

# Two-Axis Gimbal for Air-to-Air and Air-to-Ground Laser Communications

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## ABSTRACT

For bi-directional links between high-altitude-platforms (HAPs) and ground, and air-to-air communication between such platforms, a hemispherical  $+30^\circ$  field-of-regard and low-drag low-mass two-axis gimbal was designed and prototyped. The gimbal comprises two servo controlled non-orthogonal elevation over azimuth axis, and inner fast steering mirrors for fine field-of-regard adjustment. The design encompasses a 7.5cm diameter aperture refractive telescope in its elevation stage, folded between two flat mirrors with an exit lens leading to a two mirrors miniature Coude-path fixed to the azimuth stage. Multiple gimbal configurations were traded prior to finalizing a selection that met the requirements. The selected design was manifested onboard a carbon fiber and magnesium composite structure, motorized by custom-built servo motors, and commutated by optical encoders. The azimuth stage is electrically connected to the stationary base via slip ring while the elevation stage made of passive optics. Both axes are aligned by custom-built ceramic-on-steel angular contact duplex bearings, and controlled by embedded electronics featuring a rigid-flex PCB architecture. FEA analysis showed that the design is mechanically robust over a temperature range of  $+60^\circ\text{C}$  to  $-80^\circ\text{C}$ , and with first mode of natural frequencies above 400Hz. The total mass of the prototyped gimbal is 3.5kg, including the inner optical bench, which contains fast steering mirrors (FSMs) and tracking sensors. Future version of this gimbal, in prototyping stage, shall weigh less than 3.0kg.

**Keywords:** laser communications, gimbal, HAPs, air-to-ground, air-to-air

## INTRODUCTION

Compact, lightweight, and high performance two-axis gimbals are of interest to airborne and space-borne free space optical (laser) communications [1]. Here, we describe the design and development of such a gimbal for airborne applications, however it could be applicable to space borne applications as well.

The design drivers for the gimbal are: (a) field of regard coverage, (b) weight, and (c) size and aerodynamic drag. For air-to-ground communications, the desired field-of-regard is  $\pm 60^\circ$  cone around nadir; and for air-to-air communications the field of regard is an annulus of  $\pm 20^\circ$ . The design goal was for a single configuration to address both air-to-ground and air-to-air requirements and with minimum weight and cross section to minimize aerodynamic drag.

## DESIGN TRADES

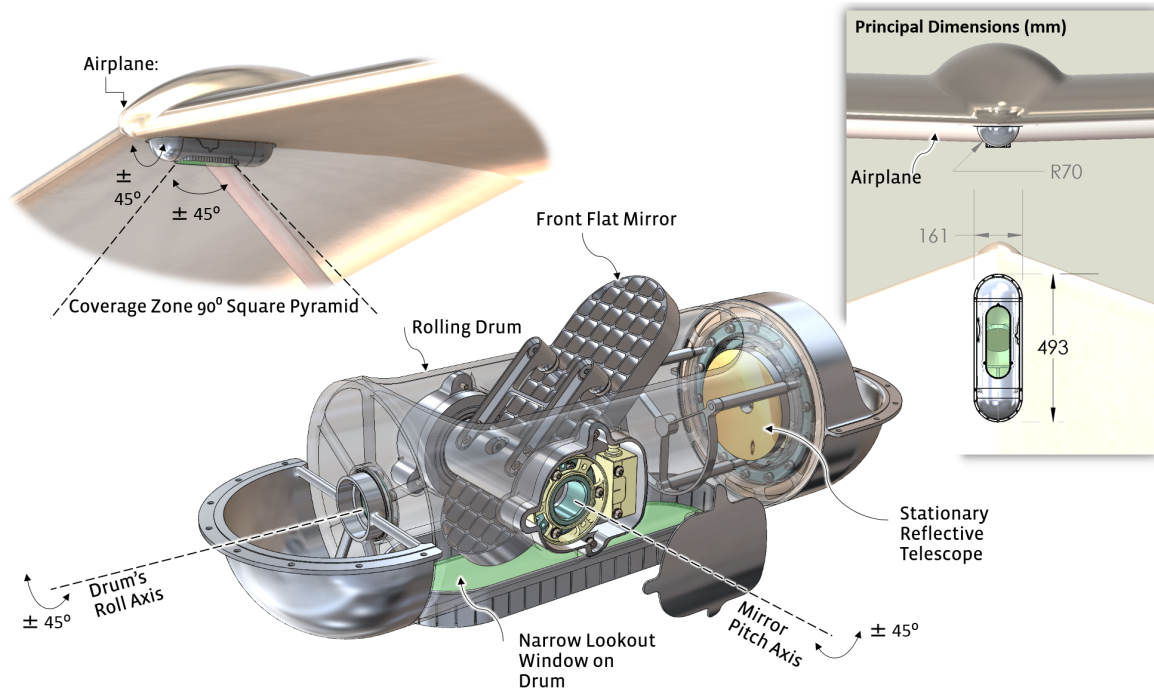
Four gimbal configurations were traded early. Some configurations, such as a Coelostat, were not considered due to higher weight compared to the selected design options. Figure 1 schematically shows a gimballed flat configuration. In this design, a stationary reflective Cassegrain telescope is located at one of the bases of a rolling drum, while an articulated flat mirror is mounted within the drum and motorized for pitching. The rolling drum is mounted half exposed on the bottom of the airframe, allowing  $\pm 45^\circ$  rolling motion. An elongated looking down window on the rolling drum permits the pitching flat mirror to cover an orthogonal  $\pm 45^\circ$  field of regard. In all, the coverage of the air-to-ground projected gimbal is a  $90^\circ$  solid square pyramid.

