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ABSTRACT

NOVA is involved in the development and realization of various optical astronomical instruments for ground-based as well as space telescopes, with a focus on near- and mid-infrared instrumentation. NOVA has developed a suite of scientific instruments with cryogenic optics for the ESO VLT and VLTI instruments: VISIR, MIDI, the SPIFFI 2Kcamera for SINFONI, X-shooter and MATISSE. Other projects include the cryogenic optics for MIRI for the James Webb Space Telescope and several E-ELT instruments.

Mounting optics is always a compromise between firmly fixing the optics and preventing stresses within the optics. The fixing should ensure mechanical stability and thus accurate positioning in various gravity orientations, temperature ranges, during launch, transport or earthquake. On the other hand, the fixings can induce deformations and sometimes birefringence in the optics and thus cause optical errors. Even cracking or breaking of the optics is a risk, especially when using brittle infrared optical materials at the cryogenic temperatures required in instruments for infrared astronomy, where differential expansion of various materials amounts easily to several millimeters per meter. Special kinematic mounts are therefore needed to ensure both accurate positioning and low stress.

This paper concentrates on the opto-mechanical design of optics mountings, especially for large transmission optics in cryogenic circumstances in space instruments. It describes the development of temperature-invariant (“a-thermal”) kinematic designs, their implementation in ground based instrumentation and ways to make them suitable for space instruments.

Keywords: Opto-mechanics, transmission optics, large optics, cryogenic, lens mount, prism mount, a-thermal, kinematic

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1. INTRODUCTION

Within the electromagnetic spectrum infrared (IR) radiation is usually called “near-IR” for the wavelength range $\lambda = 1\text{-}3\ \mu\text{m}$ and “mid-IR” for wavelengths $\lambda = 3\text{-}30\ \mu\text{m}$. The final performance of infrared instruments depends strongly on the minimization of instrumental thermal background radiation. In order to keep this internal thermal background as low as possible, IR instruments are cooled to cryogenic temperatures, usually at or below liquid nitrogen temperature (77 K).

Because of the properties of Planck’s radiation law the instrumental background requirements are most demanding for mid-IR instruments, resulting in instrument temperatures below 30 K. For the infrared detector arrays an even more extreme temperature regime is required; they generally operate at temperatures below 10K.

The various temperature regimes, warm circumstances during manufacturing/integration and cryogenic operational conditions, complicate the design and development of these cryogenic instruments. In general the material properties (CTE, heat capacity, E-moduli, refractive indices etc.) of various materials change differently and in a non-linear fashion during cooling. These varying material properties cause not only geometrical changes but also optical differences between the instrument at room temperature (manufacturing, assembly, integration and verification) and the operational temperature (verification and functioning).

Geometrical differences are mainly caused by the CTE differences between the various materials which can cause misalignments, deformations and even breakage. In addition other optical differences are caused by changes in the refractive indices.

If all parts the optics as well as the structural parts are from the same material then the optical performance of an instrument is invariant to temperature changes. Although the physical dimensions of the instrument change with temperature, the surface curvatures of the optical components will scale homogeneously, resulting in an exactly scaled instrument. Within transmissive optical designs the optics are (inevitably) of very specific material. During cooling inhomogeneous scaling will occur and the optical performance changes/deteriorates.

2. OPTICS MOUNTING

Mounting optics is always a compromise between firmly fixing the optics and preventing stresses within the optics. The fixing should ensure mechanical stability and thus accurate positioning in various gravity orientations, temperature ranges, during/after launch, transport or earthquake. Unfortunately these fixings can induce deformations, stresses and birefringence in the optics, and thus cause optical errors.

When transmission optics are used within demanding environments like cryogenics and launch, additional risks of cracking or breaking arise. The glass-like materials of transmission optics have specific material properties compared to the commonly used material for the structural parts (aluminium). They usually have relatively low (non-linear) CTE and are brittle and sensitive to stress.

High stresses occur not just because of the severe launch loads but also due to the cryogenic temperatures, where differential shrinkage of various materials amounts easily to several millimeters per meter. This makes it very important to provide kinematic mountings with sufficient freedom of movement that allow safe compensation for CTE differences and maintain accurate and repeatable positioning in all circumstances and preferably at all temperatures.

Transmission optics

The following general requirements can be identified for mounts in the case of transmission optics:

- Low/no stresses within the optics
- Accurate positioning environments
- Survive launch/transport environment
- Adjustment free
- Simple optics geometry
- Good heat conductance
- Accessibility of refs during manufacturing
- Limited number of (additional) components
- Detachable not bonded optics

Kinematic mount

The position of an optical element can be defined uniquely in terms of six independent coordinates, degrees of freedom (DOF): three translations (T_x , T_y , T_z) and three rotations (R_x , R_y , R_z). A mount is called “kinematic” when each DOF of the element is at most only once constrained. Kinematic couplings can be used to constrain all 6 (accurate positioning) or any (accurate movement) of these DOF without distortion and with excellent repeatability.

