Development of a Mirror Pointing Mechanism for an Atmospheric Gas Measurement Instrument

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Abstract

Development of the Open Path Tunable Infrared Monitor of the Atmosphere (OPTIMA) instrument involved designing a pair of motion systems that could maintain a precise alignment and spatial distance between two mirrors installed on the NASA DC-8 research laboratory aircraft. This is the first airborne optical instrument that allows direct measurement of the gases in the freestream airflow on the exterior of the aircraft. One mirror is mounted within a specially constructed open port cavity in the cabin of the aircraft and the second is mounted 6 meters away on top of the inboard port side (number 2) engine pylon. Three co-aligned laser beams are reflected between the two mirrors 64 times in a Herriott pattern. The resulting sample path length of 384 meters is used to perform a spectral absorption analysis of the airflow between the mirrors. To compensate for normal wing movement and engine oscillations both mirrors were designed as continuously driven mechanisms to maintain alignment within allowable limits. The motion systems of the two mirror assemblies provide five degrees of freedom and are designed to maintain a pointing accuracy within seven arc-sec with a response frequency in excess of 10 Hz. The pylon motion system incorporates controlled pitch and yaw movement. The fuselage motion system compensates for pitch variation as well as linear translation for focal length and vertical aiming of the laser beam via a controlled beam guidance mechanism.

Introduction

The OPTIMA instrument was designed to make direct in-situ measurements of nitric acid and nitrogen dioxide. The previous methods used to determine the quantities of these gases have yielded results of doubtful accuracy. Generally, measurements of these gases have been derived from theoretical relationships to other compounds being measured. On the occasions where actual measurements were made they did not correlate to the theoretically derived quantities.

To obtain appropriate sensitivity and accuracy the operation of the OPTIMA instrument is based on differential absorption of tunable infrared (IR) lasers, a proven technique used on various instruments developed over the last 20 years. To minimize the effects of water absorption and atmospheric pressure, measurements are made in the upper troposphere and lower stratosphere (6-12 km). OPTIMA provides an optical path through which two infrared laser beams are directed. As the beams travel this path,

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they encounter molecules of the target gases that absorb a portion of the light energy. Analysis of the signal difference at the start and end of the optical path indicates the quantity of the gases encountered. In order to get the resolution down to 3 to 16 parts per trillion of volume, the optical path includes a Herriott pattern.

Generally, Herriott patterns are generated in a Herriott cell, a cylinder with two fixed spherical mirrors at either end. One of the end mirrors has an optical opening through which a laser is directed to strike the reflective surface of the opposite mirror. The beam reflects between the two mirrors a prescribed number of times before it exits the opening through which it entered and is directed to a detector for analysis. The path the light takes within the cylinder is called a Herriott pattern and the number of passes produced is determined by the relationship of the spherical radii to the distance between the mirrors. By using a Herriott cell a relatively long path length can be generated in a small physical space.

When a Herriott cell is used the sample has to be ducted into the cylinder for evaluation. The OPTIMA instrument removes the cylinder walls and creates the first known actively aligned multipass Herriott "cell" with an open absorption path that allows the direct detection and measurement of the target gases in the airflow between the two mirrors.

General Description **(Figure 1)**

A Fuselage Pressure Box is attached at a modified window opening on the interior of the aircraft to provide an open port cavity to the exterior of the aircraft. An optics table is attached to the top of the Fuselage Pressure Box where two specially selected and tuned infrared lasers are co-aligned with a visible laser into a single beam. This single combined beam is directed via fixed turning mirrors through an optical window into the Fuselage Pressure Box and onto the surface of the Beam Guidance Mirror Assembly (BGMA). The beam then passes through an opening in the Fuselage Pitch Motion Base (FPMB) and on to the Pylon Mirror Motion Base (PMMB). The reflective angle of the BGMA is constantly adjusted over a 3 degree range to compensate for vertical motions of the wing at the number 2 engine pylon. The beam is then reflected between the mirrors of the PMMB and FPMB in a 64 pass Herriott pattern in the airflow between these two locations. The mirrors are kept face to face by pitch mechanisms in both the PMMB and the FPMB that respond to vertical wing movement, while rotational motions of the engine pylon are compensated for by the yaw mechanism of the PMMB. This alignment is maintained by feedback from a pair of visible lasers set to strike two position sensing detectors (PSDs). The vertical motion of the pylon also affects the distance between the two reflective surfaces. This focal length is held constant by attaching the FPMB to a linear translation stage. As the beam completes the Herriott pattern, it returns to the BGMA where it is reflected out of the Fuselage Pressure Box and back onto the optics table. The combined beam is separated into the three component beams with the visible beam directed to a third PSD to provide positioning feedback for the adjustment of the BGMA angle and the focal length of the Herriott pattern. The infrared beams are then guided to detectors where the remaining signal is analyzed.

