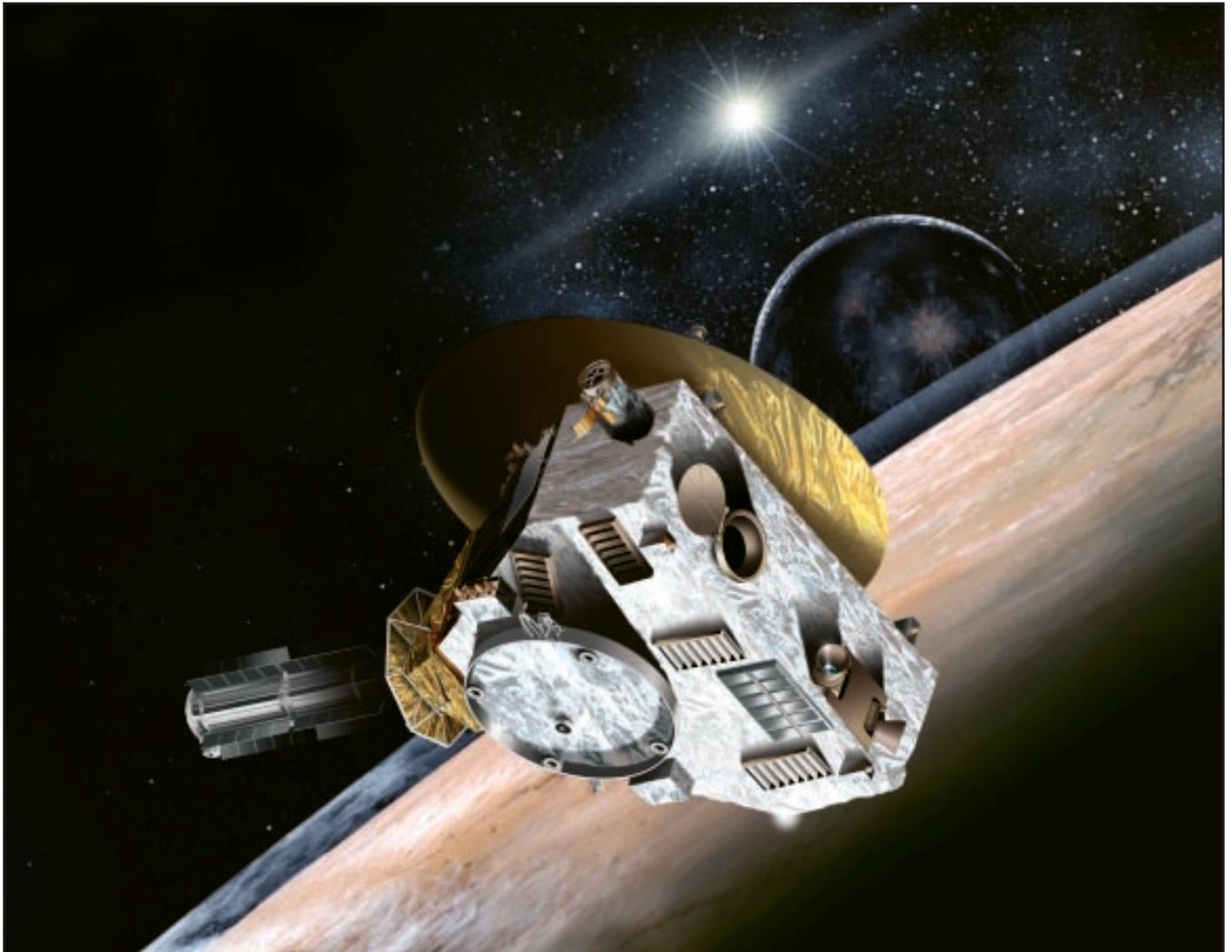


The Journal *of the* CMSC

THE PUBLICATION FOR 3-D MEASUREMENT TECHNOLOGY



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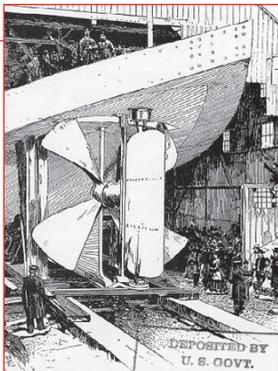
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Chairman's Message

Welcome to the CMSC!



Dear CMSC Member:

It is with great pride that the Coordinate Metrology Systems Conference (CMSC) announces its first-ever Journal of the CMSC. This publication consists of three outstanding white papers presented at CMSC 2005 in Austin, TX. These white papers are only a sampling of the interesting, thought-provoking technical content associated with our unique conference. The new journal greatly enhances our core mission to advance 3D measurement system technology and application.