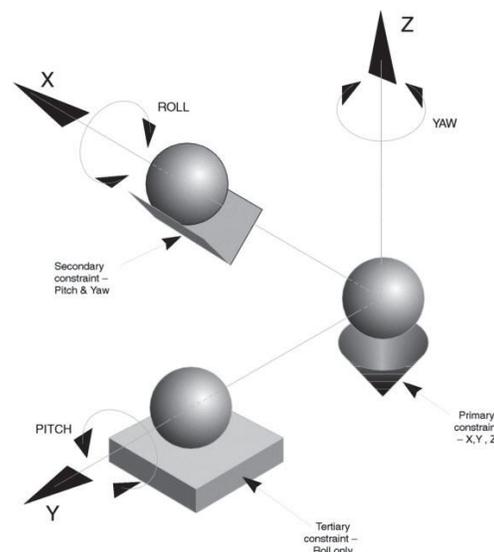


Figure 1: The theoretical representation of the classical “cone, groove and flat” kinematic mount (figure: courtesy Newport Corp.). The three balls are part of the element. With this type of mounting extra precautions are necessary to ensure correct positioning of all parts e.g. under varying gravity orientation. That makes this type of mounting less suitable for many astronomical applications (instruments in cassegrain foci, space instruments).

Non-kinematic mount

In practice it is not always possible and/or necessary to create full kinematic mountings. Sometimes support points are needed in order to avoid too much deformation of the optical element under its own weight (sagging), or there is not enough space available around the optical elements to provide room for the necessary structures/compensation mechanisms.

In special cases the choice is even made to overconstrain one or more of the DOF. By accomplishing high manufacturing accuracies e.g. super flat and accurate mounting surfaces the optical element can remain unstressed when mounted ‘non-kinematically’.

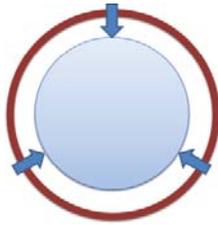
3. CONCEPTS

When a low-CTE optical element will be enclosed by a high-CTE support (this is the case for all aluminium and IR transmission material combinations) the optical component will get tightly squeezed by the support when cooled. Preferably the alignment should remain accurate for both ambient as well as at cryogenic conditions, this allows for maximum freedom regarding test/verification.

Radial mount principle

There are several ways for radial mounting of the lens.

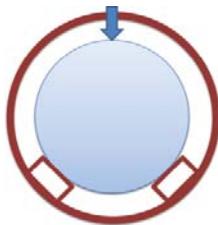
Kinematic springs



Most commonly a set of three leaf spring/pivot hinge constructions (located symmetrically at $3 \times 120^\circ$ around the Centre of Gravity (CoG) of the optical element) is used. The leaf springs are very effective to release or constrain specific

DOF, free of friction, wear and hysteresis. When possible this type of mounting is integrated within the optical element itself, but for transmission optics this needs to be provided within the support structures or in a dedicated substructure.

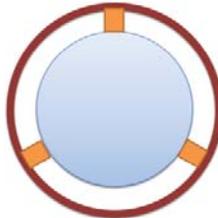
V-block



The v-block solution will cause decentre errors between ambient and cryo conditions. The necessary spring loading would make it susceptible to errors at changing gravity directions. High spring loading would be necessary to survive launch

loads, causing additional (to high) stresses and thus Wave Front Errors (WFE).

Compensation



In special CTE compensation mounts the shrinkage differences between the support and the optical element are compensated by special kinematic couplings. These special pads have higher CTE than the structural or optical

material and are dimensioned for each optical element individually. The pads are dimensioned such that they shrink sufficiently to compensate for the CTE differences between support and optics. The CTE compensation mount is successfully used within several ground based high accurate cryogenic instruments, SPIFFI (2K camera) and X-Shooter (NIR arm).

Bonding lens and holder

When fully detachable optical elements are required, the combination of maximum allowed stress on the element and the relatively large CTE differences makes the design of a traditional kinematic mount with leaf springs/pivot hinges virtually impossible. At all times only part of the springs can bear the lens load. So the spring rate of each spring should be sufficiently high to keep the optical element from sagging, but also low enough to avoid overstressing (resulting in deformation, birefringence or even breakage) of the optical element. It is very difficult to find a spring rate that fits both requirements at ambient and cryogenic temperatures,

especially for larger optics because the absolute shrinkages differences increase with size.

Using a kinematic spring mount the lens requires the lens to be bonded to the springs. This allows all the spring at the circumference of the lens to bear the load of the lens. Particular issues arise when bonding to the typical lens material. The CTE of cryogenically suited glues are generally very different in comparison to the lens materials. This means that extreme care should be taken to avoid stresses due to the glue spots.

