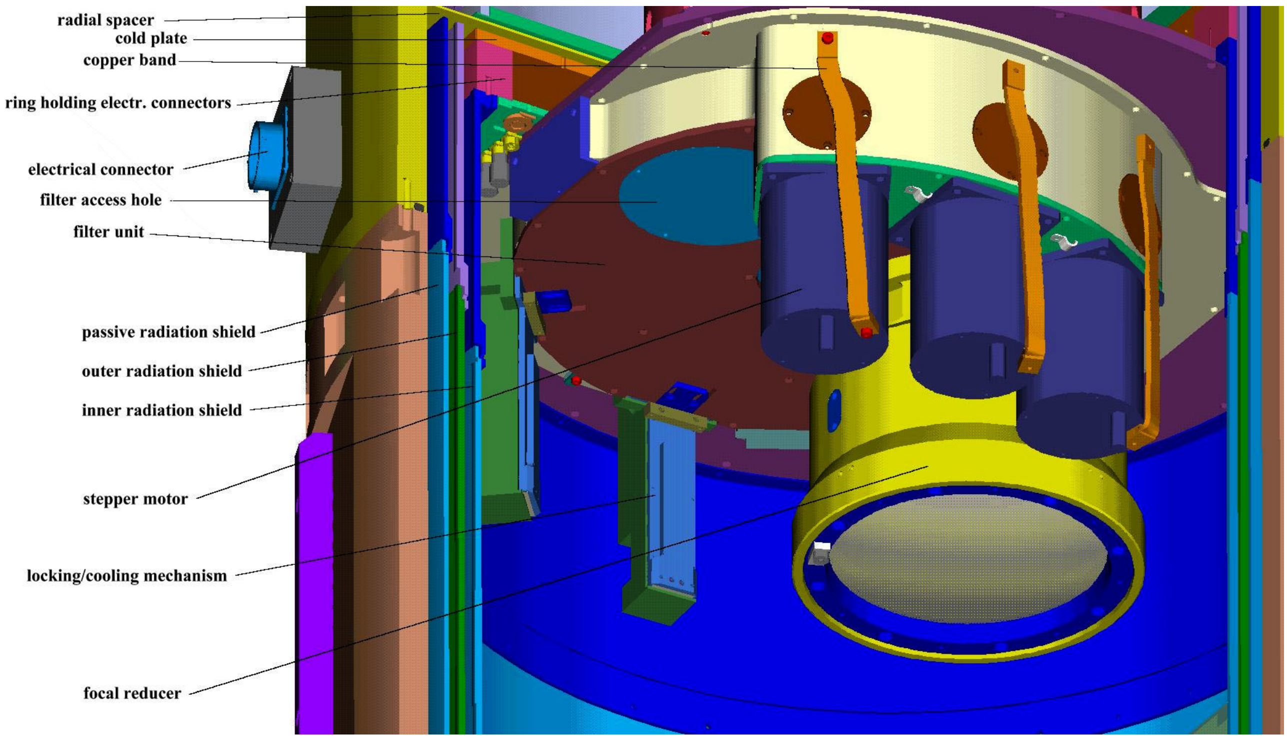



**Figure 3:** Filter unit and focal reducer mounted on the cold plate of the dewar

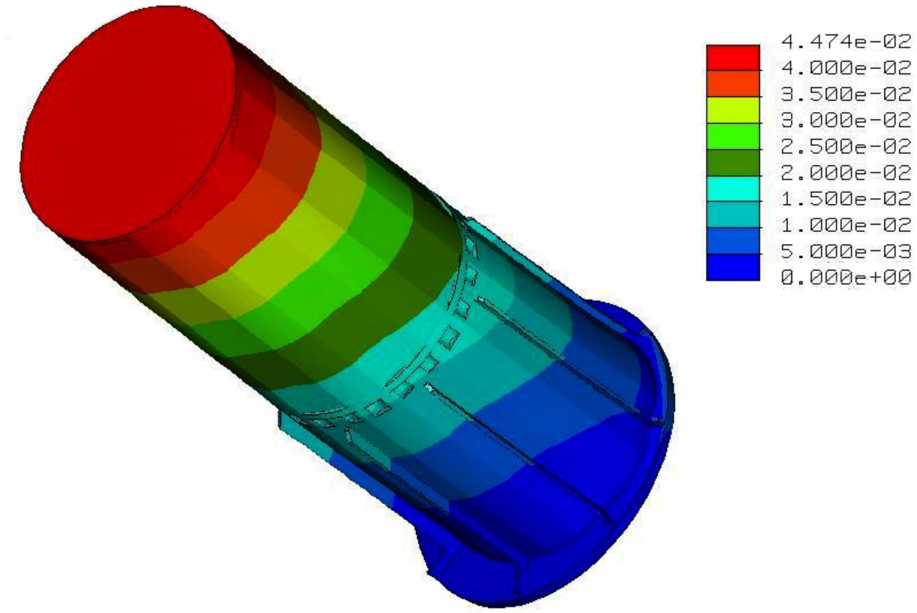



**Figure 4:** Finite element simulations show that the maximum deformation of the dewar due to its own weight and the weight of the liquid nitrogen is 15 _m at airmass 2 for the position of the detector. The colour scale is in mm.