In spite of its apparent simplicity, this approach present certain drawbacks, rendering this configuration non-desirable:

- a) The large size flat mirror is expensive and would not scale well in large quantities.
- b) The elongated structural footprint of the gimbal on the airframe was found to be undesirable.

- c) The need for different set of gimbals for air-to-air or air-to-ground conflicted with the requirement of the gimbal to serve both missions in a case of a neighboring gimbal malfunction.

The second configuration that the team evaluated is shown in Figure 2. This configuration is a traditional elevation over azimuth spherical gimbal with long-legs Coude path attached to the azimuth stage. The Coude path comprised of multiple relay optics and three folding mirrors.



**Figure 1:** Initial configuration for consideration is an air-to-ground gimbal system with a stationary reflective telescope and two axis motorized flat mirror in front of its aperture

The elevation stage houses a refractive telescope with 7.5cm diameter aperture folded twice in order to fit a minimum possible sphere, with an exit optics aligned with the elevation axis at the entrance to the Coude path.

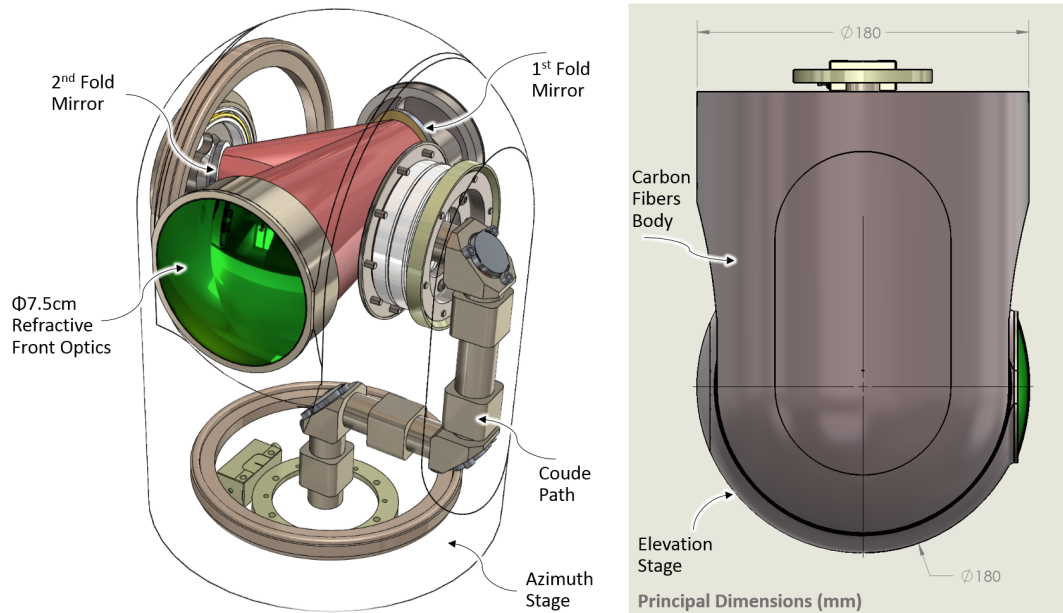
This configuration offered air-to-air and air-to-ground capability, which the first configuration is lacking, but was eventually rejected for the following reasons:

- The long and complex Coude path presented a challenge in alignment and cost-prohibitive for mass production.
- The size of the sphere could not be reduced beyond a certain minimum, while the gimbal inner arrangement presented a low packaging efficiency.
- The traditional yolk approach for the azimuth to elevation transition was found to be counterproductive in hollow-bore circumstances and it was rendered as difficult to produce and to align cost effectively.

