Recent development in cryogenic optical and mechanical design

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ABSTRACT

With the advanced of instrument design for space exploration and NIR application, the optical systems working at cold temperature become more and more common. Over the past, many lens system has been used at cryogenic temperature making available a lot of cryogenic material data including CTEs and index of refraction. It is now more accessible than ever to design cryogenic lens system. However making a lens design working at cryogenic temperature is still a challenge. To avoid any problem during operation (mostly at cold temperature), both optical and mechanical designer must work together. This paper gives a modest overview of the most recent progress in this field. It provides the basic knowledge that can be used by both lens and mechanical designers to perform cryogenic optical design with success.

Keywords: Mechanical design, lens design, material properties, cryogenic optics

1. INTRODUCTION

From the web site 'wikipedia'[1], cryogenics is defined by the study of the production of very low temperature (below −150 °C, −238 °F or 123 K) and the behavior of materials at those temperatures. A person who studies elements that have been subjected to extremely cold temperatures is called a cryogenicist. Rather than the relative temperature scales of Celsius and Fahrenheit, cryogenicists use the absolute temperature scales. These are Kelvin (SI units) or Rankine scale (Imperial & US units). To design an optical system that will work at cryogenic temperature relies on knowing the behaviour of materials at those temperatures.

In the IR (wavelength higher than 1um), the final performance of instruments depends strongly on the minimization of thermal background radiation. In order to keep this thermal background as low as possible, the instruments are therefore cooled to cryogenic temperatures, usually at or below liquid nitrogen temperature (77 K) or even lower for space applications.

The increasing ambitions to find answers with astronomical or space observations and explorations drive the development of technical capabilities for instrumentation forwards. The development of instruments is thus evolving strongly and every new instrument tends to be more sophisticated than the precursor. This instrument sophistication relies on the realisations of well designed cryogenic optics. . An important part of this sophistication lies in the realization of cryogenic optics.

This paper gives a modest overview of the most recent progress in the optical design of a cryogenic instrument. To operate in this harsh environment (cold), we rely on some basic knowledge that can be used by both lens and mechanical designers to perform cryogenic optical design with success.

2. BASIC CRYOGENIC DESIGN

The development of a new instrument starts with the translation of the science requirements into a basic optical design. This set of optical requirements is used to develop a conceptual design which will demonstrate if the requirement can be meet or if it needs refinements. Modification of the science requirements is not an easy task since optical designer or instrument system engineer and astronomers (if it is about astronomical instrument) doesn't necessarily speak to same language. The conceptual design is certainly an ideal review milestone to tune the goal of the instrument according to technological limits. Assume that we have 'GO' to pursuit the design, we will perform a preliminary design. I preferred to make a hot design (at room temperature) at this stage from a selected set of glasses which I know (or where I can find) the cryogenic data (indices and CTE). The preliminary design is nearly a final design but at room temperature. The next step is the final design. The final design is the optimization of the PDR design using cold data (and vacuum between

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optical components if it is applicable). All the prescription data are cold from the lens dimension to the airspace. Having a cold design is not the end. Full optical prescriptions for both cold and room temperature are necessary: a cold design at cryogenic operation temperature and a warm design at room temperature for manufacturing, integration, alignment and test purposes. All lens parameters will be scaled, thickness and radius. If the housing (mechanical) is in aluminum, we can also scale the air space (vacuum) with the Al CTE. The new scale prescription is a hot version of the lens design. This is the version that you will have in the laboratory when all components will be mounted. The tolerance between warm and cold are very strict and proper error budgets are critical. Proper error budget requires appropriate knowledge of both optical and mechanical design and their interaction for the warm as well as the cold design. Moreover, the interaction between optical and mechanical parts must be also understood during cold down. Appropriate cold down time is required. The figure 1 shows a BaF2 lens (160mm in diameter) which brakes after a rapid cool down time of 40min. The lens brakes at 100 K under the internal tension. The brakeage does not seem to be related to the mount according to the author of the paper [2].