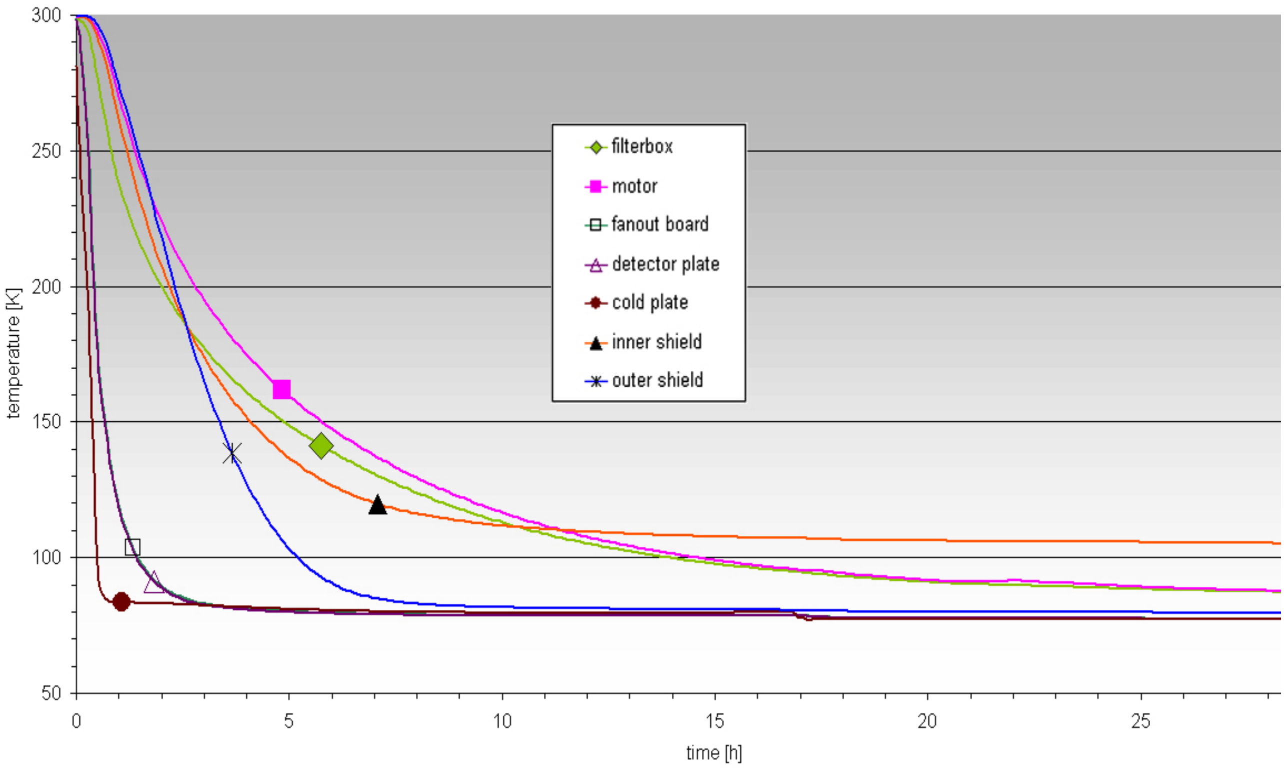



**Figure 5**: Temperature curves of some dewar parts while cooling from 300 K to 77 K.

Since the dewar is quite long compared to its diameter, and since the mounting point on the telescope front ring is at the end opposite of the nitrogen tanks, the maximum deformation of the dewar due to its own weight and the weight of the liquid nitrogen is a critical issue. Finite element analyses (see Figure 4) of the dewar show that the upper end (pointing at the sky) does not deflect more than 45 _m with the telescope looking to the horizon. At the detector position the deformation is on the order of one pixel (18 _m) at this extreme position. At airmass 2, this deformation is about 15 _m, which is less than the size of one pixel.

The curves in Figure 5 show that all cold parts reach their minimum temperature in about 24 hours when cooled from ambient condition. The slowest components in this process are the upper parts of the filter unit and the stepper motors. The instrument can already be used to collect useful data after about 13 hours of cooling. Although the inner shield has direct contact to the inner nitrogen vessel, it does not become colder than 104 K because of the thermal radiation through the dewar window.

## 3. CRYOGENIC LENS MOUNT

Since the Omega2000 instrument is designed to work with the existing 3.5m Calar Alto telescope, the pixel scale of the telescope is increased to 0.45"/pixel by means of a focal reducer. This consists of 4 lenses with diameters between 106 and 150 mm (see Table 1). The lenses are mounted in a single assembly. Each lens is fixed by a spring-loaded retainer ring (see Figure 6). To achieve an excellent optical image quality[1] and to minimize the lens diameters, the focal reducer unit has to be as close to the detector as possible, which of course means that it is located inside the dewar where it is cooled down to a temperature of about 80 K.