In addition the adhesion of the glue to the lens is so high (which is normally preferred for glue constructions) that, instead of simply delaminating, the glue pulls small chips of the brittle material from the actual lens, causing severe damage and high risk of cracking. This effect could be predicted [1], but requires detailed knowledge on the glue properties; adhesion/cohesion/viscosity/CTE etc. of the glue at the full temperature range. Also precise dimensioning of the glue spot [2]; size/thickness etc. is needed. Generally rather small glue spots [3] are required and special tooling is needed to apply the glue with sufficient accuracy.

Axial position of radial support

The axial position of the radial pads is another important aspect to reduce the deformation effects on the lens. An axial position at the full material of the lens is important or (unnecessary) additional deformation is the result. This effect can be illustrated with a meniscus shaped lens. When mounted at the lens centre plane:



This way additional deformation is created. By mounting at the thickest part in this case more at the edge:



The additional deformation is limited due to the guiding of the stresses through the main bulk of the material.

Axial mount principle

The axial positional accuracy is provided by the hard mounting against the holder/mount on a preselected number of support points. For positional accuracy (at operational conditions) the lens should remain pressed against this reference at all times. A simple spring can be used:



Specifically when facing high loads (e.g. during launch) gapping should be avoided thus the dimensioning of this spring can be problematic. A similar CTE compensation as for the radial support can be used for the axial support eliminating this gapping problem.



The axial mounting is less critical than the radial mounting due to the location and direction of the forces. When the spring or CTE location is opposite the support points the lens will only experience local compression forces, but no additional surface deformations will occur. Birefringence effects due to the compression stresses around the mounting points should be checked, however the affected zone will be limited.

Number of mounting points

As previously described a proper kinematic mount requires no more than three mounting points between the lens and the holder.

Especially larger rather thin lenses may require more support points. Not just the total surface deformation is but also the actual surface shape should be considered, which has a direct impact on the wave front error. Some typical shapes can be more easily compensated than others; e.g. a defocus shape error can be compensated by a simple translation of the component while trefoil and derivative forms are very difficult to compensate for.

Figure 2 shows the effect of either three or six radial support points on a lens. The 6 points allow for a smaller overall deformation together with a more favourable and easier compensated surface form.

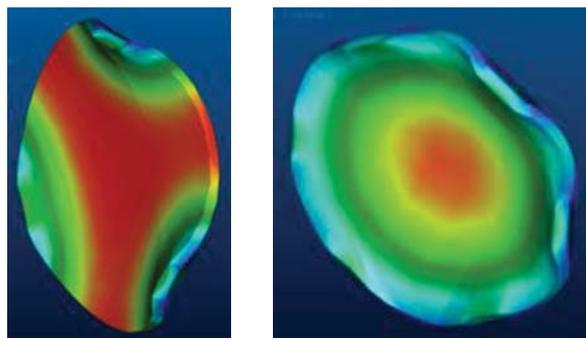
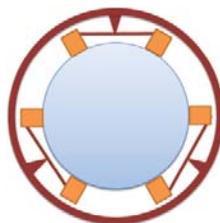


Figure 2: Deformation of a lens (SPIFFI L1) with 3 and 6 pads. The total force is identical for both situations but divided over respectively 3 or 6 points, resulting in a surface deformation of L1 of respectively 3.83 nm and 2.04 nm. The 6 mounting pads show less deformation 2.04 nm, compared to 3.83 nm for three pads, and in addition a much favourable surface shape

By means of special Whiffletree constructions the number of support points can be increased without compromising the kinematic quality. However these constructions are rather complex and space consuming:



So the design of a proper kinematic mount should remain the key driver, however as mentioned before sometimes it is necessary and more practical to have a semi/non-kinematic mount. This decision cannot be taken mildly, and proper risk

assessment should be provided to prove necessity and to analyse the solution.

Isostatic point of optics

Every component inside the instrument will have its individual isostatic point; this is the point that remains stable and unchanged in either warm or cold circumstances. This point is a result of component shape and mounting principle. Within the special CTE compensated mount this isostatic point can be (re)located at a more favorable location which has a positive influence on the warm-cold conversion through less additional component and thus beam shifts. This is illustrated in Figure 3.

