Cryogenic Lens Design Case Study: Gemini Planet Imager Spectrograph

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ABSTRACT

Making a lens design working at cryogenic temperature is a real challenge. Both optical and mechanical designer must work together to prevent problems during operation. The Gemini Planet Imager (GPI), currently under construction will be a facility instrument for the 8-m Gemini South telescope. The science instrument is a cryogenic integral field spectrograph based on a lenslet array. The integral field nature of the instrument allows for a full mapping of the focal plane at coarse spectral resolution. With such a data cube, artifacts within the PSF such as residual speckles can be suppressed. Additionally, the initial detection of any candidate planet will include spectral information that can be used to distinguish it from a background object: candidates can be followed up with detailed spectroscopic observations. The optics between the lenslet array and the detector are essentially a standard spectrograph with a collimating set of lenses, a dispersive prism and a camera set of lenses in a folded assembly. This paper describes the process from the first preliminary design to the final cryogenic system for both optical and mechanical design to achieve cryogenic working solution. We also discussed the assembly procedure (room temperature vs cryogenic compensation), the test support equipments and finally the laboratory optical performances over the field of view.
Keywords: Planet imager, cryogenic, spectrograph, test, image quality

1. INTRODUCTION

The Gemini Planet Imager (GPI), currently under construction for the 8-m Gemini South telescope, is a high contrast adaptive optics instrument intended for direct imaging of extrasolar planets and circumstellar disks [1,2]. The science instrument is a cryogenic integral field spectrograph (IFS) based on a lenslet array. The integral field nature of the instrument allows for a full mapping of the focal plane at coarse spectral resolution.

The GPI output 2.8'' (square) image from the coronagraph is first reimaged on a lenslet array (about 200X200, 0.014'' sampling). The image plane is then dissected by a lenslet array producing an array of micro-pupils. The input focal ratio is such that there are at least 2 micro-lenses per λ/D, each micro-lens having a pitch 110um. The micro-pupils are then re-imaged through an optical train (spectrograph optics) and disperse by a prism on NIR detector (2048X2048 pixels), the spacing of spectra on the detector is 4.5 pixels perpendicular to dispersion. The spectral image is reconstructed by integrating the signal of each micro-pupil spread on the detector. Non-common aberrations are still present in this design but they affect only the shape of individual micro-pupil PSFs, the integrated signal being hardly affected. One important implementation of this design is that there is a minimum contamination from one wavelength to another (wavelength crosstalk).

The spectrograph collimator consists of a refractive F/3.52 (including the square corners) and the spectrograph camera is also all refractive design with a F/5.89. The IFS is composed of 8 lenses, 3 cleartran, 4 BaF_2 and 1 S-FTM16. All lenses have spherical only surfaces.

This paper describes the process from the preliminary design to the final cryogenic system for both optical and mechanical design to achieve cryogenic working solution. We also discussed the assembly procedure (room temperature vs cryogenic compensation), the test support equipment and finally the laboratory optical performances over the field of view.