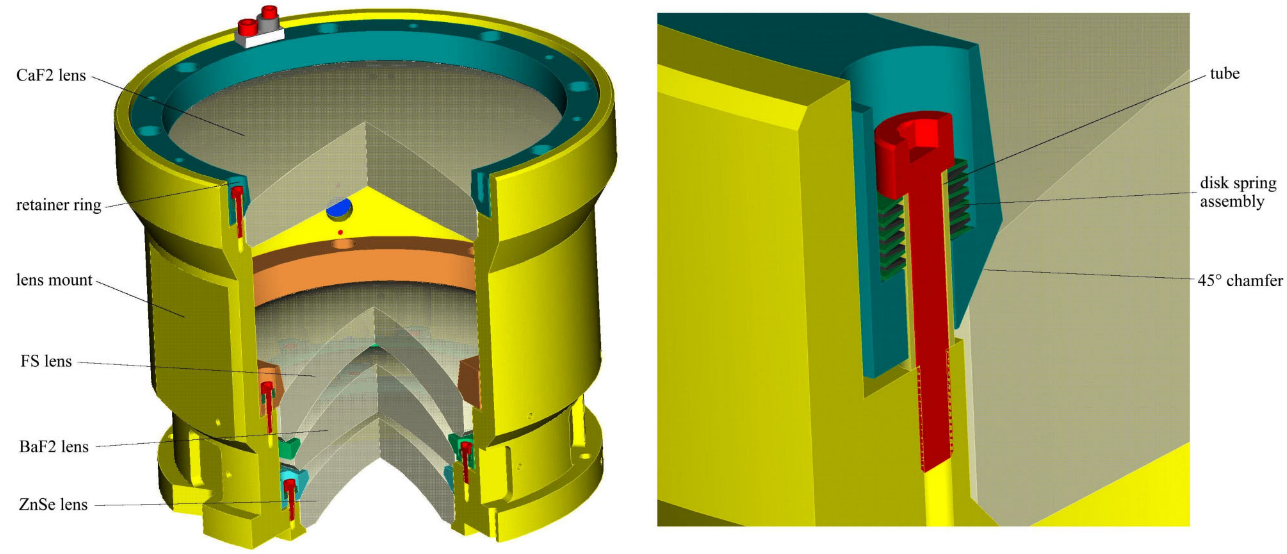
| lens | material | thermal expansion between T=300K and 77 K [%] | diameter [mm] |
|---|---|---|---|
| 1 | $CaF_2$ | -0.284 | 150 |
| 2 | fused silica (FS) | 0.001 | 140 |
| 3 | $BaF_2$ | -0.306 | 114 |
| 4 | ZnSe | -0.115 | 106 |
| - | AlMg4.5Mn | -0,378 | - |

**Table 1:** Focal reducer material data[7]

The acceptable tolerances in the optical design are ± 0.05 mm for lens centricity and ± 30 arcsec for lens tilt. The focal reducer parts are made of at least five different materials, each material having different thermal expansion properties: four optical materials for the lenses and aluminium AlMg4.5Mn for the mount parts. Table 1 shows that the fused silica (FS) lens actually becomes slightly larger when cooled down to 80 K, whereas the $BaF_2$ lens shrinks by about 0.3 %. This behavior is nonlinear for all the materials used, which means that e.g. the fused silica lens shrinks and expands again while temperature changes from 300 K to 80 K.

The most difficult task of the lens mount design is to make sure that the lenses survive cooling and at the same time achieve the tight tolerances required by the optical design. If the lenses were mounted in a conventional way, e.g. with a threaded retainer ring, the different thermal expansion properties of the materials used might lead to severe damage during cooling. Therefore, we employ a mounting method that uses chamfers at both the lenses and the mount parts. In this case, we chose a chamfer angle of 45° for both outer edges of each lens, the lens mount and the retainer ring (see Figure 6). The lenses sit in the conical surfaces of the mount. The retainer rings keep the lenses in this position by the forces of eight disk spring packages each. Temperature changes result in diameter changes of the parts. These changes lead to an axial displacement of the lenses and retainer rings because the parts can slide on the chamfer surfaces relatively to each other, assuming that the chamfers are manufactured very precisely and that friction can be neglected.

Of course, cooling of the mount parts and the lenses does not start simultaneously, because the lenses are cooled by the mount, and the retainer rings are cooled by the corresponding lenses and by the screws in the spring packages. To understand the movements of the lens mount parts while being cooled from 300 K to 77 K, Figure 7 shows a sequence of snapshots of thermal conditions. In Figure 7a the lens mount, the lens and the retainer ring are at room temperature (300 K). When the cryostat is filled and the cold plate and the filter unit are cooling, the mount starts cooling only after a certain delay (see Figure 8 for temperature curves). This means that the lens mount shrinks, as shown in Figure 7b. The lens and the retainer ring are shifted upwards because the lens can slide on the 45° chamfer relatively to the mount.




In the next phase (see Figure 7c, the lens changes its diameter and thickness since its cooling via the chamfer contact surface to the mount. Therefore lens and retainer ring move downwards. Finally, in Figure 7d, the retainer ring cools down and shrinks, causing an upward movement relative to the lens.