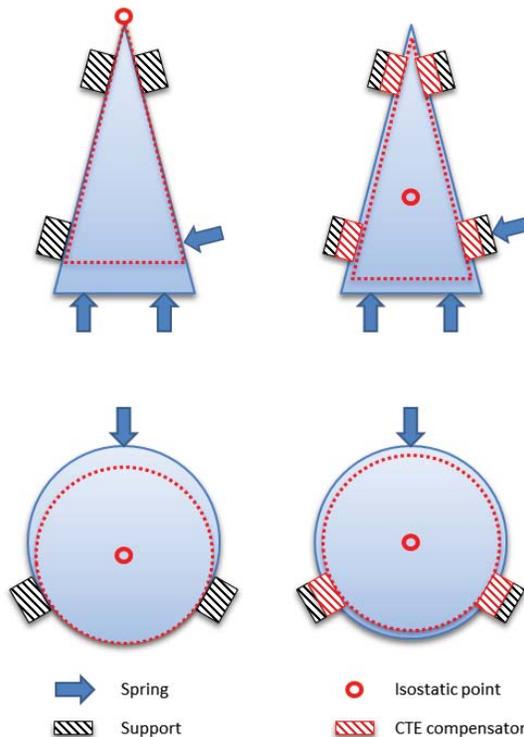


Figure 3: Isostatic points for various mounting methods of lenses and prisms. The circle indicates the location of the isostatic point. The situation at operational temperatures is shown with the red dotted lines.

4. FULLY CTE COMPENSATION MOUNT

The holder will have CTE compensation for radial as well as axial support, this way creating a very stable mounting, while maintaining low stresses and accurate alignment at ambient as well as operational temperatures. A minimum of 6 pads, radially as well as axially is preferred. Axial support and CTE compensation will be located opposite each other in order to minimize additional lens deformations.

Assembly build up

The holder consists of a dedicated mounting ring with a cover. Within the mounting ring 6 slots are provided for the 6 combined axial and radial CTE compensation pads. The pads can slide within their slots in axial direction. The CTE fixation screws are used to accurately manoeuvre and fixate the CTE pads in radial direction. Axial fixation is provided by the cover with 6 integrated but elevated pads.

The CTE compensation pads are made of high CTE material, higher than the used holder and lens materials. Accurate dimensioning of the CTE pads will ensure that the dimensional differences between the (faster shrinking) holder and the lens (not/limited shrinking) is compensated for. Resulting in accurate positioning together with no/low internal stresses.

Material choice

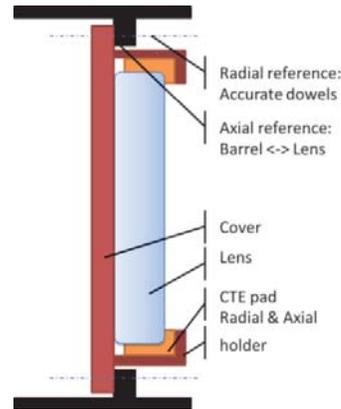
The main building material used within cryogenic instrumentation is (still) aluminium, due to the favourable material properties from (relative) low density, to ease of manufacturing. Unfortunately aluminium is amongst the metals with the highest CTE. The material for the CTE compensation needs higher CTE than either the lens or holder material, also the higher the CTE the smaller the overall packaging.

Thermo elastic plastics like POM and PTFE have suitable high CTE together with some less desirable properties like; high thermal resistance, sensitive to creep, non-linear CTE (and different progression than metals). However by proper dimensioning these issues can be overcome.

Alignment

Axial

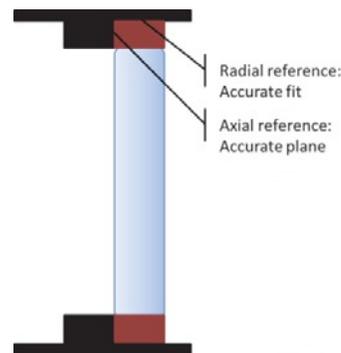
The axial positioning of the lens and holder assembly can be provided by means of the cover. This way the same reference is used for the lens position in the holder as well as for the final positioning of the lens assembly in the instrument/barrel. Accuracy of this reference plane can be improved by precision lapping of the surface.



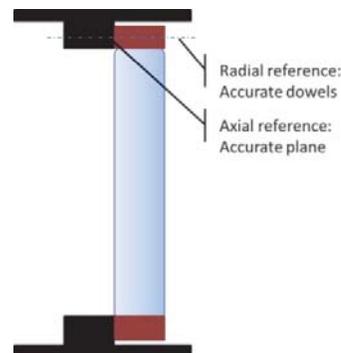
Radial

The radial positioning of the lens within the holder is accomplished by means of several accurate references. For the radial alignment the holder is provided with accurate flat surfaces at the circumference of the holder. These surfaces can be accurately positioned with respect to the interface features of the holder with respect to the instrument/barrel. The CTE pads and thus the lens will be referenced to these flat surfaces, thus no referencing with respect to the inner geometry of the holder is used/required.

The positioning of the lens assembly with respect to the instrument/barrel can be done in several ways either by an accurate fit between the holder outside periphery and the instrument/barrel inside periphery:



Or by means of two small dowel pins:



Due to the decrease in manufacturing accuracy of the large diameters the accurate fit solution turns out to be less accurate. The table shows final positional accuracy with a precise but normal manufacturing strategy.