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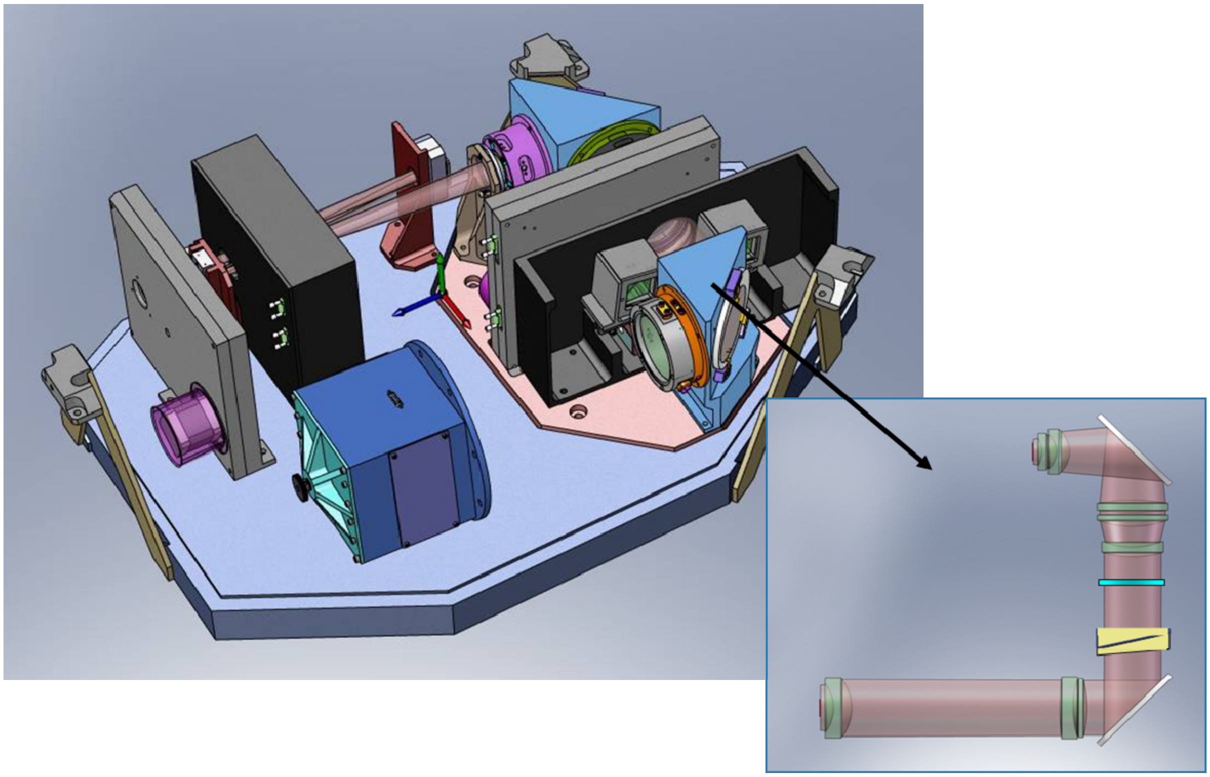

Figure 1: CAD view of GPI science cryostat with science spectrograph optical train.

2. CRYOGENIC DESIGN CONSIDERATION

Due to large FOV, refractive design seems to be the better choice as long as we are able to manage the chromatic. Because the design will be used at 80K (around), the lens design must be able to find (validated) information about cold indices of refraction and CTE for all glass used within the design. The two other important aspects were the need for a good mechanical design and to consider the test issue early during the design phase.

The first step is the preliminary design. I preferred to make a hot design (at room temperature) at this stage from the selected set of glasses which I know (or where I can find) the cold data (indices and CTE). The preliminary design is nearly a final design but at room temperature. If the specs are not change after the PDR, the original lens design (PDR) is modified to a cold version. I keep the pressure and the temperature in the lens design software as original (room temperature and 1 atm) and I define a new glass catalogue with 80K data for each glasses (I don't care about the CTE at this point). The PDR design is them optimised using the new glasses. The final design is now a cold version at 80K of the spectrograph. You can also replace the air between lenses by vacuum at this point but the impact is generally negligible. All the prescription data are cold from the lens dimension to the airspace.

To build the lenses, we need a version of each lenses (hot version) which corresponds to the lens prescription data after cooling down to 80K. I highly prefer at this stage to make the scale by hand by applying the proper CTE to each lens independently. 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 hot and the cold prescription is now transferred to the mechanical designer. He or she will be able to confirm the difference (if the scale is right) between the hot and the cold version with the mechanical software. The mechanical design is very important particularly if you have large lenses with small tolerances. Differences between housing CTE and lens CTE may lead to dramatic failure during cold down. In order to prevent such problem we must used a particular mounting technic which one example is described in the following section. The tolerance analysis must be done on the cold design and it is more or less the same as a hot design. However, I highly suggest 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). The cold design is also used to make a ghost analysis. As usual, the detector reflectivity is very important (more or less 20%). The lens coating must also survive to 80K. I use as built data from supplier to avoid any mistake. However, I have no space in the present paper to discuss about coating.