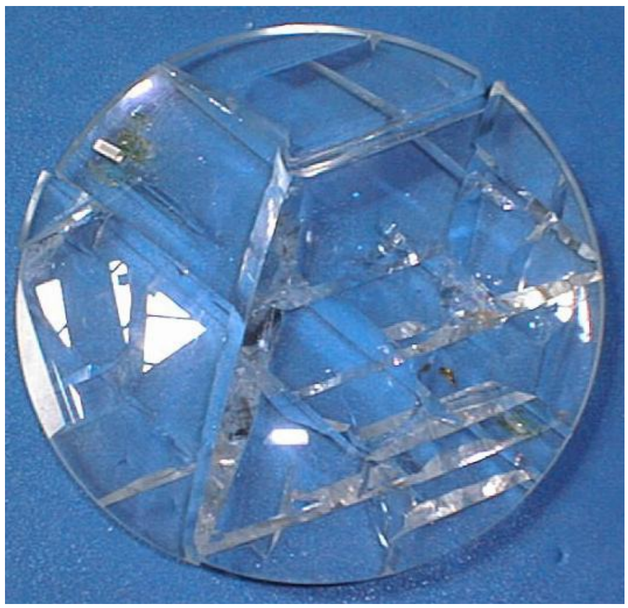

Figure 1: BaF2 lens brakes during a cooling in 40 mn[2]

One question remains, do we trust the cold data from the literature? This is a very good question and the answer is not satisfactory. The answer is yes and no. Yes, many optical systems have been developed using the cold data available in the literature so it seems that we can trust it. No, we always have to be careful and to include safety margin within the tolerance analysis. For example, I highly recommend to keep +/-0.001 for the tolerance of the indices of refraction at cold temperature (safer approach, the temperature can be more or less different at the final stage and the data are always not as good as room temperature where you can measure the index easily). For the CTE, maybe a +/-10% is also a safe approach.

The temperature dependant Sellmeier coefficient of refractive index (in vacuum) can be obtained from previous works. Pioneer works were done by Tropf (1995)[3]. Measurements have been done by NASA with the CHARMs cryogenic refractometer (thanks to JWST development project) by Leviton & al (2005 and 2006) [4-5] for most of the available material for 0.6 to 5um applications. The data for the S-FTM16 have been obtained by Brown et al (2004) [6] with University of Arizona. Examples are given in [7], the figure 2 gives the glass data at 77K using the zemax catalogue file format which is a very good starting point.

The following figures show Thermal coefficients ($\Delta L/L_0$, %) for glasses and metal between room and cold temperature [8-10].

GLASS	TEMPERATURE (K) 77	100	110	150	Density g/cm^3
BaF2	-0,317	-0,298	-0,288	-0,24	4,9
CaF2	-0,302	-0,287	-0,278	-0,236	3,2
ZnSe	-0,117	-0,112	-0,108	-0,092	5,3
ZnS	-0,096	-0,093	-0,091	-0,079	4,1
SF6	-0.151				
SiO2	-0,0001	-0,0013	-0,0023	-0,0035	2,2

Figure 2: Glass thermal coefficient (% change)

METAL	TEMPERATURE (K) 77	100	110	150	Density g/cm^3
Magnesium	-0,421	-0,416	-0,381	-0,315	1,8
Aluminum	-0,392	-0,371	-0,356	-0,297	2,7
Brass 70/30	-0,34	-0,313	-0,301	-0,245	8,5
Copper	-0,304	-0,282	-0,27	-0,215	9
Berylco 25	-0,301	-0,279	-0,269	-0,221	8,4
Nickel	-0,221	-0,208	-0,199	-0,161	8,9
Hastelloy X	-0,217	-0,2	-0,191	-0,153	9
Steel 1075	-0,183	-0,169	-0,161	-0,13	7,9
Platinum	-0,17	-0,157	-0,149	-0,119	21,5
Ti + 6Al	-0,171	-0,155	-0,148	-0,118	5(?)
SS410	-0,164	-0,152	-0,146	-0,12	7,7
Ti + 4Al	-0,154	-0,14	-0,133	-0,106	5(?)
Titanium	-0,143	-0,136	-0,13	-0,105	5
Ti + 16V	-0,145	-0,133	-0,127	-0,101	5(?)
Molybdenu m	-0,087	-0,083	-0,079	-0,064	10,2
Invar 36	-0,0162	-0,0137	-0,0121	-0,006	8,1