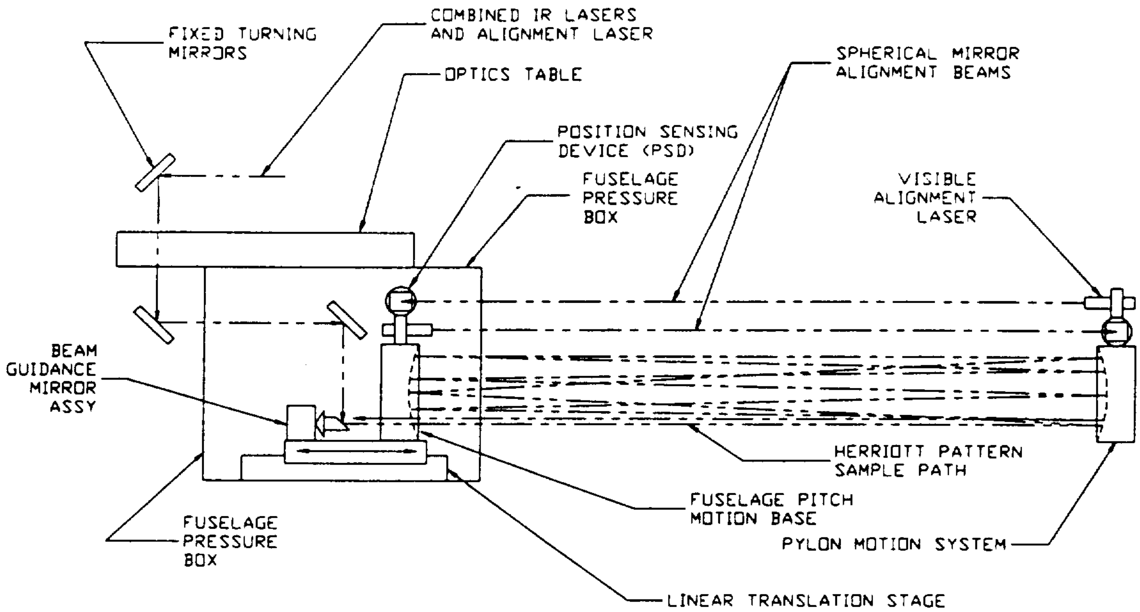

Figure 1. General layout of OPTIMA instrument

Design Considerations

The initial concept was to have a fixed mirror mounted on top of an inboard engine pylon of the NASA DC-8 aircraft. At the fuselage, near the leading edge of the wing, a window would be removed and a structural box attached to the window frame on the interior of the fuselage wall **(Figure 2)**. The cavity of this Fuselage Pressure Box would house a special mirror mounted to a pointing mechanism that would compensate for the expected movement of the mirror placed on the pylon. Pitch rotation, vertical translation and focal length translation would be the only motions required and that these could be incorporated into the fuselage mechanism.

A series of measurements of the DC-8 aircraft were made to determine the relationship of the component locations. These included static ground measurements with and without fuel loads as well as in-flight measurements to quantify the relative displacements at the proposed locations of the OPTIMA components. Analysis of these results indicated that 5 degrees of freedom would be required to accommodate the measured deflections. Pylon motions were more complex than anticipated and would require inclusion of a yaw motion and a second pitch motion. Provisions for accommodating the tracking system components would have to be made. All of the exterior components would have to be protected during ascent, descent and ground activities. The inboard unit would be enclosed in its cavity, but a special housing would have to be built for the pylon module. Both the cavity and the pylon housing would incorporate shutter mechanisms for protection of the optical surfaces and mechanisms within.

Figure 2. OPTIMA Fuselage Pressure Box / Optics Table installed on fuselage wall of DC-8 with the No. 2 engine pylon and pylon mirror / fairing visible out the exit door.

Size would have to be minimized to simplify packaging. Any additions to the exterior of the aircraft had to be evaluated for its aerodynamic impact. This was particularly true at the engine pylon unit as it sat immediately in front of the leading edge of the wing and just aft of the engine intake. A special fairing was required to minimize airflow disturbance. There was a possibility that the mirrors themselves would be subjected to buffeting from impingement of the freestream airflow while the shutters were open during operation as well as the chance of acoustic effects. Provisions for mounting fences to deflect airflow "over" the openings were therefore incorporated into the design.

The mechanisms also have to be able to operate under severe environmental conditions. Temperature excursions of the ambient air in excess of 80 degrees C are not unusual. Thermal stability of the materials selected would be important to maintain critical optical alignments and mechanical tolerances. The temperature excursions would also lead to severe condensation of water on the instrument. This could lead to corrosion of mechanical components, water damage to the mirror surfaces and effects on the electronics.

Mechanism Description

The OPTIMA mirror alignment mechanism can be broken into two main component systems: the Pylon Mirror Motion Base (PMMB) and the Fuselage Mirror Motion Base (FMMB). The FMMB consists of three main subassemblies: the Fuselage Pitch Motion Base (FPMB), the Beam Guidance Mirror Assembly (BGMA) and a linear translation stage.

