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The art of cryogenic lens design: the Gemini Planet Imager

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A systematic approach to designing a cryogenic optical system is required to develop a successful instrument.

During the last few decades, various near-IR (NIR: 0.9–2.4μm) astronomical instruments have been commissioned on ground-based telescopes. One common characteristic is that these detectors operate at cryogenic temperatures (approximately 80–100K). To limit IR light contamination, their optical components are also located inside the cryostats. Consequently, optical designers must be familiar with lens design at cryogenic temperatures. The Gemini Planet Imager (GPI) is an example of a recently designed NIR instrument. It is a high-contrast adaptive-optics device for direct imaging of extrasolar planets and circumstellar disks.[1,2] GPI consists of a cryogenic integral-field spectrograph (IFS) based on a lenslet array (see Figure 1).

Because of the large field of view of the lenslet focal plane, a refractive design has been selected. Optical designs of NIR refractive systems are strongly constrained by a limited range of optical materials with known 'cold' indices of refraction and coefficients of thermal expansion (CTEs). Glasses are mainly limited to calcium and barium fluoride (CaF_2, BaF_2), zinc sulfide and selenide (ZnS, ZnSe), Cleartran^{TM}, fused silica, and S-FTM16 (Ohara).[3–5] At the preliminary design stage, it is acceptable to adopt room-temperature conditions (and an atmospheric pressure of 1atm), although with the selected set of cryogenic-glass specimens. Upon acceptance of the preliminary design, it must be modified with cold data. We recommend to keep the pressure and temperature in the lens-design software at 1atm and room temperature, respectively, and define a new glass catalog for each of the specimens assuming an operating temperature of 80K. (We do not consider the CTE at this stage.)

The design must then be re-optimized for the new, cold glass specimens, leading to a final configuration that is now a cold version (80K) of the spectrograph. One can also replace the air between the lenses by vacuum, but the impact is generally negligible. Because the prescription data is now cold, the design cannot be built as is. To construct the lenses, we need a design

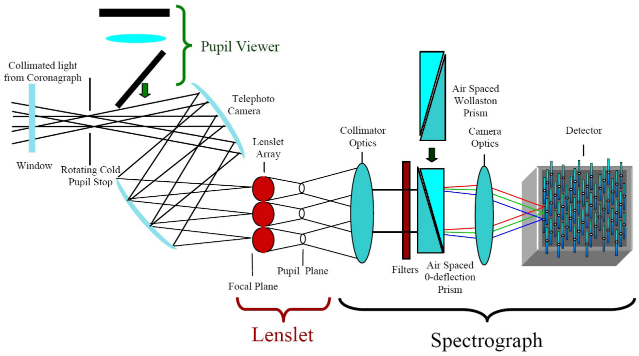

Figure 1. *Schematic of the Gemini Planet Imager (GPI)'s cold science camera (located after the coronograph in the light path).*

version at room temperature. We strongly recommend to manually scale all lens parameters by both thickness and radius by applying the proper CTE from 80 to 270K to each lens independently. We can also scale the air space (vacuum) according to the mechanical material CTE. The new scale prescription is a hot version of the lens. This is the laboratory version that will result from mounting all components. The hot and cold prescriptions can be transferred to the mechanical designer, who will be able to confirm the difference (if the scaling has been done correctly) between both versions (a double-check step).

To mount the lenses, differences between housing and lens CTEs may lead to dramatic failure during cooldown. A good match between housing and lens provides an ideal situation between cold and room temperature (caution must be exercised with CTE-slope values to avoid problems during cryo cycling). For example, a good match for CaF_2 or BaF_2 is brass 70/30 (copper/zinc), characterized by $-0.287, -0.298$, and -0.313% CTE, respectively, at 100K. However, this is not always practical to achieve because of the different glasses used in the design.

The GPI spectrograph is composed of eight lenses, three Cleartran, one S-FTM16, and four BaF_2 elements. The lenses are

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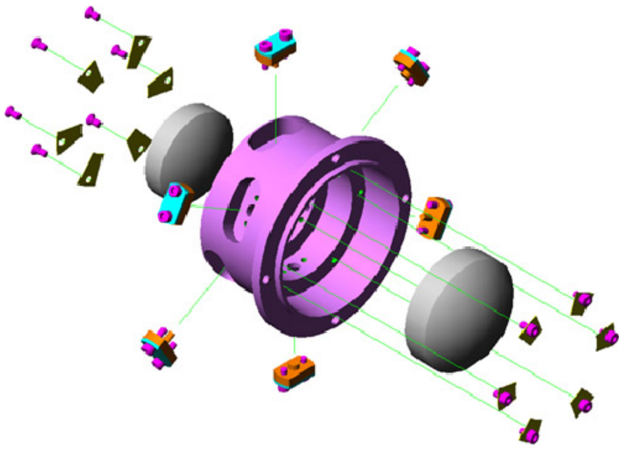

Figure 2. *Exploded view of the lens-mounting techniques (showing two lenses using a double-sided custom aluminum lens holder).*

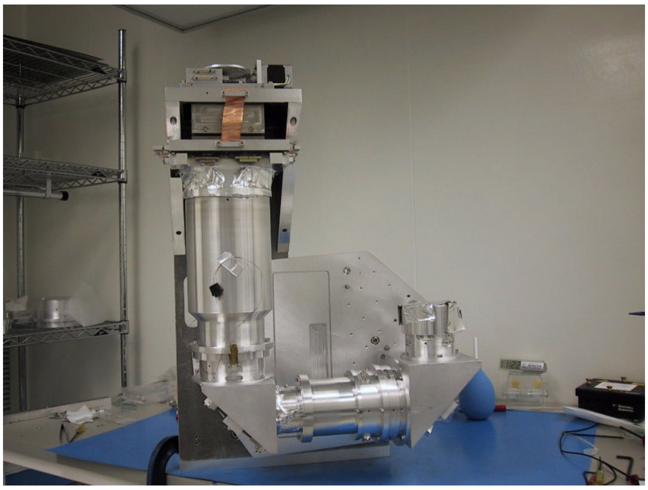

Figure 3. *GPI spectrograph before cryogenic testing.*

all mounted in the same manner (see Figure 2). A lens is first placed in a cell with a conical surface tangent to its peripheral surface. It is then maintained axially using a ring loaded with beryllium-copper springs. The force applied on the lens is approximately five times its weight. To maintain centering without applying excessive stress, nylon or teflon pads are used. Both materials have large contraction coefficients (1.22 and 1.94%, respectively, at 80K). There is certain a pad length that allows a perfect match between lens/pad diameter and cell size at room and cryogenic temperatures for all lenses.

In summary, the most important input for the design of a cryogenic refractive optical system is the available cold data. Because the mechanical and lens designs are almost equally important for meeting the tolerance requirements, data exchange between the lens and mechanical designers is very important. A systematic approach to hot and cold design with well-known material data will lead to successful instrument development. For GPI (see Figure 3), the measured image quality, plate scale, distortion, and dispersion of the IFS optics at operating temperature are in excellent agreement with the optical model.[6] GPI is currently under construction for installation at the 8m (diameter) Gemini telescope.

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