Figure 3: Metal thermal coefficient (% change)

Good match provides an ideal situation between cold and room temperature [7]. Brass 70/30 can match pretty well with BaF2 and CaF2, ZnSe and Steel 1075, SiO2 and Invar 36. However, as the optical design uses various types of glasses, it is not practical to use different type of metal mounts which may result in serious matching problems. Consequently we need a good mechanical mounting scheme to ensure a stable cold system.

Various approaches are possible. Gal et coll. presented test results in 2012 regarding the mounting of large CaF2 lenses [11] that can survive the launch loads. Adhesive bond to hold lens at cryogenic temperature have been also studied for NIRCam (JWST) [12]. They studied the mounting of ZnSe and BaF2 lenses using a particular scheme. Three adhesives have been studied: Epibond 1210, 3M 2216, and Lord 7450. The following figure is a from [12] (figure 1). It shows the particular mounting scheme used in the system.

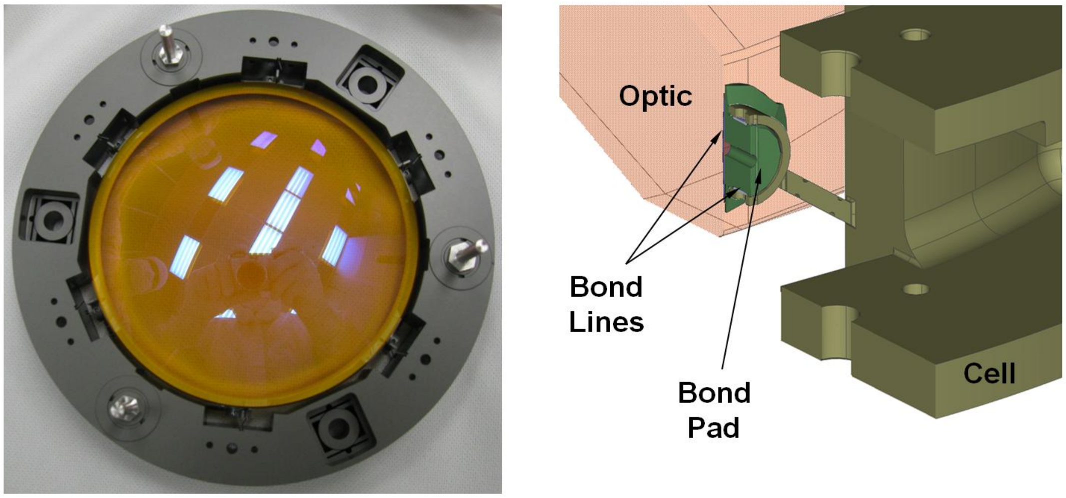

Figure 4: Bonded ZnSe Flight Lens Cell (left), Cutaway View at Bond Pad (right) [12]

In our laboratory, we use an approach which was described in [13]. The lens is first placed in a cell with a conical surface tangent to its surface at periphery (figure 5). The lens is then maintained axially via a ring loaded with beryllium-copper springs which compensate for the axial differential contraction. The force applied on the lens by the springs is about 5 times its weight. To maintain lenses in their positions while not applying excessive stress on them, the lenses are centered with nylon or teflon pads. Both materials have large contraction coefficients (1.22% and 1.94% respectively between 77K and room temperature) and for all lenses there is a pad length that allows a perfect match between the lens + pad diameter and the cell size at room and cryogenic temperatures. The optimal length of the pad is Lpad = Rlens (C-Al – C-lens)/(C-pad – C-Al), where Lpad is the pad length, Rlens the lens radius, and C-Al, C-lens and C-pad the contraction coefficient of aluminum, the lens glass and the pad material respectively.