Spherical Mirror Assemblies

Both the PMMB and the FPMB contain spherical Mirror Assemblies, consisting of a specially shaped block of dimensionally stable glass, 4 cm X 10 cm X 30 cm (1.5 in X 4 in X 12 in) and approximately 3 kg (6.6 lb). The mirrors are bonded into 0.7 kg (1.5 lb) four sided frames made of Invar which have flanges to allow fastening to their respective motion base inner housings. This arrangement allows for easy change out of the mirrors with relatively minor adjustments to reestablish the proper position. The fuselage mirror has a small notch along one long edge as a pass through hole for the entrance and exit of the Herriott pattern laser beam.

Mirror Pointing

Mirror pointing is accomplished using accurately controlled limited rotation torque motors to drive specially designed ramped motion cams. The PMMB, FPMB and the BGMA all use the same basic method but the smaller overall size of the BGMA requires the downsizing of the components used in the other units. This method converts the relatively large rotation of a controlled servo motor into small and very precise mirror motions.

The torque motors are the key to a reliable, accurate and responsive positioning system **(Figure 3)**. They consist of a wound stator ring which is installed in recesses in the motion base housings and clamped into position. A magnetic rotor is inserted into the interior of this ring and by providing current through the stator ring, the rotor is driven through a 120 degree range of motion (±60 degrees from a central position). The rotor has a hole at its center through which the stem of the motion cam is inserted to provide a fixed rotating axis to maintain concentricity of the stator and the rotor. The cam disc is oriented onto the rotor to allow full range of motion and fastened to it maintain that position. The rotor is supported by a needle thrust bearing placed between two thrust washers. To prevent rocking of the rotor cam assembly and maintain concentricity between the rotor and stator, the motion cam stem spins in a shouldered radial ball bearing and bushing arrangement where the stem passes through the housing body. A radial resolver is used on the back side of the housing to provide positioning data for the control system.

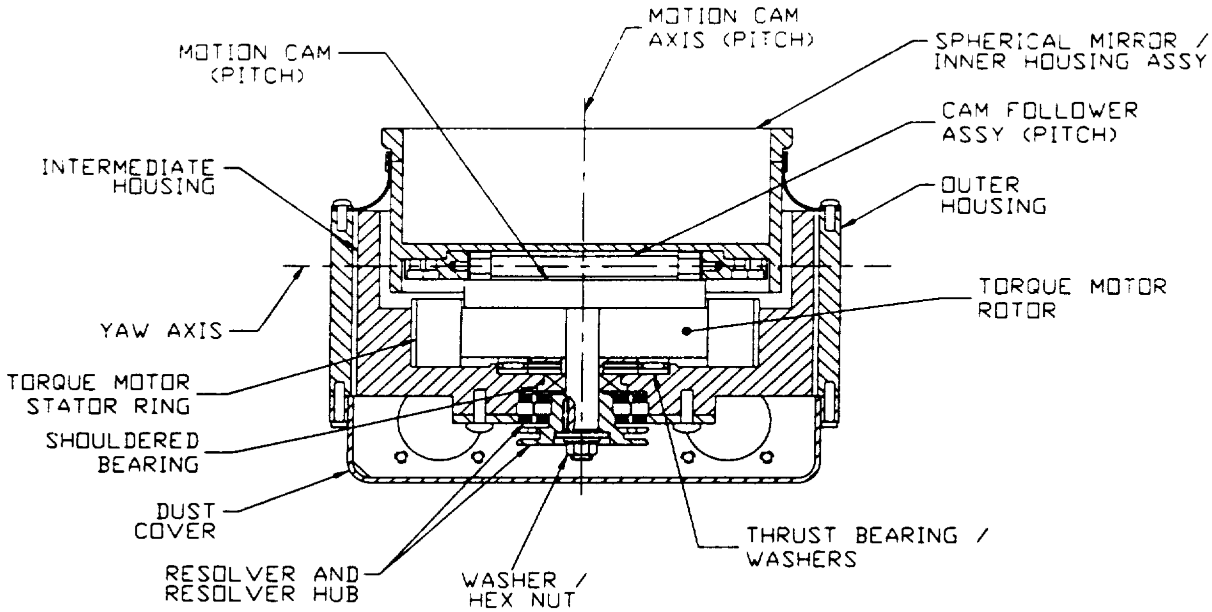

Figure 3. Motion System in section showing Pylon Mirror Motion Base pitch axis.

The resolver provides rotational position information to a control computer that compares this information with the linear displacement of a laser striking the surface of a position sensing device (PSD). As the impact point of the laser moves on the 360 mm^2 (.56 in^2) sensing surface of the PSD, the control system sends positioning commands to the torque motor to maintain the strike point near the center of the PSD.

Motion Cams

There are four motion actuating cams (three large and one small) in the OPTIMA instrument, each made of 17-4PH stainless steel **(Figure 4)**. The PMMB contains two large cams, one for inducing a ±1 degree yaw motion of the mirror, the other for inducing a ±2 degree pitch motion. The FPMB uses a ±2 degree cam identical to the PMMB cam. The BGMA uses a scaled down cam that produces ±1.5 degrees of deflection. Each cam consists of a flat disc with an inclined track around the perimeter of the top surface and a stem extending from the bottom surface. When assembled into the motion bases and the BGMA, cam followers on the driven components come into contact with the track. As the torque motor rotates the cam through its range of motion, the cam followers ride along the inclined track and cause their respective housings and mirrors to be pivoted.