**Figure 6:** Four-lens focal reducer with spring loaded cryogenic lens mount

This cooling model is of course very schematic. The real process is much more complicated because the parts change their dimensions simultaneously after a certain time. The delay depends very much on material properties like thermal conductivity (which is a function of the temperature itself) and thermal expansion as well as on the size and quality of contact surfaces. A rough surface will slide less easily and give poorer thermal contact to another part than a smooth one. For this reason, the chamfers are diamond turned. Note that low thermal conductivity will lead to an inhomogeneous temperature distribution inside one part.

Measurements have shown that in the case of the $CaF_2$ lens the maximum temperature difference between the lens and the mount during the whole cooling period is about 40 K. In the case of fused silica this difference is about 60 K. The maximum temperature gradient in the lens from its center to its edge is 5 K and 12 K respectively (Figure 8). This does not cause much thermal stress. The larger temperature difference in the case of a fused silica test plate is mainly due to the fact that the surface quality and angle of its chamfer, being hand-polished, are less accurate than the surface and angles of the diamond-turned $CaF_2$ test plate.

Although the chamfers of all parts were machined with the highest possible accuracy (both shape and surface quality), it is not possible to simply put the parts together to meet the optical specification for lens alignment. Radial holes in the lens mount allow the measurement and adjustment by fine-pitch threaded screws of each lens. In principle, the lens adjustment can also be done by cooling down and warming up again. However this self-centering only works for radial misalignments of more than about 0.1 mm. For values smaller than that, the centering forces seem to be too low to overcome friction. The manufacturing tolerances for the chamfer angle were ± 3 arcmin for the mount parts and ± 2 arcmin for the lenses. The tolerances of the chamfer position were ± 0.01 mm.

A slightly smaller chamfer angle relative to the optical axis would facilitate lens self-centering without significantly increasing the forces during a temperature change. We would recommend angles between 40° and 45° at the expense of bigger forces.

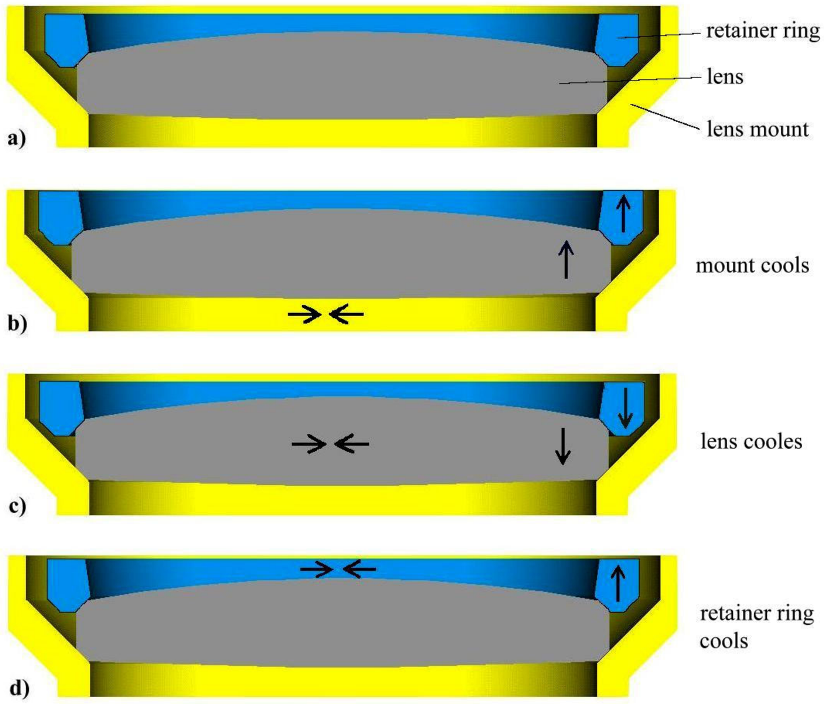



**Figure 7:** Displacements of lens and retainer ring due to thermal shrinkage during cooling from room temperature to 80 K. The arrows in axial direction show movements relative to the lens mount supporting surface. a) all parts at room temperature, b) lens mount cooling, lens and ring still much warmer, c) cold lens mount, lens cooling, retainer ring still much warmer, d) cold lens and lens mount, retainer ring cooling

The radial force component $F_R$ of the spring force $F_F$ which centers the lens can be calculated as

$F_R = F_F$ _ sin _ _ cos _

with _ being the chamfer angle relative to the optical axis, assuming that friction can be neglected. This means that the spring force which is required to generate a certain radial force for _ = 40° is only 1.5 % bigger than for _ = 45°.

Tests with the focal reducer have shown that once the lenses are aligned as accurately as possible, e.g. to ± 0.01 mm, changes in the lens position introduced by multiple cooling cycles and changes in cryostat orientation cannot be measured. The accuracy of the measuring device is ± 0.005 mm.

## 4. FILTER MECHANISM

Omega2000 contains 17 filters of 3 inch diameter for wavelengths between 0.8 to 2.4 _m and one closed blank. These filters and the blank are distributed in three filter wheels. A filter unit (which consists of the wheels, the cryogenic stepper motors and the locking/cooling mechanisms) is placed between the detector and the focal reducer.