The third gimbal configuration considered is shown on figure 3. It is a modified version of the second one where the azimuth to elevation yoke is replaced by an integrated pancake hollow-bore motorized stage, comprised of thin ceramic-on-steel angular contact duplex bearings, optical encoder and a frameless permanent magnet motor. The azimuth stage is motorized by a virtually identical stage.

The noticeable departure from the second configuration is the manner by which the refractive telescope is folded, where the elevation axis situated between 1<sup>st</sup> and 2<sup>nd</sup> fold mirrors and the long-legged Coude path of the second configuration is substituted by a miniature two-mirror Coude path at the center of the pancake-drive of the azimuth stage. In effect, the telescope is folded in such particular way, which minimizes the size and complexity of the Coude path.

The foremost weaknesses of the third configuration are realized to be:



**Figure 2:** Second configuration for consideration is an air-to-air or air-to-ground capable, elevation over azimuth spherical gimbal with refractive telescope folded twice, and a three mirrors long-legs Coude path fixed to the azimuth stage. The optical bench is situated in the stationary base

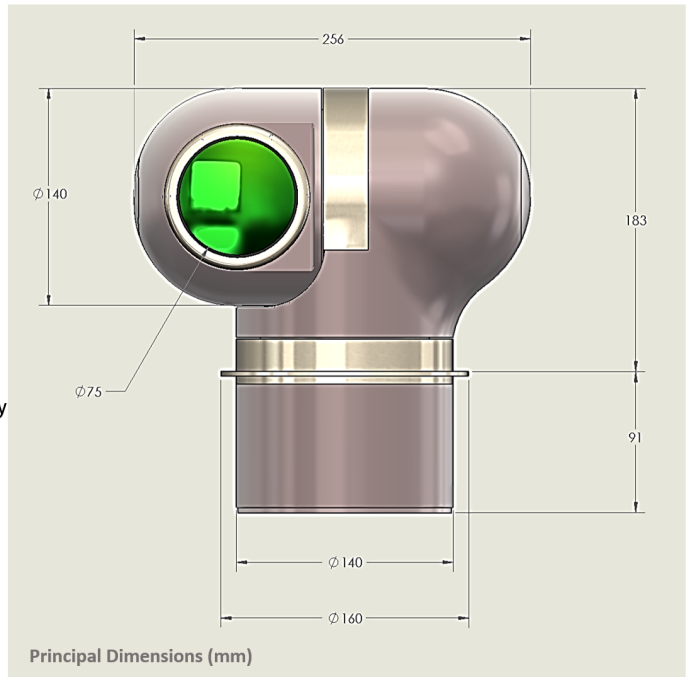
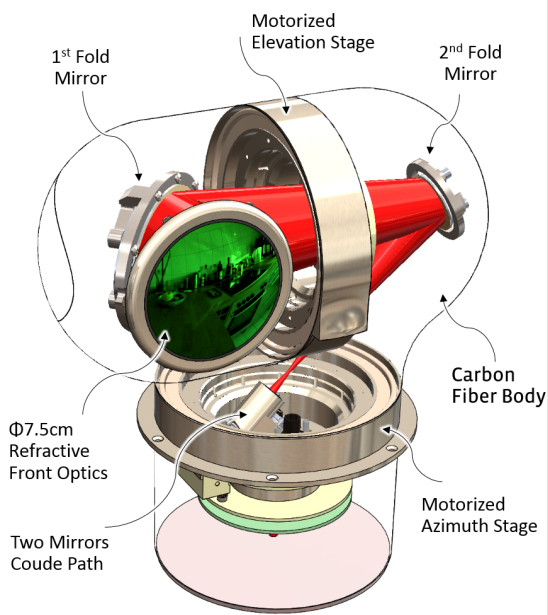
- a) The 1<sup>st</sup> fold mirror was larger in comparison due to its proximity to the front optics and would challenge the affordability of the mass production version.
- b) The elongation of the gimbal (needed for the telescope light to bypass the motorized elevation stage centrally situated in front the azimuth stage) created non-symmetrical aerodynamic loadings and added torque requirement on the azimuth stage

All of which led the team to the fourth and selected gimbal configuration.