	Tolerance	Displacement	
		2 pins	1 fit
Pos. Tol. holes mount	$\varnothing 140 \pm 0.02$	0.01	0.01
Pos. Tol. holes barrel	$\varnothing 140 \pm 0.02$	0.01	0.01
Play 2 pins - holder	5h6/H7	0.0042	
Play 2 pins - barrel	5h6/H7	0.0042	
Play barrel - mount	140h6/H7		0.029
RSS		0.0153	0.032

Another disadvantage of the accurate fit is the difficult assembly and integration of such a construction. The lens assembly must be assembled accurately perpendicular with the centre axis or there is a high risk for getting stuck before the final mounting position is achieved.

Isostatic barrel mounting

When necessary, if for instance a different material for the instrument/barrel compared to the holder additional isostatic mounting features can be easily added to either the holder cover or (partly) within the instrument/barrel geometry.



Figure 4: Kinematic mount with 3 double ended clamped leaf springs at 120 degrees each at the circumference, for accurate a-thermal alignment. The three centrally located dowel pins are key for the alignment accuracy of this kinematic mount

Integration

Maximum positional accuracy is accomplished by means of design (limit interfaces), manufacturing (design and location of interfaces are chosen at positions for maximum manufacturability) and integration (avoid tolerance build-up by means of preliminary measurements on components and integration order).

To maximize positional accuracies the following integration order is used:

- Mount CTE pads
- Position accurate hard stops (referenced to flat surfaces at holder circumference)
- Determine torque for CTE fixation
- Mount 3 (or 6) CTE fixations
- Replace hard stops with CTE fixations
- Mount cover

In general the lens centre is accurately located with respect to the outer diameter, however the actual diameter is not that accurate. So previous to the fabrication of the hard stops the actual lens diameter and CTE pad dimensions are measured, so these hard stops can be made to high accuracy, allowing accurate positioning of the lens.

Thermo elastic effects

The thermo elastic effects within the lens is set by the heat capacity and heat conductance values of the material itself. Because the cooling can only be delivered at the edges of the optical element the actual shape and size are an important factor.

Temperature gradients within the lens result in stresses. The allowable stress level defines the allowable gradient which then provides the safe cool down/warm up rate.

Thermal analysis is performed on the thermo elastic effects on the SPIFFI L1 lens. A gradient of 18 K was found at a cooling rate of 24 K/h, causing a maximum stress of 8.2 N/mm² which is well below the damage limit. Remember that these maximum stresses occur during warm-up/cool-down thus accurate performance is not required.

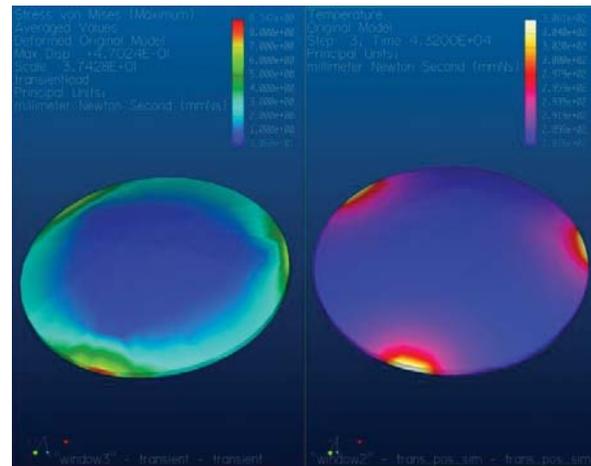


Figure 5: Thermo elastic analysis of the SPIFFI L1 lens. Left the maximum von Mises stresses of 8.2 N/mm² due to the temperature gradient of 18 K (right) caused by a cool down rate of 24 W/h. cooling input at three spots at the lens circumference.

Thermal coupling

For the SPIFFI lens mount POM is successfully used as CTE compensation material. Although thermal conductivity of this material is low and thus the cooling through the radial pads was not ideal, no addition cooling leads where necessary. For the X-shooter instrument additional cool leads are used to provide additional cool capacity to the lens.



Figure 6: X-shooter corrector lens with additional thermal leads; the copper strips at the lens circumference

5. ANALYSES

CTE uncertainty

One remaining risk at operational temperatures is set by the uncertainty regarding the actual CTE values of the various materials and the manufacturing accuracy of the CTE pads. This results in deviations regarding the final dimensions of the various components at operational temperature which subsequently may result in additional stresses in the lens or play between the lens and holder.

Analyses on three specific lenses show that the effect of these CTE uncertainties is rather small.