Each filter wheel is mounted on a cryogenic ball bearing, specifically designed for operation at 77 K. A wheel has seven equally spaced locking positions (six for filters and one free opening). Filters in all wheels can be replaced through an access hole in the housing. Each filter position has a 3-bit magnet arrangement for determining the selected filter by three Hall sensors.

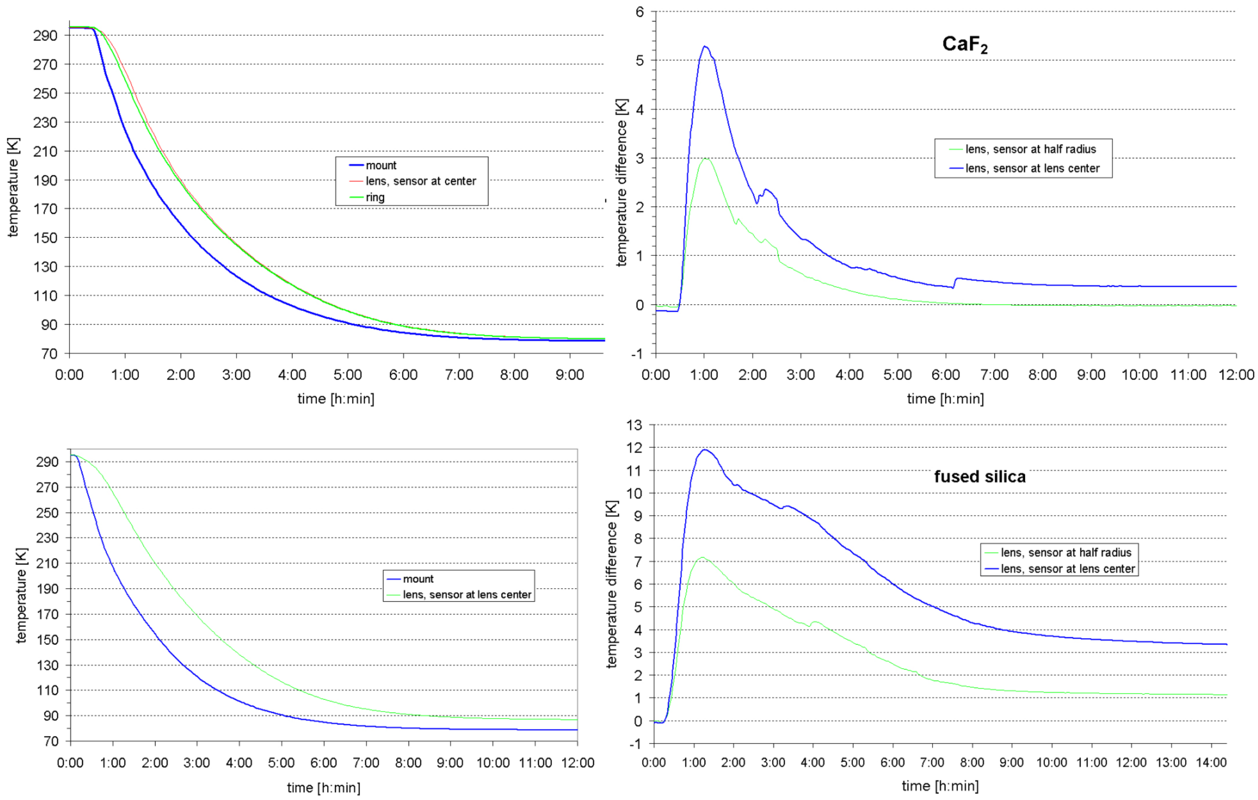



**Figure 8:** Temperature curves for $CaF_2$ (upper row) and fused silica (lower row). The diagrams on the left show the temperature behaviour of a test plate (instead of a lens) and test mount while cooling from 300 K to 77 K, the right diagrams show the temperature gradient of the test plate relative to the edge temperature. The diameters are 160 mm for the $CaF_2$ plate and 150 mm for the fused silica plate. This measurements were made in a test dewar.

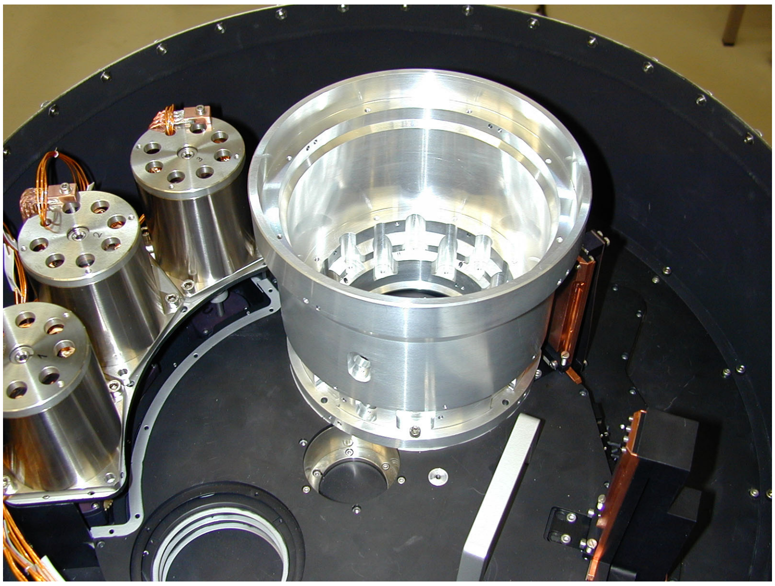


**Figure 9**: Filter unit and lens mount (without lenses) in open dewar

Ball bearings provide poor thermal contact for cooling the filter wheels. The points of contact between the balls and the rings of the bearing are very small, requiring a long time for the temperature of the filter wheel to match the temperature of the other parts of the filter unit. To improve heat transfer, the locking mechanism also acts as a cooling mechanism when locked into one of the locking positions.