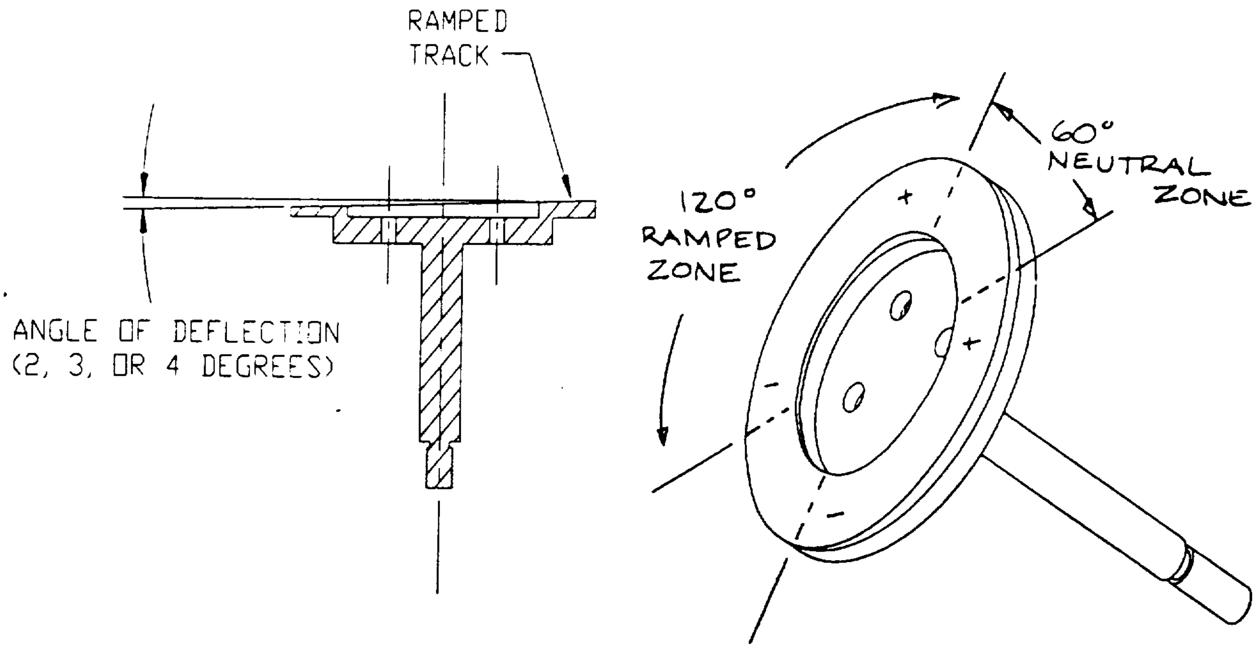

Figure 4. Detail of Motion Cam showing ramped track rising in (+) direction and dropping in (–) direction. Neutral zone is beyond torque motor's range of motion and is not used.

<u>Pylon Mirror Motion Base</u>

The PMMB provides 2 of the 5 degrees of freedom (pitch and yaw) with a nested series of rectangular housings arranged in a gimbal like configuration **(Figure 5)**. The outer housing is an open top box of 17-4 stainless steel and approximately 9cm X 15cm X 40cm (3.5in X 6in X 16in) and contains the yaw drive motion system. The intermediate housing is suspended from this via bearing supports, one fixed and the other a pillow block style flexure arm that provides the yaw axis pivot. The intermediate housing is also made of 17-4PH stainless steel, houses the pitch drive motion system and contains a similar bearing support system to provide a pitch axis (@ 90 to the yaw axis) for the suspension of the inner housing. The inner housing is a five sided box made of Invar to minimize the differential thermal expansion between it and the Spherical Mirror Assembly which nests inside. A module containing a position sensing device and an alignment laser is installed at one end of the inner housing to provide positioning feedback.