The CMSC Society cordially invites you to attend our 22nd annual CMSC in Orlando, FL. This yearly event introduces expert and novice users of portable three-dimensional measurement systems to leading metrology companies who provide hardware, software, and measurement services. CMSC fulfills its mission each year by providing a professional venue where ideas, concepts, and theory flow freely. Technical presentations, workshops, and exhibition booths are only a portion of our popular conference. By providing breakfast, lunch and evening social events, and this year a tour of Cape Canaveral, CMSC successfully promotes a relaxed, open atmosphere where competing exhibitors can talk; attendees can present new ideas, and the field of metrology advances.

The numerous benefits associated with CMSC attract many attendees year after year. Our organization takes great pride in the quality, quantity, and professionalism of technical papers contributed each year. Proud of their industry endeavors, our presenters work diligently to provide a glimpse into how they use 3D measurement systems in a variety of environments.

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The Executive Committee would like to offer a very special thank you to Quality Digest, the official CMSC magazine, for their guidance and support in making the Journal of the CMSC a reality.

So please, go get a cup of coffee, sit back and enjoy your Journal. Based on the early response to our 2006 Call For Papers, you can be assured the next issue of our Journal will continue on the same track of excellence. CMSC Executive Committee members are working feverishly to make CMSC 2006 the best conference to date. We kindly ask our members and supporters to make a special effort this year to reach out to your industry colleagues and invite them to attend the CMSC Conference. We hope to see you in Orlando, FL.

Glen P. Cork
2006 CMSC Chairman



Measurement Techniques Used to Boresight, Flight Qualify and Align the 2.1-Meter High Gain Antenna for NASA's *New Horizons* mission to Pluto

by John R. Troll and Ron Schulze

It takes a large antenna to send data over billions of miles. This article presents how the *New Horizons* antenna was developed, as well as some interesting lessons learned from the use of differing metrology techniques.

Measurements were made on a 2.1-meter high gain antenna (HGA) that launched aboard NASA's *New Horizons* Pluto-bound observatory in January 2006. These measurements included boresighting, surface profiling, assessing mechanical thermal distortion and aligning the HGA to the spacecraft. Various techniques were used, including optical cube vector metrology, coherent laser radar, close-range digital photogrammetry and multiple-theodolite coordinate measurements.

After providing some background on the HGA, this article introduces the overall measurement plan and results. Based on the measurement approaches taken, certain assumptions are explored and the suitability of the differing techniques is examined.

BACKGROUND

Mission overview

As the first voyage to a whole new class of planets in the farthest zone of the solar system, *New Horizons* is a visionary mission of exploration.¹ The United States has made history

by being the first nation to send a space probe to every planet from Mercury to Neptune. The *New Horizons* mission to Pluto and the Kuiper Belt—planned to be the first NASA launch to a “new” planet since Voyager nearly 30 years ago—would allow the United States to complete its reconnaissance of the solar system. This proposed mission to Pluto-Charon and the Kuiper Belt will explore the mysterious, icy worlds at the edge of our solar system and tell us about the origin and evolution of our planetary neighbors.

The *New Horizons* spacecraft is roughly 8 feet (2.5 meters) across and weighs approximately 1,025 pounds (465 kilograms)—about half a ton—when fueled.

More facts about the proposed mission:

Launch date—January 19, 2006

Location—Cape Canaveral Air Force Station, Florida

Launch Vehicle—Atlas V 551 first stage; Centaur second stage; STAR 48B solid rocket third stage

Trajectory—To Pluto via Jupiter gravity assist. (See figure 1.)

Arrival—2015-2017. (At the earliest, current second graders would see *New Horizons* arrive at Pluto during the summer before 12th grade).

High gain antenna functional requirements

The planned *New Horizons* observatory will carry a complement of seven instruments to gather information about Pluto/Charon and beyond. Communications to Earth at that distance will be achieved using a 2.1-meter-diameter shaped (not precisely parabolic) HGA, as shown in Figure 2.

To accommodate both the science goals and minimize the propellant needed, the planned observatory functions in both three-axis stabilized and spin-stabilized modes. Communications occur in spin-stabilized mode, leading to a relatively tight requirement for the angle of the HGA boresight relative to the major moment of inertia, or spin-axis (as shown in figure 2). The total system requirement for alignment to the spin axis is 0.2° . At a Pluto-like distance of 3 billion miles, the HGA boresight mispointed by 0.2° would miss Earth by over 10 million miles (the antenna beam width makes up for it, however).