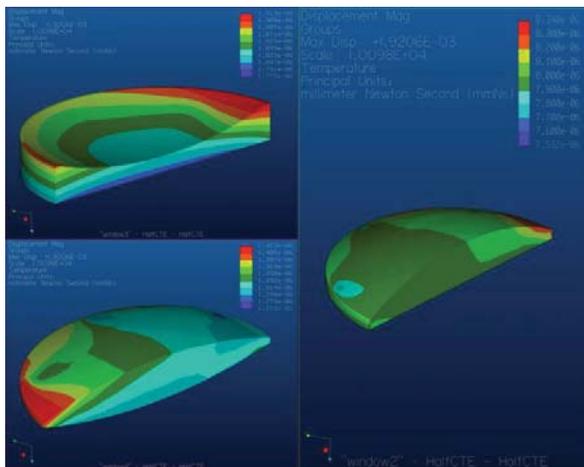


Figure 7: Additional expected lens deformation due to CTE uncertainties within SPIFFI; L1 1.4 nm (lower left), L2 1.9 nm (upper left) and L3 (right) 8.3 nm at an operational temperature of 77K.

This minor effect can be explained by the intrinsic flexibility of the holder and the CTE pads. Effectively the lens is mounted within a very stiff spring (the mount) which provides some flexibility to cope with the dimensional differences, though very small, caused by the CTE deviations.

Because the relative stiff nature of the holder the alignment problems and stresses, as described previously for kinematic spring mounts, are avoided and the lens remains accurately located.

Launch

During launch it is important that the optical element survives the extreme loads without alignment or other implications. However the stringent positional and surface form accuracies do not apply during launch.

At the ambient conditions during launch the lens is held accurately and play free by the CTE compensation mount. Finite Element Analysis show, as can be expected, a relative high Eigen frequency and low stresses.

60G static load

A 60 G gravity loading analysis is performed in the three main directions. Highest stresses occur with the gravity z loading where the holder shows the maximum stresses, specifically in the (weaker) cover, though within the safety limits of aluminium 6061.

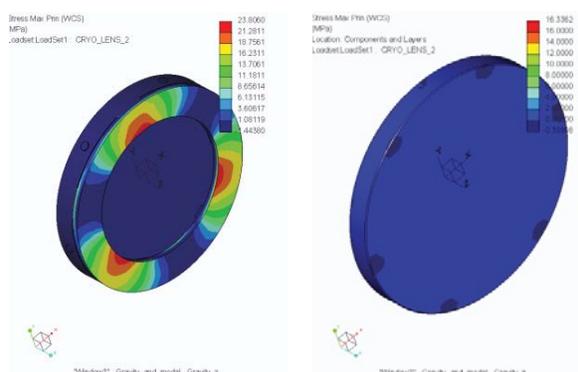
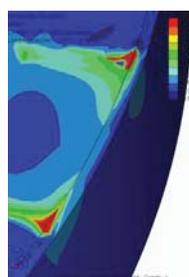


Figure 8: Stress distribution within the total assembly (left) and the lens (right).



The lens itself shows smaller overall stresses, although on first glance outside safe limits. Due to the simplifications within the analysis, surfaces touching each other are assumed rigidly connected, locally high stress points are found. These singularities can be ignored.

Modal Analysis

The analysis show a first frequency of 3105 Hz. Due to the FEA simplifications, rigid connections between components, this number will be lower in practise.

6. GROUND BASED APPLICATIONS

Large optical transmission components are successfully used within several ground based high accurate cryogenic instruments [4]; SPIFFI (2K camera) and X-Shooter (NIR spectrograph). Typical lens sizes of \varnothing 176 mm at operational temperatures as low as 77 K and under changing gravity loading where used.

SPIFFI 2K Camera

The first cryogenic lens mounts with CTE compensation mount were developed for the SPectrograph for Infrared Faint Field Imaging (SPIFFI) 2K camera. SPIFFI is part of the SINFONI instrument on the ESO Very Large Telescope (VLT) in Chili. The SPIFFI instrument is located at the cassegrain focus and thus feels a varying gravity. Due to the wavelength range λ : 1.1 μ m to 2.45 μ m the instrument operating temperature is 77K.

A new camera was designed to allow the use of an extended 2Kx2K pixel detector. The camera consists of 5 different lenses of various materials and sizes, see Figure 9. The camera is folded by means of a folding flat in order to fit the camera within the available space envelope.

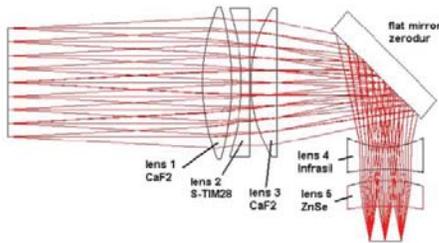


Figure 9: Optical design of the SPIFFI 2K camera consisting of 5 lenses and one folding flat. The lens triplet consists of the first three lenses while the last two lenses are joined in the doublet.