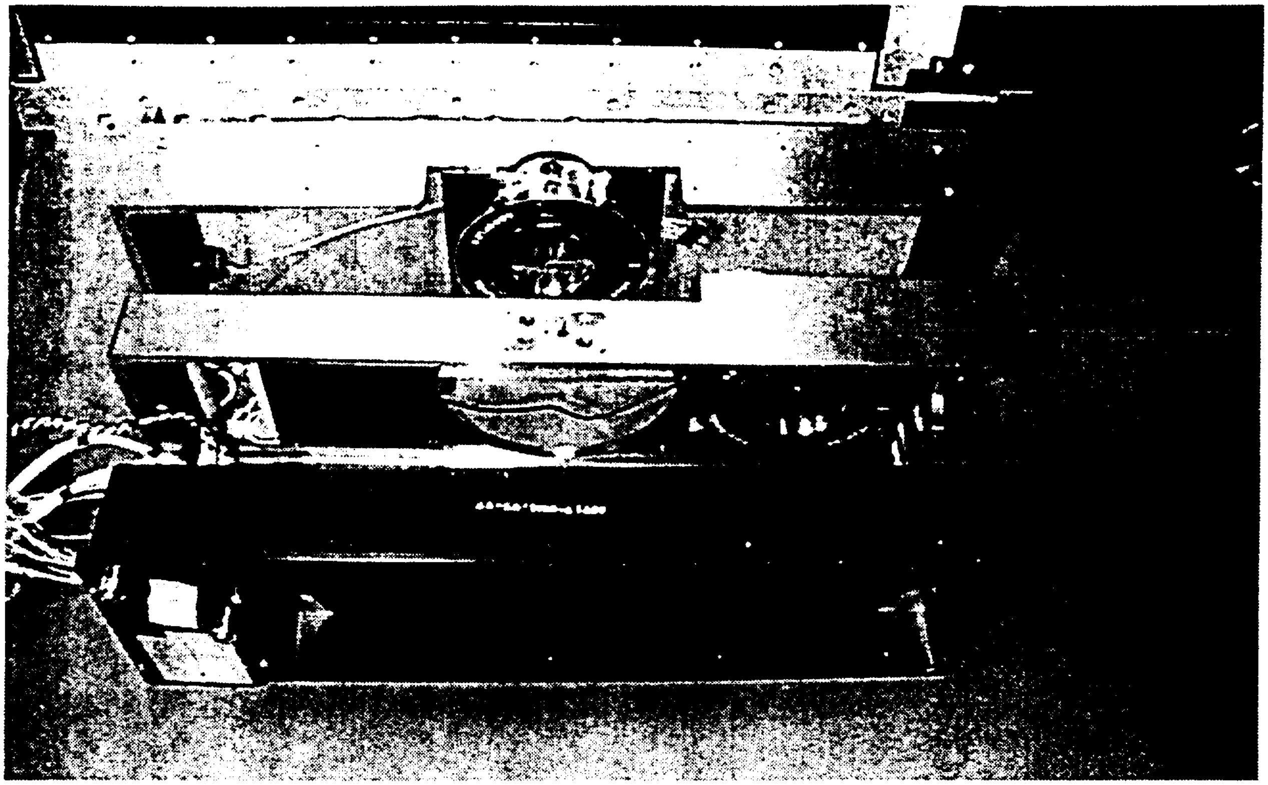

Figure 5. Nested housing arrangement of Pylon Mirror Motion Base assembly with torque motors and motion cams installed.

When assembled, roller bearings of two cam follower assemblies on the bottom of the Inner Housing fit against the motion cams of the pitch and yaw drive systems. The flexure arms of the bearing support systems are shimmed to provide a small preload of the motion system against the cams yet allow compliance to compensate for surface imperfections of the cam drive surface.

Fuselage Mirror Motion Base

The FMMB provides the remaining three degrees of freedom of the OPTIMA mirror alignment system **(Figure 6)**. Where the PMMB is designed to provide two degrees of freedom in one assembly the FMMB requires three distinct subassemblies and an integrating structure. The FMMB is installed into an open cavity created in the side of the aircraft by the installation of the Fuselage Pressure Box. A window above the leading edge of the wing is removed and replaced by an aluminum window blank with an integral shutter mechanism. The Fuselage Pressure Box is suspended off the interior surface of the window blank to provide a solid foundation for the FMMB and maintain a barrier between the pressurized cabin and the exterior test environment.

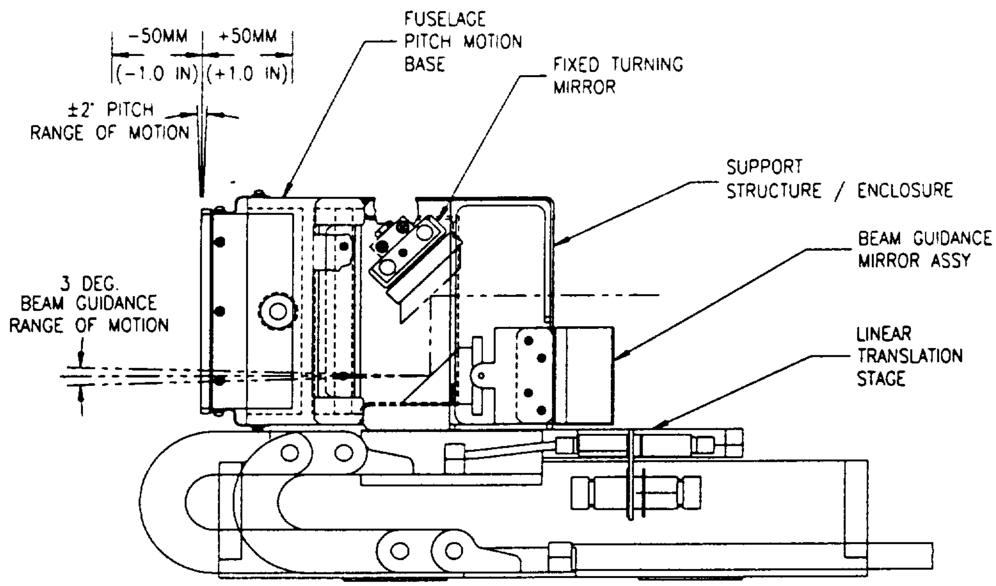

Figure 6. Assembly of the Fuselage Pitch Motion Base, Beam Guidance Mirror Assembly and linear translation stage into the Fuselage Mirror Motion Base.