To understand the accuracy with which the HGA boresight would be aligned to the spin axis, an “error tree” was used. This tree systematically identifies specific error sources and alignment requirements for each misalignment source. During the flight qualification program, error sources

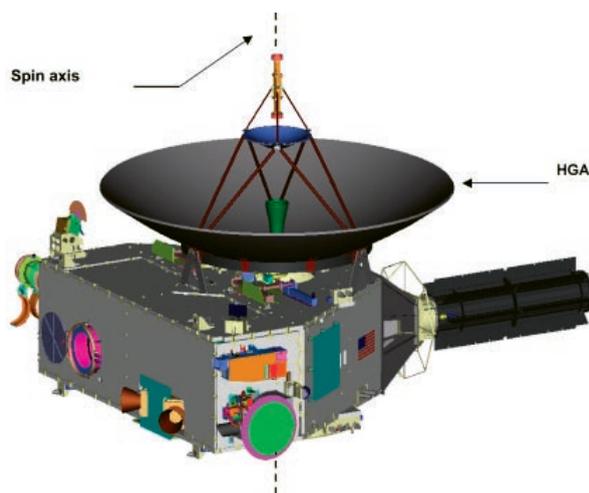


Figure 2. The *New Horizons* observatory (baseline design), showing the HGA and the spin-axis.

were quantified either through measurement or analysis. Errors were generally attributed to mechanical tolerances, environmental effects (i.e., vibration, shock or temperature change) or measurement error. This system engineering tool was the method with which the HGA was verified to have met its alignment requirements.

High gain antenna overview

The HGA reflector is made of a low coefficient of thermal expansion (CTE) graphite composite laminate with a Korex honeycomb core. This construction allows the antenna system to survive the rigors of launch with minimal mass and to maintain its alignment and shape at cryogenic temperatures. Figures 3 through

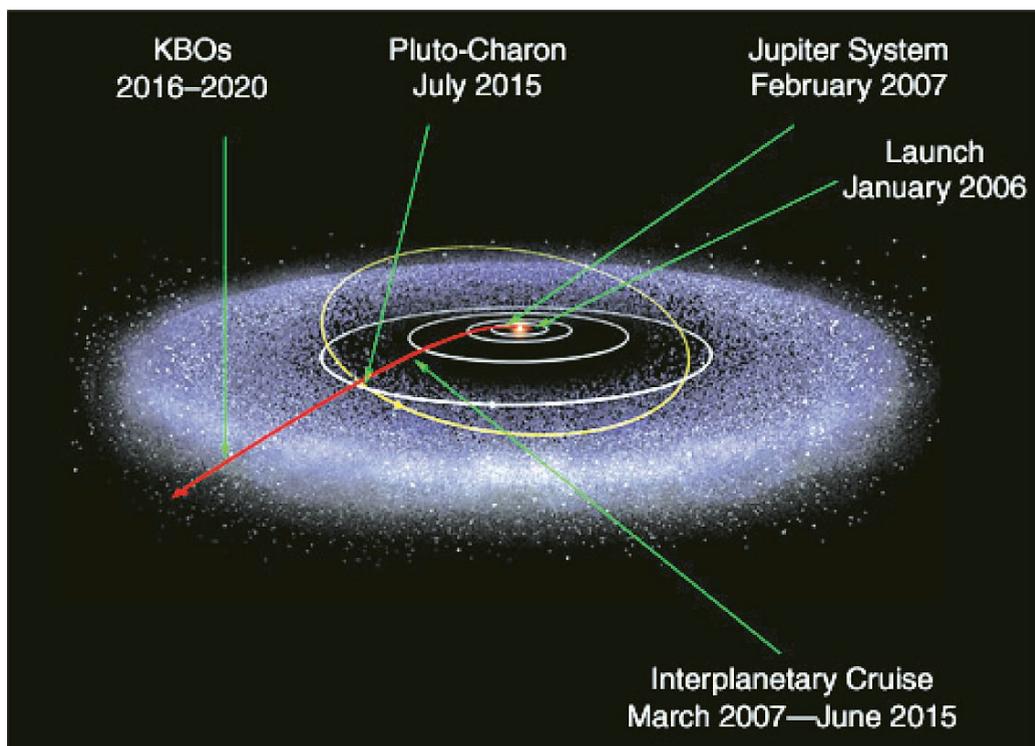


Figure 1. The *New Horizons* mission plan.

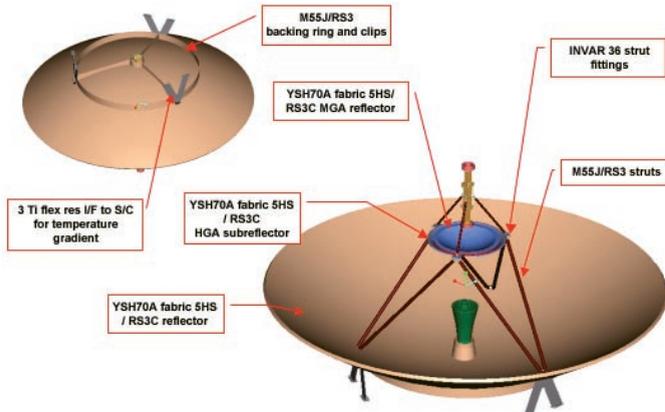


Figure 3. HGA material overview.