	Material	Size [mm]
L1	CaF2	\varnothing 176
L2	S-TiM28	\varnothing 172
L3	CaF2	\varnothing 172
Mirrors	Zerodur	NA
L4	Silica	\varnothing 88
L5	ZnSe	\varnothing 88
Support	Al 6061	NA

The lenses are combined in two separate groups, the triplet and the doublet. The triplet assembly consists of the first three lenses L1, L2 and L3 (see Figure 10), the triplet and doublet are preassembled and then located accurately within the 2K camera structure. The triplet assembly consists of the L1/L2 assembly onto which the L3 assembly can be mounted. The L1/L2 assembly holds, as the name already suggests, the L1 and L2 lenses. Both have their individual radial and axial supports but share one axial spring. The L3 assembly consists of the radial/axial support an individual axial spring.

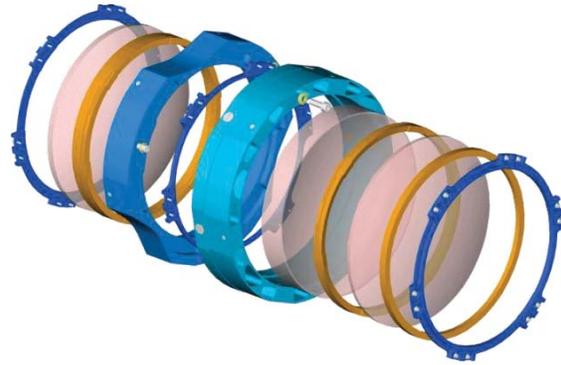


Figure 10: The main housings of the triplet are accurately lapped to the required dimensions. The axial springs push the lenses (transparent) to the axial supports (darkest colored rings) that are referenced to these outside (lapped) surfaces. The aluminium contact surfaces with the lenses are treated by Teflon-filled hard anodization to reduce internal friction. Within the housing the six radial supports are located (small light grey circles).

The triplet was the most stringent assembly as the accuracies are determined by the most demanding requirements, in this case the image position

	Position [μ m]		Tilt [$^{\circ}$]	
	Initial	stability	Initial	stability
L1	50	0.5	0.030	0.002
L2	50	0.5	0.015	0.002
L3	50	0.5	0.030	0.002

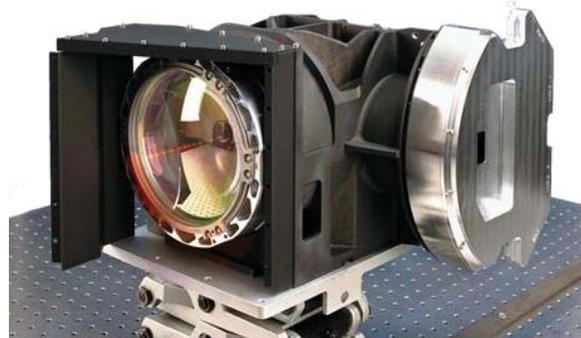


Figure 8: 2K camera assembly; at the front the triplet assembly, the doublet is located inside the camera structure (at the right hand side) and thus not visible in the photo.

X-shooter

Lens mount

In the X-shooter near IR Spectrograph both the camera and the corrector lens are mounted by means of the special CTE compensation mount.

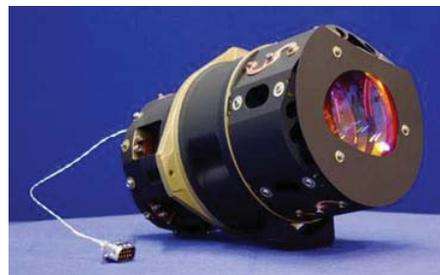


Figure 11: X-shooter camera

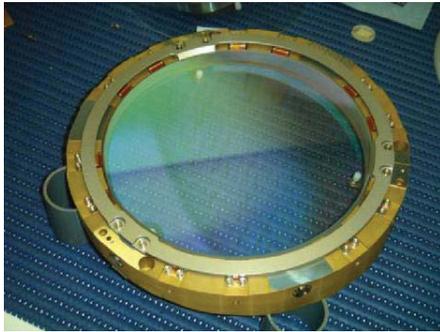


Figure 12: X-shooter corrector lens

Prism Mount

The principle of CTE compensation is also used for the mounting of prisms. Within the X-shooter near-IR spectrograph the cross dispersion is provided by three large prisms in double pass.

	Material	Dimensions [mm]	
		Base Plane	Height
Prism I	Infrasil	160x160x98	169
Prism II	ZnSe	140x140x56	149
Prism III	ZnSE	129x129x52	135

Each prism is supported by three fixed pads at the bottom. A holding force is provided by a spring-support with pads directly opposite the three base pads. The isostatic point of the prism is relocated to the centre of the prism by means of high CTE compensation pads. Of two opposite compensation pads one is spring-loaded to achieve proper positioning of the prism against the pads in all circumstances. To increase thermal contact between mount and prism extra flexible thermal pads are provided.