The locking/cooling mechanisms have two leaf springs and a V-shaped locking finger that fits into the seven grooves on the outer diameter of the wheel (see Figure 10). The springs allow the finger to move parallel and in the radial direction only. A ball bearing at the end of the finger rolls on a cam which also has seven grooves but each with a smaller angle than the finger. To lock the wheel in one of its locking positions, the stepper motor turns the wheel until the finger reaches the beginning of the groove. Then the motor is switched off and the spring forces turn the wheel into the final position. On the last 0,05 ° before the final position, the ball bearing lifts off from the cam and the finger starts sliding on one of its symmetric planes.

Figure 11 shows a comparison of the filter wheel temperature curve with and without the thermal contact of the locking/cooling finger while the dewar is cooled from 300 K to 77 K. With the cooling finger in use, the filter wheel would reach a temperature of e.g. 85 K in about 16.5 hours. With the ball bearing alone, however, cooling would take about 24 hours. The cooling finger thus saves at least 7.5 hours of cooling time.

The filter wheel can be repositioned with an accuracy of less than 22 arcsec (set by the measurement accuracy), independent of the direction of rotation. With a pixel size of the HAWAII-2 detector of 18 _m, this angle corresponds to 0.78 pixels at the outer edge of a filter.

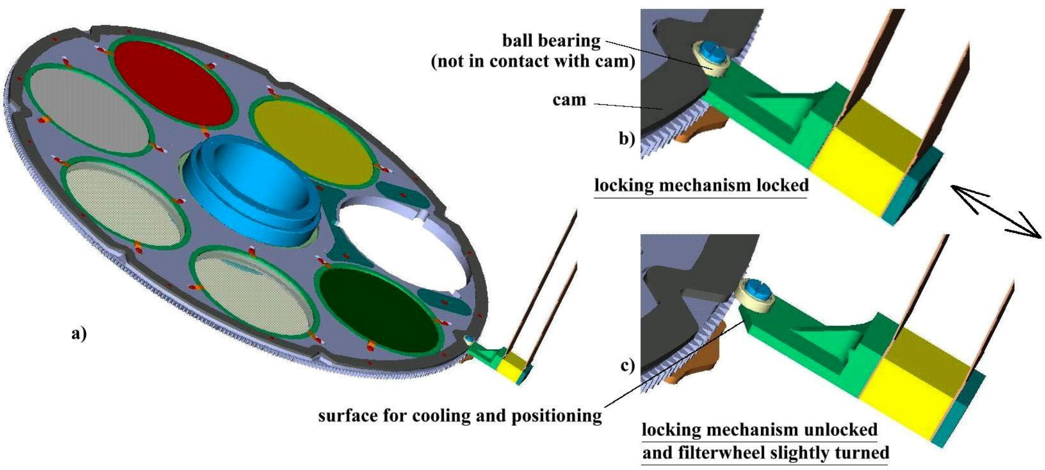



**Figure 10:** Spring mechanism for positioning and cooling the filter wheel (a), mechanism locked (b) and unlocked (c)

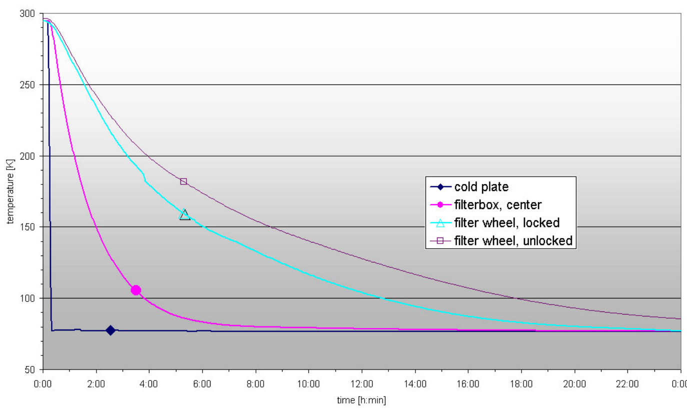


**Figure 11:** Cool-down curves of locked and unlocked wheel (with and without cooling finger).

## 5. DETECTOR MOUNT

The detector fanout board holds a Zero Insertion Force (ZIF) socket mount for the HAWAII-2 detector. The central pins of the socket and the detector can be used for thermal contact, whereas the outer two rows on each side are electrical contacts. For easy handling, the detector unit (Figure 12) consists of a rigid aluminium base plate which carries the fanout board on 12 identical cylindrical supports. The variation of the length of these bases can be used to adjust the detector position relative to the focal reducer unit to compensate manufacturing tolerances. To cool the detector, a spring-loaded cooling mechanism is used: two springs press an indium sheet against the central pins by a copper bar. This copper bar is connected to the base plate by a flexible copper band. Tests showed that after about 2 hours of cooling, all parts of the detector unit reach a state of thermal equilibrium (Figure 13). For these measurments the detector was replaced by an empty chip carrier with a temperature sensor on it. Since the ceramic material of the carrier is extremly hard and has a very smooth surface, epoxying the sensor on it was not easy. Mechanical methods to roughen the surface failed. We finally succeeded by lasering the surface.