The Fuselage Pitch Motion Base (FPMB) is essentially a PMMB with one less nested housing and one less torque motor / drive assembly, which was possible because no yaw motion was needed. The pitch motion of the FPMB allows the two spherical mirrors to maintain face to face alignment throughout the full range of vertical pylon movement.

The inner housing of the FPMB also includes an alignment module with a visible pointing laser and PSD to correspond with the arrangement on the PMMB. The laser of each motion base is aimed to strike the PSD on the opposite motion base. Initial alignment of these lasers is performed on the ground and must be adjusted to place the mechanisms in the center of their range of motion during flight. These two complementary laser / PSD modules provide the positioning feedback needed to maintain the relationship between the two spherical mirror surfaces.

Focal length is also affected by the wing movement and must be controlled to maintain the integrity of the Herriott pattern. It is controlled by mounting the FPMB onto a linear translation stage (a commercial linear slide table) that is able to maintain a constant distance between the mirrors by using 10 cm (4 in) of controlled travel.

The final component of the FMMB is the Beam Guidance Mirror Assembly (BGMA) **(Figure 7)**. This unit provides the initial aiming of the laser into the Herriott pattern and guides the returning beam back to the optics table area. This is critical to positioning the Herriott pattern onto the spherical mirrors and ensuring that the beam travels through the entire optical path.

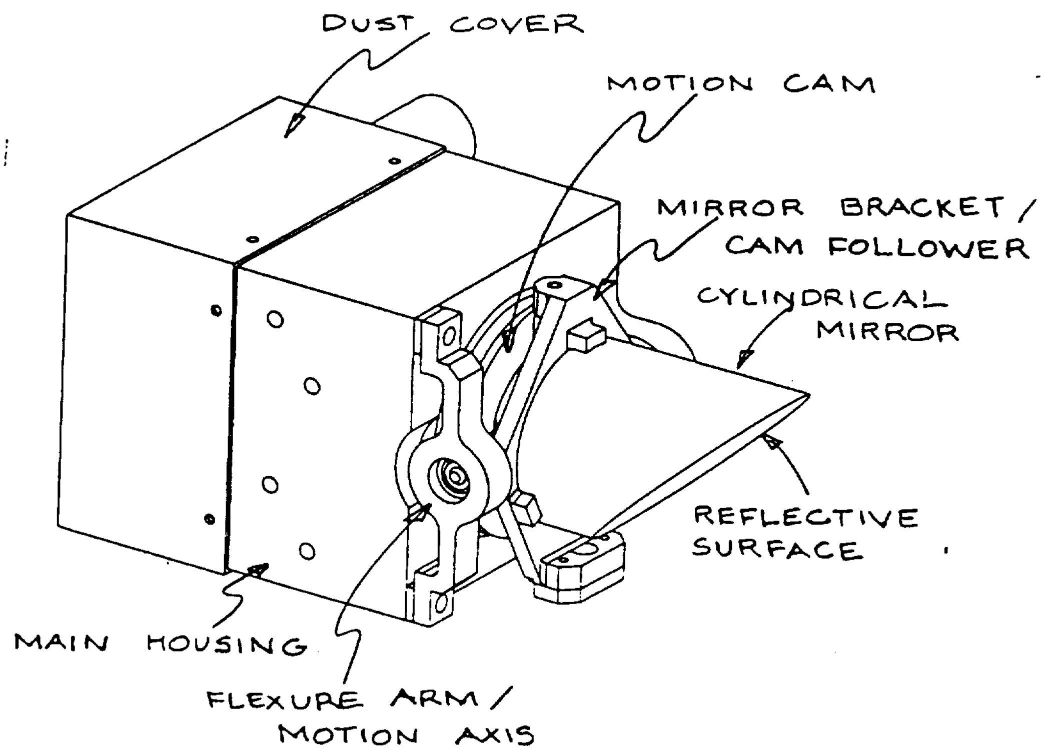

Figure 7. Beam Guidance Mirror Assembly

The mirror of the BGMA is a solid glass cylinder 25 mm (1 in) in diameter and 32 mm (1.25 in) in length and one end cut at 45 degrees with the resulting surface coated with protected silver. The end opposite the mirrored end is bonded to a plate assembly that includes radial bearing pivots to allow rotation and has a miniature cam follower assembly on the backside. The plate installs onto a single housing which incorporates a smaller limited rotation torque motor with a scaled down motion cam. This system is much smaller in overall size at 6 cm X 6 cm X 12 cm (2.25 in X 2.25 in X 4.75 in), as the size and weight of the mirror assembly it drives is considerably less than those in the PMMB and FPMB.

A third PSD and visible laser, which are integral to the IR laser system, determine the focal length and the aiming of the BGMA. The visible laser is co-aligned with the IR lasers and travels the entire Herriott pattern length and returns to the optics table. It is separated from the IR beams and guided to a third PSD. Vertical motion on the PSD surface indicates the need for focal length adjustment while horizontal movement indicates a correction is necessary in the beam guidance angle.