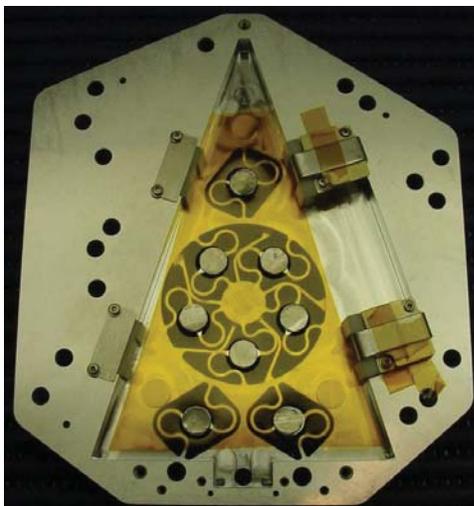


Figure 13: The X-shooter test prism base support plate. Clearly visible are the special thermal contact pads and their elaborate spring connections that ensure thermal contact with the prism at all times. On the pads the small circles of indium foil to improve thermal conductivity. The Kapton layer between prism and support pads reduces friction for maximum compensation during cool-down/warm-up. CTE compensation pads are located on either side of the prism area.

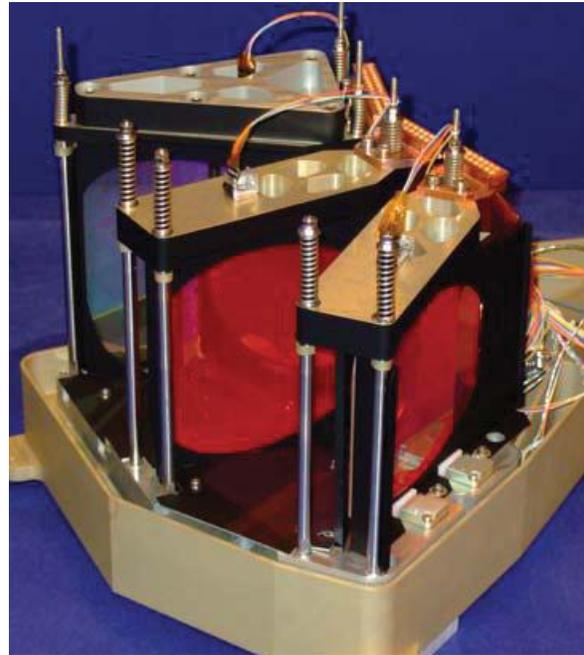


Figure 14: The X-shooter prism bench. The fully integrated prism with bench with the spring loaded top supports. The special CTE compensation pads (white) are seen at the side of the prism.

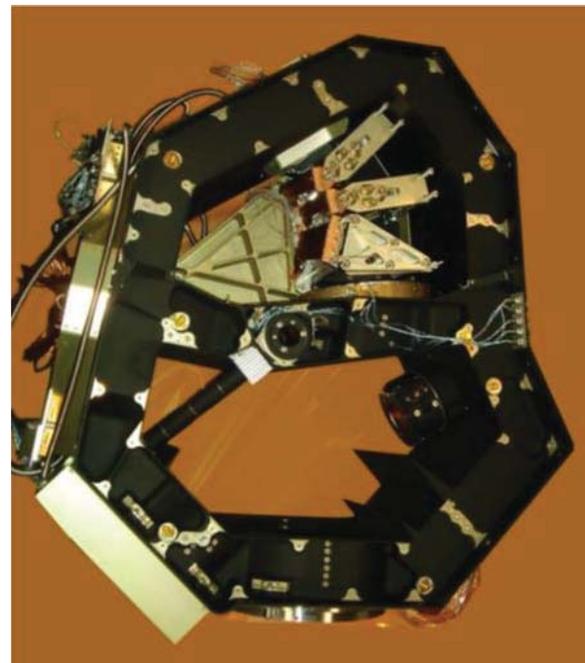


Figure 15: X-shooter near IR Spectrograph

7. CONCLUSIONS

The ever increasing ambition in observational astronomy is a driving force behind the technical research and development for infrared astronomical instrumentation. The development of astronomical IR instruments is evolving strongly and every new instrument tends to be more sophisticated.

The pursuit of a-thermal and adjustments-free instrument designs is important because it provides the new technology for the next generation of infrared instrumentation. High accuracy, stress-free mounts for cryogenic optics is the key enabling technology for these state-of-the-art IR instruments.

In this paper we discussed mount designs for cryogenic transmission optics. These mounts have been applied successfully in ground based infrared instruments like Sinfoni-SPIFFI and X-shooter. It has been shown that with simple adaptations these high accuracy, stress free mounts are well suited to supply a safe launch environment for transmission optics. This opens the possibility to use adjustment-free, cryogenic infrared instrument designs in space.

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