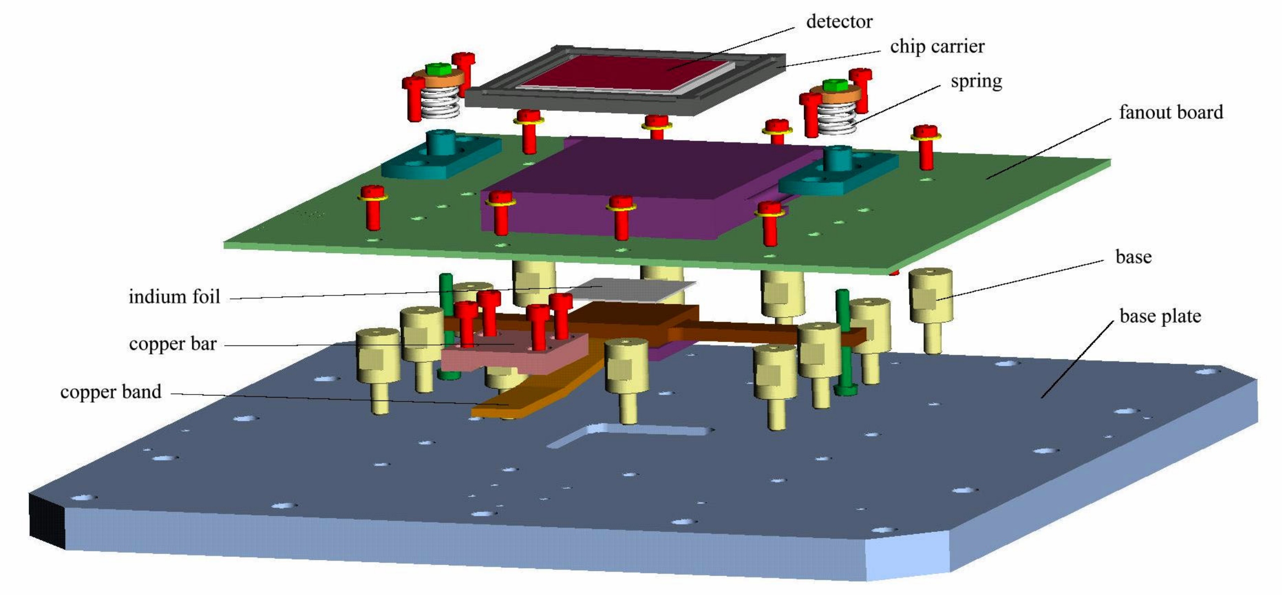



**Figure 12:** Exploded view of the detector unit with base plate, fanout board, detector and detector cooling mechanism.

## 6. BAFFLES

Omega2000 has a cold baffle inside the dewar to reduce thermal background emitted by the surrounding of the telescope pupil (floor, dome, walls, etc.). This background can be seen directly by the detector, since the optical layout has no cold pupil. The position of the cold baffle should be as far from the detector as possible, which in the f/3.5 beam of the primary mirror, leads rapidly to large diameters. The limit is defined by a reasonable diameter of the dewar window, feasible dewar dimensions and a maximum tolerated central obscuration. All these considerations are only of interest for K band imaging. For shorter wavelengths the contribution of the thermal background is negligible[8].

In addition to the cold baffle, Omega2000 is equipped with two warm mirror baffles. Both baffles are annular sections of an oblate ellipsoid with the edges (seen in a cross section) of the cold baffle as the foci. The surfaces of the mirrors are diamond turned (diameter 750 mm) and coated with protected gold to achieve a maximum reflectivity of about 95 %. The first baffle is at a fixed position and does not vignette the field of view of Omega2000. This arrangement is similar to the Omega Prime[2] setup which has proven a background reduction of ~ 20 %. The second baffle has a smaller inner diameter. It is designed to vignette the entire field of view uniformly. In this case, none of the warm surrounding or floor can be seen by the detector. Calculations show an improved S/N ratio in the K band for this set up[1]. For J and H band observations, the baffle can be moved closer to the dewar to a position where it does not vignet at all.