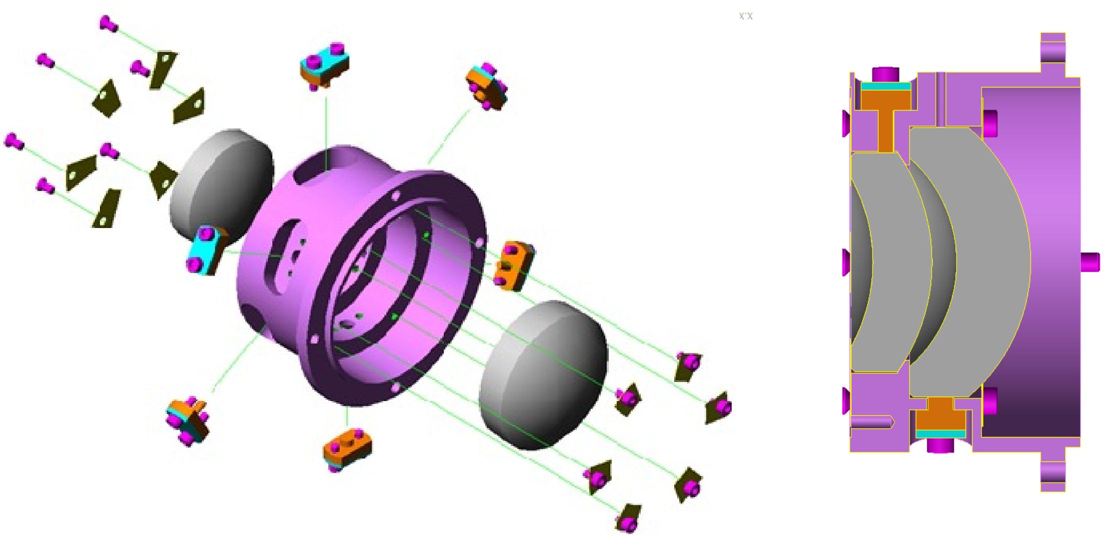

Figure 5: Explode view of GPI lens mount.

The accurate lens alignment is decisive for the final image quality. During the process of alignment of lenses in a mount, significant ring errors could result and add to the machining errors of a lens. Consequently, the requirements can be fulfilled only when all the assembly steps –from the centering tolerance measurement to the assembly of the lens in a mount-are planned and designed as an integrated concept.

The centration process is used to minimize the decenter between the lens and the mechanical holder but it is also based on the measure of the decenter. The usual procedure to identify the centering errors is to rotate the sample in transmitted or reflected light. For the measurement, an autocollimator with additional optics is focussed either to the center of curvature of the surface (Reflection Mode) or to the focal plane of the lens (Transmission Mode).

The lenses were then centered relatively to their cell using. The cells were centered with a precision of ± 2 µm and have a residual tilt < 0.005° on the centering machine. The centering machine was then used to center the lenses in their cell and measure the accuracy of the achieved centering/tilt with a precision ranging from 0.5 to 3 µm depending on the focal length of the autocollimator used to make the measurement. The alignment pads were precisely machined to match the centering position. A longer pad may result in a displacement of the lens during cold down. We control the pad length down to 10 um or less accuracy.

3. CONCLUSIONS

As discussed in the paper, the most important parameter when designing a cryogenic optical system is certainly the available cold data. Editing proper glass catalogue for each temperature gives you the flexibility to study the impact of various temperature as well as temperature gradient within the same design configuration. The second important aspect is the scale from cold to room temperature. The third point is the data exchange between mechanical and lens designer which is very important to avoid surprise. Finally, alignment and test procedure must be determined early in the design process (at PDR ideally).

Over the last 13 years, I worked with several research groups and companies on the design and built several cryogenic instruments (imagers) for space and astronomical instruments. We were successful in every project because we follow a rigorous step by step process.

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