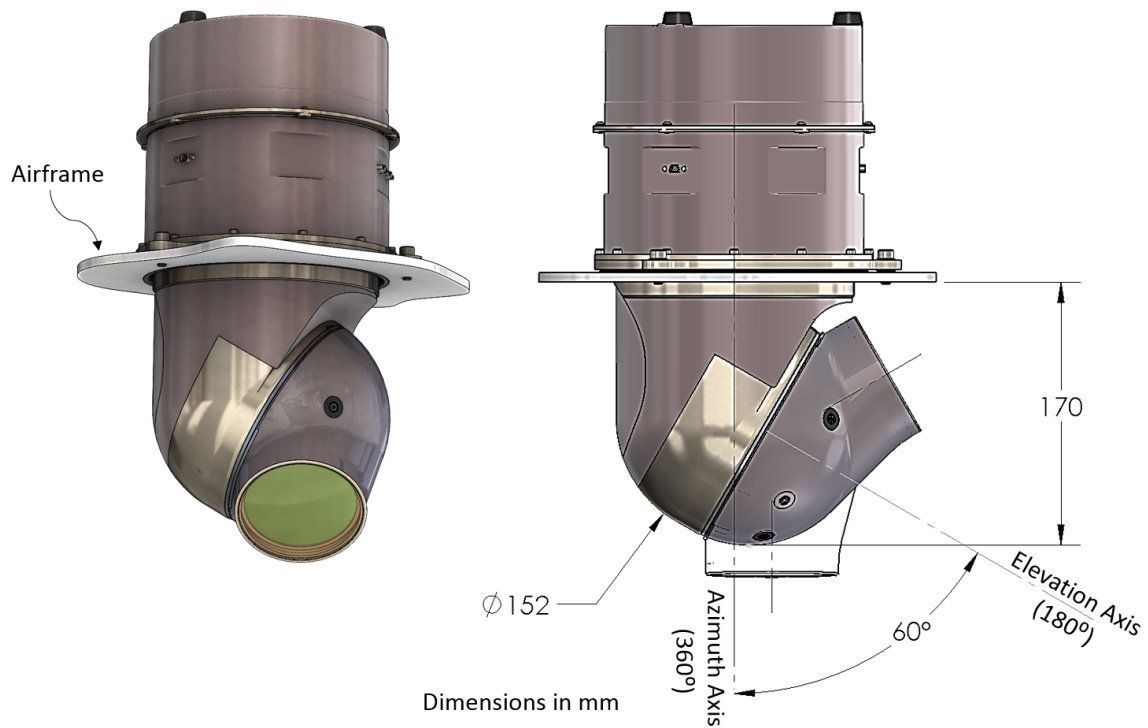
## SELECTED DESIGN

In the final gimbal permutation, the telescope is folded similarly to the second configuration in order to keep the first fold mirror at a manageable size. The motorized elevation stage of the third configuration, where it is blocking the line-of-sight through the center of the azimuth stage, has been tilted in this final configuration off its orthogonal position to 60°, measured from the azimuth axis. By tilting the elevation stage, a direct light path is channeled from the core of the elevation stage to the stationary optical bench at the base.

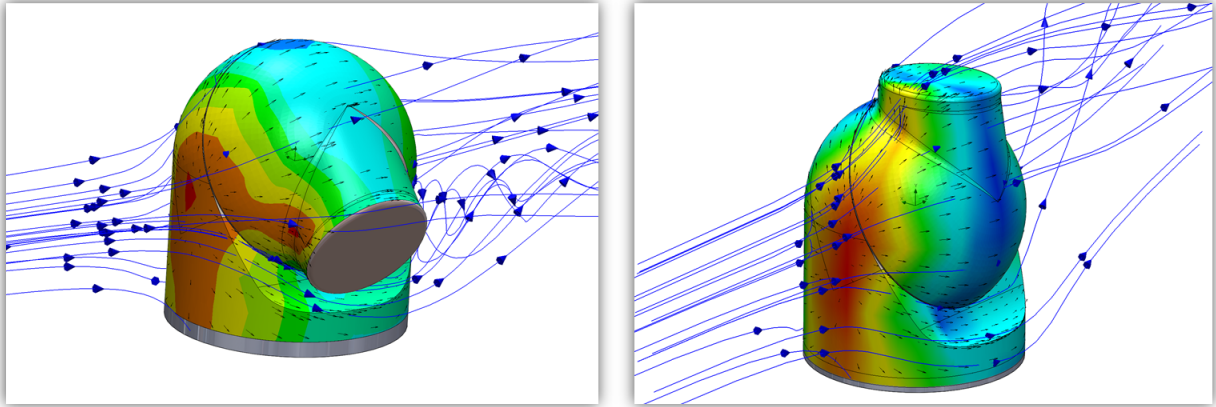
The undesirable elongation of the third configuration is truncated by the non-orthogonality of the fourth gimbal configuration to a virtual sphere of 152mm in diameter, while minimizing the aerodynamic loading and making them nearly symmetrical, shown on 5. The efficiency of the optical packaging within the elected gimbal is established in 6:



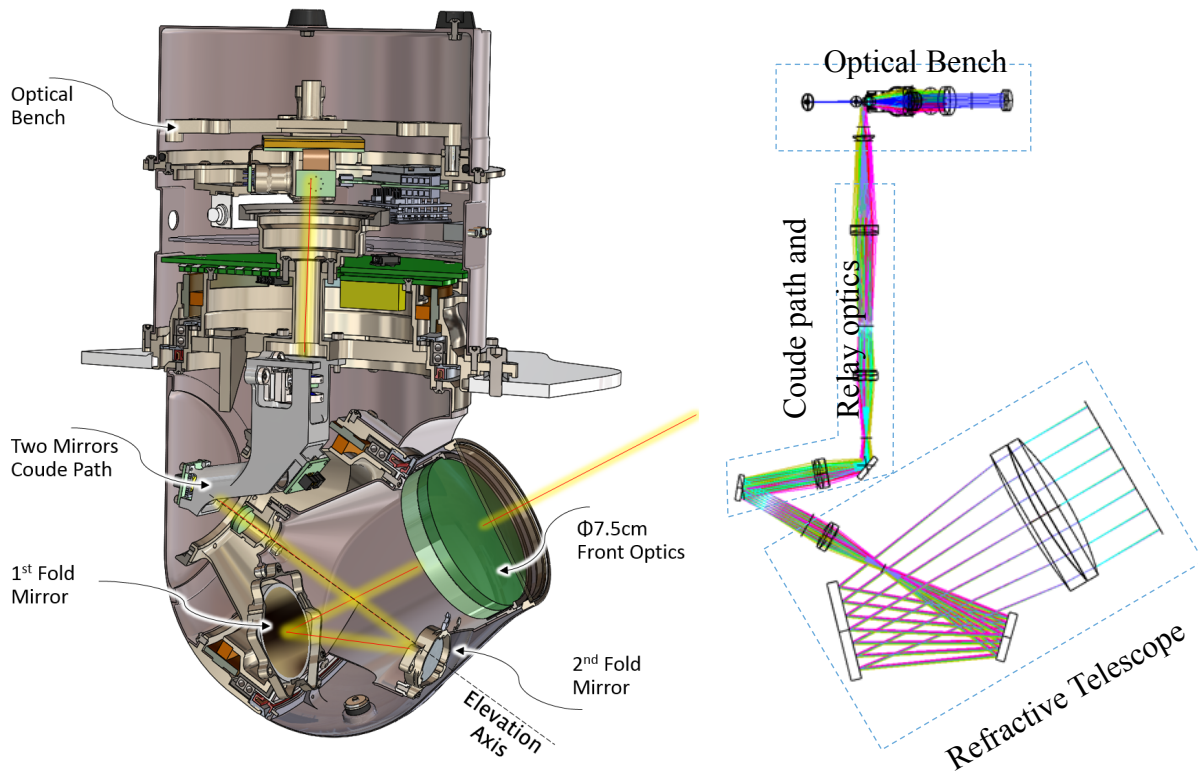
**Figure 3:** Third configuration considered is an air-to-air or air-to-ground capable gimbal with an elongated elevation stage over azimuth, refractive telescope folded twice, and a two mirrors miniature Coude path fixed to the azimuth stage. The optical bench is situated in the stationary base



**Figure 4:** Final Gimbal configuration benefitted from air-to-air and air-to-ground capability onboard a non-orthogonal elevation over azimuth small chassis, constructed of carbon fiber and magnesium composite.



**Figure 5:** Nearly symmetrical aerodynamic loading with a very low drag force and parasitic moments on the motorized axis.



**Figure 6:** Section view of the gimbal demonstrating the inner optical train and the modularity of the optical bench and the Coude path to be fitted differently for different missions

A tightly packed refractive telescope is efficiently occupying the majority of the volume of the elevation stage. The Coude path transfers the beam from the elevation axis to the azimuth axis while the relay optics keeps the beam small and contained. This allows the pupil and field of view to be accessed at the optical bench. The acquisition and tracking components as well as the interface to the communication subsystem are contained on the optical bench.