Testing and Operational Development

Due to the compressed schedule, testing was organized into two phases. First, each unique subsystem was assembled and tested for function and performance characteristics. During this phase of testing any operational deficiencies were addressed and experiments to optimize performance were conducted. The second phase was an integrated system test. The subassemblies were brought together into their final configuration and tested as a complete system to verify that mirror alignment could be maintained in a laboratory setting.

Subsystem Testing

The first phase of testing was to connect the control system to an individual motion system and verify that the unit could be moved through its full range of motion with controlled velocity and position. The second phase required reflecting a beam off of the controlled surface onto a PSD and verifying that the strike position of the beam could be maintained on the PSD as it was moved through the mechanism's range of motion. The unit undergoing testing was closely observed for opportunities to improve operational characteristics via mechanical modifications or revised assembly techniques.

The Beam Guidance Mirror Assembly was the first major subsystem available for testing. The BGMA was placed on a flat table and lightly clamped in place. An alignment laser was then mounted in a fixed stand and pointed at the BGMA from a distance of approximately one meter. The mirror position of the BGMA was set to the middle of its 3 degree range of motion. The laser was turned on and bounced off the BGMA and onto a PSD that was set into the laser's path. By driving the mirror through its full range of motion, the extreme positions of the beam deflection were noted. The PSD was then moved along the surface of the table between the extreme positions at various rates as the position of the beam strike on the PSD was monitored. This allowed the initial evaluations and refinement of the velocity control, positioning and feedback software. During this phase of testing, it became apparent that proper assembly of the mirror pointing assembly was critical to minimize friction of the motion system while eliminating backlash and freeplay.

While the BGMA was undergoing testing the PMMB was in final assembly. During this assembly a design deficiency was discovered during installation of the Spherical Mirror Assembly onto the pitch and yaw motion cams. When assembled as intended the stack-up of components was designed to deflect the bearing flexure arms slightly, producing a preload of the cam followers against the motion cams at the bottom of the mirror housing. As both cams were acting against the same surface, only one could be tensioned properly at a time, which would produce an excessive clearance at the second cam. As a result, the PMMB bearing flexure arms were modified so that when they were installed, the amount of displacement would be at a minimum.

The PMMB subsystem was then subjected to the same two phase test. At first the pitch and yaw axes were tested separately to verify control across the full range of motion of each axis. A flat mirror was bonded to the mass substitute and a test setup very similar to that used for the BGMA test was prepared. The area over which the beam could be controlled was determined. Testing and software development continued until the PSD could be moved within this two dimensional area while maintaining the laser on the center of the PSD.

Testing of the PMMB revealed several unforeseen complications. The large mass of the Intermediate Housing, Inner Housing and Spherical Mirror Assembly was all suspended and moved during yaw corrections. This arrangement generated high inertial loads and limited the yaw response performance. Additionally, the Inner Housing and Spherical Mirror Assembly are mounted in an unbalanced fashion with the majority of the mass cantilevered off to one side of the pitch pivot axis, which also required compromises in the control system that would limit performance. Despite these compromises, the functional requirements for overall system performance were still met.

Both the Linear Translation Stage and the FPMB testing were uneventful. Testing of the Linear Translation Stage was more of a characterization of a commercial assembly. The lessons learned during PMMB assembly, testing and development helped to expedite the process for the FPMB. The single axis could be centered in the housing and resulted in a better balance of the articulated mass. Also, with less suspended weight, the high inertial loads experienced in the PMMB did not occur in the FPMB.

By the end of this process, all subsystems were operating within parameters that indicated the completed system would perform as required. The subsystem testing and development had effectively refined each of the individual subassembly mechanisms.

Integrated System Testing

Once the testing of the subsystems was completed and all were determined to be operating properly, they were assembled into a laboratory simulation of the OPTIMA installation onto the DC-8. Mirror mass substitutes were replaced with the actual Spherical Mirror Assemblies and physical spatial relationships were approximated. A "floating" base for the PMMB was improvised to allow simulation of the motion of the PMMB during flight, as the results of the subsystem testing had indicated the integrated system could be made to track all 5 degrees of freedom fairly easily. Once this was accomplished the testing program involved further development and refinement of the control software and troubleshooting of the electronics.

Problems

Some of the difficulties encountered during the development of this device were:

<u>Selection Materials</u>

Invar was selected as the material for several major components. It has a rate of thermal expansion (one tenth that of carbon steel) which is very similar to the glass spherical mirrors. This dimensional stability would help minimize structural stresses due to differential expansion rates and maintain the critical optical alignments.

These advantages are somewhat negated by the difficulties Invar presents when machining. The processes of annealing, machining and heat treatment cause the accumulation and relief of internal stresses, resulting in distortions in the finished part. The warpage in some of these parts was occasionally much greater than the movement expected from differential thermal expansion.