3. COLD GLASS & MECHANICAL DATA

As described in the last section, the availability of cold data is probably the most important aspect. As the starting point, you should list the material (optical) with cold data. 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.

As a few examples, the following figure gives the glass data at 77K using the zemax catalogue file format. ZEMAX stores glass catalog data in two file formats, called the ANSI Glass Format (AGF) and the Binary Glass Format (BGF). The glass catalog data supplied with ZEMAX is in the AGF format, and AGF files may be used when glass catalog data needs to be modified or created by a leng designer. When ZEMAX runs, AGF files are automatically converted, if required, to BGF files. The BGF files are only used by ZEMAX to speed up the loading of the glass catalogs, and should never be edited. ZEMAX will create or update a BGF whenever required. The AGF file is the "master" file used to define glass catalog data The AGF file consists of a header line followed by a series of records, one for each glass. The next figure provide the text of the AGF file (you can copy it to make your own catalogue). You should notice that the catalogue only contain the refractive index coefficient. As I said in the previous version, I did not use the CTE coefficient. Consequently, I keep the temperature and pressure normal in zemax. The cold design will use the cold glass catalogue (CaF2-77K) and the hot design will use the standard room temperature glass (CaF2 from zemax standard catalogue.

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NM BAF2-77K 2 1 1.550000 30.000000 0
ED 0.000000 0.000000 1.000000 0.000000 0
CD 6.474726200E-001 3.419993200E-003 5.108345700E-001 1.186779400E-002 3.824147000E+000 2.150760500E+003
TD 0.000000E+000 0.000000E+000 0.000000E+000 0.000000E+000 0.000000E+000 0.000000E+000 2.000000E+001
OD -1.0000 -1.0000 -1.0000 -1.0000 -1.0000 -1.0000
LD 5.0000E-001 5.0000E+000
NM CAF2-77K 3 1 1.550000 30.000000 0
ED 0.000000 0.000000 1.000000 0.000000 0
CD 1.429662490E+000 2.153196550E-003 -3.855575500E-005 -1.123884320E-003 -1.320689660E-006 -2.620053940E-009
TD 0.000000E+000 0.000000E+000 0.000000E+000 0.000000E+000 0.000000E+000 0.000000E+000 2.000000E+001
OD -1.0000 -1.0000 -1.0000 -1.0000 -1.0000 -1.0000
LD 5.0000E-001 5.0000E+000
NM FSILICA-77K 3 0 1.457046 68.283974 0
ED 0.000000 0.000000 1.000000 0.000000 0
CD 1.449392030E+000 2.903988240E-003 -3.924757760E-005 -3.203540440E-003 -3.573692500E-005 -4.546293340E-007
TD 0.000000E+000 0.000000E+000 0.000000E+000 0.000000E+000 0.000000E+000 0.000000E+000 2.000000E+001
OD -1.0000 -1.0000 -1.0000 -1.0000 -1.0000 -1.0000
LD 0.5000E-001 5.0000E+000
NM ZNS-77K 1 1 1.550000 30.000000 0
ED 0.000000 0.000000 1.000000 0.000000 0
CD 5.065896500E+000 -2.460004440E-003 1.401285010E-001 9.512620500E-003 -5.845571790E-004 1.827080170E-004
TD 0.000000E+000 0.000000E+000 0.000000E+000 0.000000E+000 0.000000E+000 0.000000E+000 2.000000E+001
OD -1.0000 -1.0000 -1.0000 -1.0000 -1.0000 -1.0000
LD 5.0000E-001 5.0000E+000
NM ZNSE-77K 1 1 1.550000 30.000000 1
ED 0.000000 0.000000 1.000000 0.000000 0
CD 5.865586590E+000 -1.312344940E-003 2.400362130E-001 1.939477020E-002 9.230446720E-004 2.398793120E-004
TD 0.000000E+000 0.000000E+000 0.000000E+000 0.000000E+000 0.000000E+000 0.000000E+000 2.000000E+001
OD -1.0000 -1.0000 -1.0000 -1.0000 -1.0000 -1.0000
LD 5.0000E-001 5.0000E+000
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Figure 2: Zemax AGF file with some cold data.