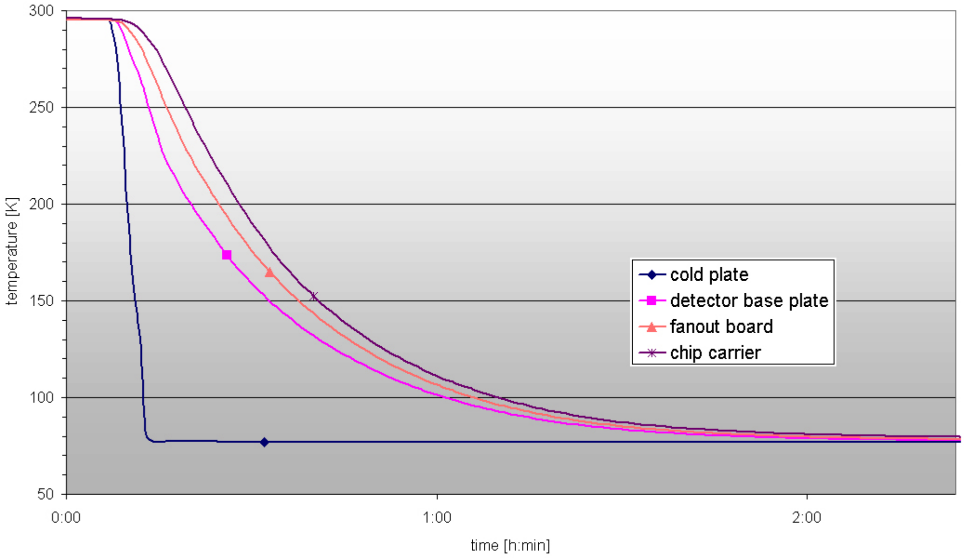



**Figure 13:** Temperature curves of detector unit parts

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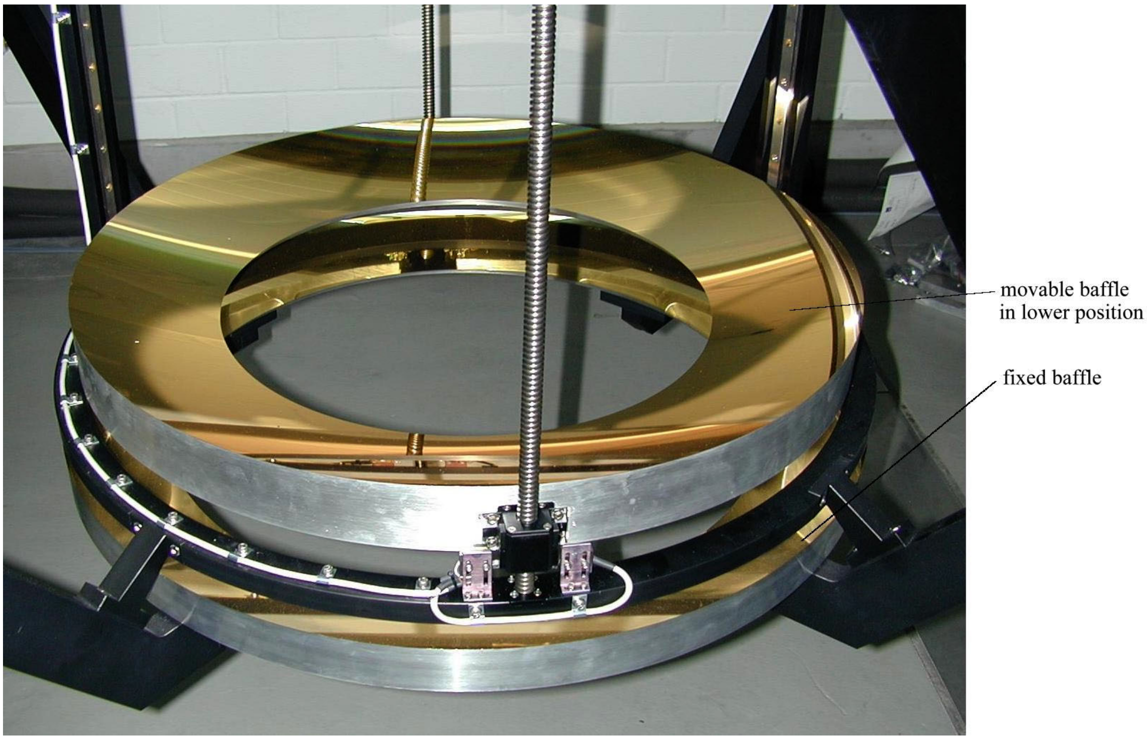


**Figure 14:** Warm baffles of Omega2000

## 7. CONCLUSION

The mechanical and optical parts as well as the control and readout electronics of Omega2000 are finished and have been tested successfully. All the components are working as expected. The integration of externally ordered parts and parts built in house has worked smoothly after a careful integration of both types in a common mechanical design. This requires a good collaboration with the companies since a lot of detail information is needed for the design and the simulations (FEA, cryo performance, etc.).

The science grade detector has recently been integrated in the instrument. After some more fine-tuning and several weeks of testing the whole instrument, Omega2000 will see first light at the telescope in January 2003.

## 8. ACKNOWLEDGEMENT

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- Firma Kaufmann, Crailsheim, Germany who made the large window;
- SwissOptic, Heerbrugg, Switzerland, who provided the second window with AR coating;
- Barr, Westford, MA, USA for plenty of filters;
- Rockwell, Thousand Oaks, CA, USA who developed the detector;
- Gatir, St. Archer, FL, USA for the fanout board.

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