All external components of the OPTIMA instrument would be exposed to considerable condensation. The system would be primarily operated at altitudes above 20,000 ft where ambient temperatures would cold soak the metal housings. While Invar is dimensionally very stable, it is very susceptible to corrosion. The method selected to control corrosion was to plate the Invar with a black chrome process per Mil-C-14538. This required a preplating with nickel (QQ-N-290, class 1, grade G). The combination of the movement of the Invar during manufacturing and the dimensional changes due to the plating process resulted in several key components not meeting drawing dimensional requirements.

In retrospect, it appears that the Invar could be replaced by 17-4PH stainless steel with little negative consequence. The stainless steel has superior machining characteristics, would not require plating and its thermal expansion rate could be accommodated.

<u>Torque Motor Performance</u>

17-4PH stainless steel was selected for the main housings and motion cams to take advantage of its strength, hardness, machinability, and corrosion resistance and was utilized where thermal stability was not a paramount concern.

The housings were designed and made with cup like depressions to hold the limited rotation torque motors. Initial consultations with the manufacturers of the motors did not reveal a cause for concern. The motors were installed into the housings and tests conducted to characterize performance and measure actual output. The results indicated an output torque less than 40% of the manufacturer specification. After consultation with the motor vendor, it was concluded that the close proximity of the magnetic material of the housings, cams and bearing was short circuiting the permanent magnet rotor and reducing the flux through the motor stator. The vendor suggested substituting newly developed rare earth magnets or changing the material the cams were made of to a non-magnetic material. Long lead times for the new rotors dictated a search for a suitable material to make replacement motion cams. 300 series stainless steels and hard anodized aluminum alloys were investigated and rejected due to strength and durability concerns. To match existing geometric constraints, the cams had to have thin cross sections in an area that created significant stresses within the cam. In addition the contact stresses between the cam and the cam follower bearings are high enough to create local deformation in the cams. As these problems could not be resolved, the decision was made to procure the new, stronger rare earth rotors.

After the new rotors were installed and tested the results showed an improvement to only 45% of rated torque. Experiments replacing the magnetic 17-4PH housings with aluminum test housings demonstrated the need to remove as much magnetic material as possible from direct contact with the stators. This improved measured output to about 60% of rated torque which was considered to be adequate for the instrument.

The lack of power contributed to difficulties during testing and continues to compromise the performance of the PMMB and FPMA. The BGMA did not suffer as much from this effect; even though it was less powerful, it moved a much smaller and lighter mirror assembly.

Mirror Pointing Assembly

During evaluating and troubleshooting of the torque motor problem, it became apparent that considerable attention would be required during the assembly of the torque motor / motion cam stack-up. The initial attempts to assemble the BGMA confirmed this conclusion. The assembly and operation of the motion drive mechanism revealed that the preload of the component stack-up was critical. The ideal amount of torque took up all of the slop in the drive system but added very little friction to the system. Additionally, when originally assembled the cam could "rock" in the housing, even when preloaded. The original radial bearings were replaced with a shouldered bearing capable of both radial and thrust loads. Using this new type of bearing, preload could be applied to the cam to prevent rocking without the need of high contact forces between the cam and the cam followers.

During initial testing of the BGMA it was not possible to control the torque motor over 100% of its motion. Characteristics of the resolver and motor caused the control system to overdrive at the extreme end of each direction of travel. This necessitated the installation of mechanical stops that would restrict travel to approximately ±58 degrees from the center point. Without the stops it would be possible to over-rotate the rotor, resulting in damage to the resolver wiring and prevent any further control over the pointing of the mirrors. Similar stops were also incorporated into the PMMB and FPMB motors.

The type and quantity of grease was determined to be important at this point as well. Grease with very low friction and low start torque as well as the ability to maintain these properties throughout the expected operating temperature range was located and used with excellent results.

The most critical aspect of the mechanism proved to be loading the cam followers against the motion cams as mentioned in the previous **Testing and Operational Development** section. No free play could be tolerated yet even slightly excessive preloads would cause binding due to small irregularities in the surface of the tracks of the motion cams. The control system was extremely sensitive to these conditions. Ideally the force required to rotate the cam would be consistent or at least linear in quality to allow optimal tuning of the control system.

Conclusion

The OPTIMA instrument was successfully installed onto the NASA DC-8 research platform during September 1997. After local checkout flights it was deployed for a period of one month to Shannon, Ireland, the Azores Islands and Bangor, Maine. Despite the difficulties discussed above, the instrument performed as intended during all flight conditions encountered. Mirror alignment was easily obtained once in flight and tracking was only infrequently interrupted, and then only for periods of 5 to 10 seconds. These interruptions were primarily due to PSD saturation by ambient lighting or the requirement to open control loops for beam guidance and focal length due to degradation of spherical mirror reflectivity. Some flight operations, such as descending with reduced engine power, produced conditions where control of the PMMB yaw axis became difficult. This may be a result of the displacement frequency of the engine changing to a natural frequency of the motion system.

No mechanical failures were experienced during the 3 checkout or the 14 mission flights. The trouble free operation of the mechanical mirror alignment system and the outstanding performance of the control system allowed full concentration on the refinement of the science portion of the instrument during deployment.