Of course, the make a hot version of the design, we need to scale the cold version according to the CTE of each glass type. The following figures show Thermal coefficients ($\Delta L/L_0$, %) for glasses and metal between room and cold temperature [7-9].

GLASS	77	100	110	150	Density g/cm^3
	TEMPERATURE (K)				
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 3: Glass thermal coefficient (% change)

METAL	77	100	110	150	Density g/cm^3
	TEMPERATURE (K)				
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 4: Metal thermal coefficient (% change)

Good match provides an ideal situation between cold and room temperature (caution with CTE slope values to avoid problem during cold down cycle). For example, 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 type of glasses, it is not practical to use many metal component which may result in serious matching problems. In GPI, we use Aluminum for the housing, it is very well known, we can make various thermal treatment. However, we will have a different CTE mismatch for each lens. Consequently we have developed over the last 12 years a mechanical mounting scheme to ensure a stable cold system.

4. MECHANICAL DESIGN

Of primary concern in cryogenic lens mounting is the differential contraction between the lens and its cell.. In GPI spectro, all lenses are mounted in the same manner. The lens is first placed in a cell with a conical surface tangent to its surface at periphery. 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.

All cells are made of aluminium (alloy 6061T6, 0.392% of contraction between 300 K and 77 K), and lenses are made of fused silica, BaF2, CaF2 and zinc sulfide and S-FTM16 (contracting respectively by 0.0001%, 0.317%, 0.302%, 0.096%, 0.167% between 300 K and 80 K). Consequently, all lenses contract less than their cell. 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.

The main concern in this design is the thermal behaviour of the cell and lens during cooldown. In order to establish this technique, we did several studies. Two extreme models of lens cooling have been considered: one where the conduction is dominant and the lens is always at the mount temperature and the other one where the lens cools only via radiation. Any realistic cooling profile should be between these two extremes. A cooling profile has been also obtained for a CaF2 lens and its mount. The cooling profile is indeed intermediate between the two extremes, but lies much closer to the model dominated by conductivity. The highest observed temperature difference between the lens and its mount is 18 K.

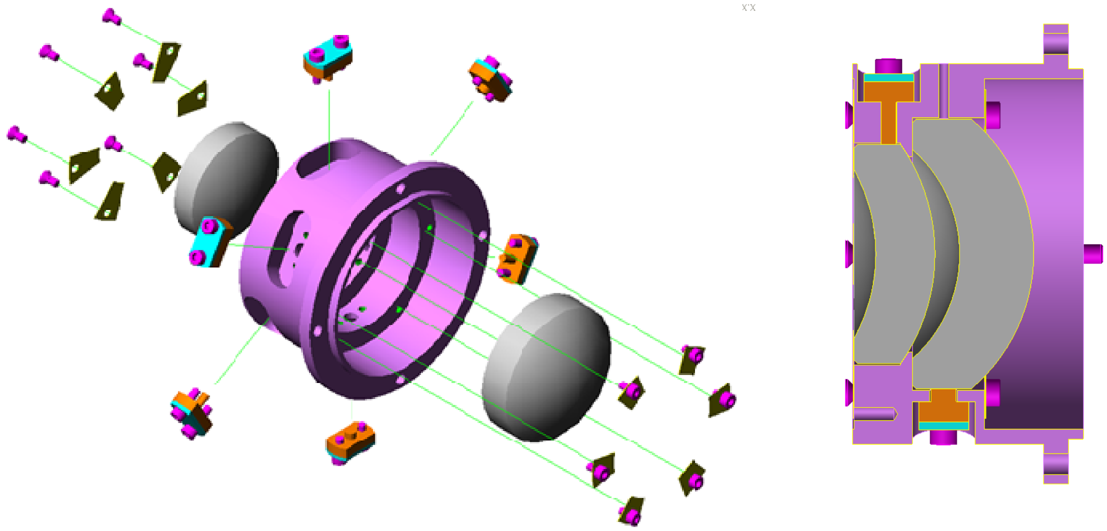

Figure 5: Explode view of GPI lens mount.