The optics and opto-mechanical structures are designed to withstand and operate within the temperature requirements of the platform. This robust system design can be aligned and tested at room temperature and still

retains performance at the required temperature extremes. The dominant error at these extremes is a focus error that is removed actively on the optical bench in both the tracking and communication paths.

The Coude path and the optical bench are modular and can be flavored differently for different missions. For example, for a fast moving airframes where transmit and receive line of sights are separated due to optical point-ahead, one may desire to separate the optical paths onboard with dedicated fast steering mirrors (FSM) for each transmit and receive paths. In this case, the modular optical bench may be fitted with separate transmit-receive paths.

In a case of lightweight slow moving airframe, where mass production and affordability is a main driver, one may elect to install a single FSM in the modular Coude path, and simplify the optical bench to a monolithic structure with embedded electrics as shown in 6.

The optical substructure of the elevation stage is stable through the full temperature range, and is protected by a streamlined hood, see Figure 7. The duplex bearings are mounted on a dedicated flexure that permits large temperature swings, in order to keep the required motor torque under control. The gimbal is protected against moisture and dust by custom-made low-friction rotary seals.

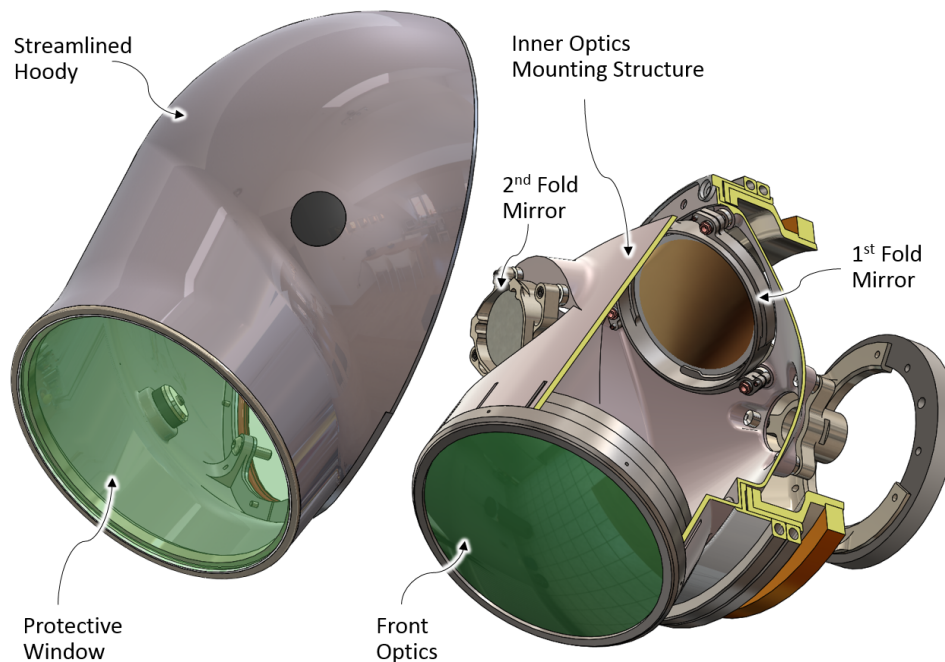


Figure 7: Exploded and partially cut view of the elevation stage.

## DEVELOPMENT STATUS

A prototype gimbal design is currently being assembled and its performance is under evaluation. Shown in Figure 8 is the assembled gimbal in the laboratory. The next steps of development will focus on the cost reduction. This will include: refinement of optical mounts; simplification of the alignment; build procedure; and the development of molds and alignment jigs. The objective is to bring the cost of mass production and cost of ownership to well defined challenging prices.



**Figure 8:** Operational prototype gimbal complete with motors, encoders and optics.

## SUMMARY

Stringent weight requirement for the airborne application dictates that the design of the gimbal be very lightweight, yet support the aperture size to meet the desired link budget and a wide-field-of-regard to cover the various communication scenarios. The selected gimbal presented is one such design option. By folding the optical path in a non-orthogonal fashion, the resulting gimbal is very compact to reduce the aerodynamic drag, and by using a combination of carbon fiber and magnesium composite structure, the final gimbal should weigh in the 3kg range. The main challenge ahead is to develop the processes and procedures to reduce the recurring production, assembling and optical alignment cost for the mass produced gimbal.

## REFERENCES

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