5. ALIGNMENT

The accurate lens alignment is decisive for the final image quality of the GPI. 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 of IFS 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.

6. TEST

As it is not the purpose of the paper, you should refer to a previous paper about the test results[10].   The IFS optics was tested at cryogenic (~80 K) temperature in the H-band (1.5-1.8 um) with the dispersion prism (without lenslet). All tests were performed with a Hawaii-2 engineering grade detector (18 um pixel pitch) mounted on a focussing stage and controlled by a cryogenic stepper motor. The total course of the focussing stage was measured warm and found to be 390 µm. A grid of pin-hole is placed in the object plane of the spectrograph. The object plane is located at the focal plane of the lenslet array.   The grid consists of several group of 10X10 pinholes with 100 um pitch which covers the entire spectrograph field of view. Each pinhole has a diameter of 5um (-0, +3um).

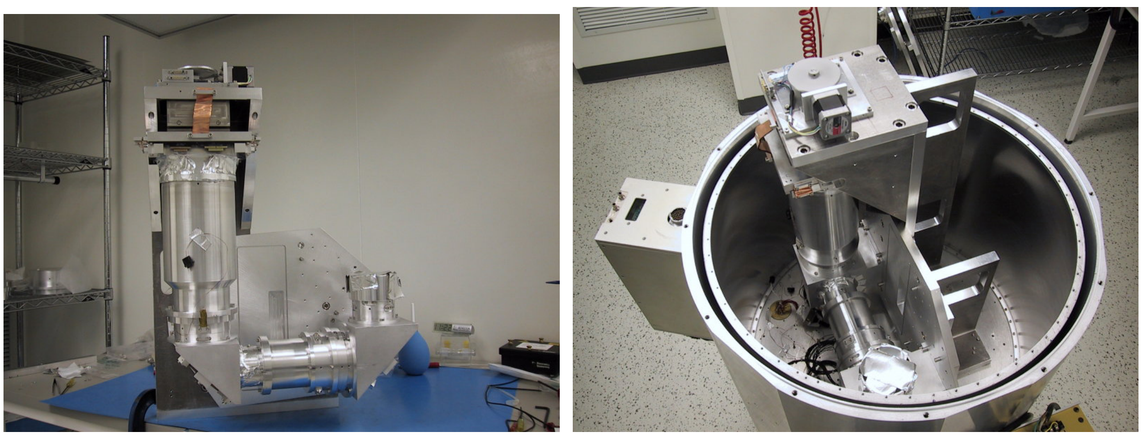

Figure 6: GPI spectro under test

The FWHM for each grid pinhole images were estimated from the median of Gaussian widths to determine the image quality. The measured optical quality is consistent with the tolerance analysis. The dispersion was measured and compared to the Zemax IFS model and to a linear fit. Raw images from Argon and Xenon lamps were used to extract centroid locations of pinholes PSF at 1.695um (Ar) and [1.542,1.605,1.6732,1.733] um (Xe), after dark subtraction. Distance of each peaks were calculated for each spectrum and the mean value of these distances were calculated for a given 10x10 pinhole grid. The measured image quality, plate scale, distortion and dispersion of the IFS optics at operating temperature are in excellent agreement with the optical model. The optics experienced three cryo-cycles. The described test procedure is adequate to characterize the spectrograph optical quality.

7. CONCLUSIONS

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. By hand calculation is sometime better than using automatic function in the lens design. 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 12 years, I worked with several research groups and companies on the design and built several cryogenic instruments (imagers). We were successful in every project because we follow a rigorous step by step process.

8. ACKNOWLEDGMENTS

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