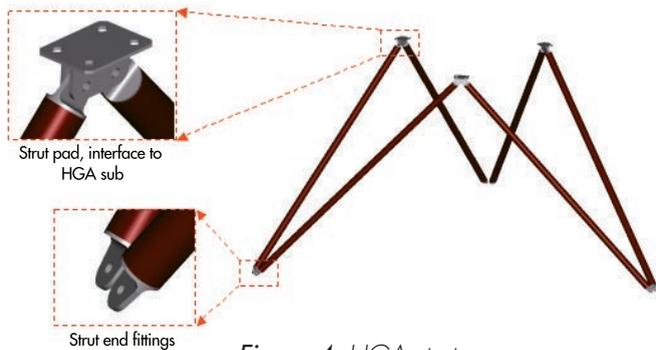


Figure 4. HGA struts.



Figure 5. HGA main reflector.

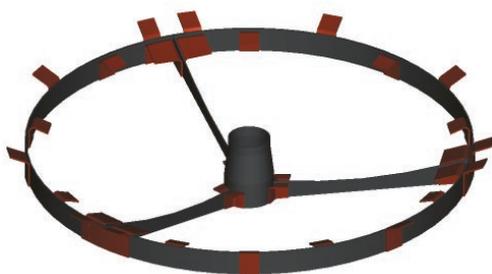


Figure 6. HGA backing ring/structure.



Figure 7. HGA mounting flexures.



Figure 8. Actual HGA, as delivered, with tooling ball "ears" around circumference.

7 depict the HGA construction and major components. The composite reflector was fabricated by Programmed Composites (PCI) in Corona, California.

Assembly of the HGA components was completed at Johns Hopkins University Applied Physics Laboratory (JHU/APL) in October of 2004. The assembled HGA is shown in figure 8. The eight "ears" around the dish perimeter were used by the vendor to aid in making surface profile measurements and were later removed.

As designed, the HGA boresight was closely coupled to the orientation of the primary reflector. A change in the subreflector angle (tilt) relative to the primary reflector affected the boresight by a factor of only 1:10.

Table 1. Original and final HGA alignment measurement plan, in time order

Step	Original	Final
Internal alignment	Optical cubes	Optical cubes
Initial boresighting	Optical cubes	Optical cubes
Subsystem vibration	Optical cubes	Optical cubes
Subsystem thermal vacuum/distortion	Initial and final optical cube shots, analysis	Initial and final cube shots, analysis, photogrammetry
Surface profile	Not planned	Coherent laser radar
Final boresighting	Optical cubes	Optical cubes, theodolite system triangulation
Alignment to spacecraft and further checks	Optical cubes	Optical cubes, theodolite system triangulation

MEASUREMENTS

The alignment test program for the *New Horizons* HGA system was designed to: (1) reference the radio frequency (RF) boresight to a physical mechanical reference, (2) qualify the mechanical system design by measuring the relative alignment of the HGA feed, subreflector and primary reflector components at cryogenic temperature and (3) align the RF boresight to the observatory coordinate system. As qualification proceeded, the alignment tests were modified to accommodate realistic limitations on the measurement of a large structure such as the *New Horizons* HGA. Achieving quality measurements required using alternate techniques including close-range digital photogrammetry, coherent laser radar and multiple-theodolite coordinate triangulation.

Measurement plan overview

Table 1 outlines both the original and final measurement plans. Originally, the alignment measurement plan relied only on measuring attached optical references for vector metrology.

As the HGA subsystem requirements and design elements were refined, additions to the test program were made. A programmatic risk-reduction trade resulted in the addition of a photogrammetric measurement of the dish profile during thermal vacuum testing (a costly effort). Unclear test results (and the low density of coordinate targets) then prompted a high-density coherent laser radar mapping of the dish to characterize its surface. Finally, multiple-theodolite coordinate triangulation was used to measure the dish axis as a backup reference to the dish cube—a necessity after cube instability became evident.

The remaining subsections outline the application of each measurement technique to the required HGA qualification step.



Figure 9. Leica T5100A autocollimating theodolite² (left) and reference optical cubes³ (right).

Vector metrology using optical references

Vector metrology, as applied here, utilizes autocollimating theodolites to precisely measure angles between polished optical surfaces and other theodolites. This technique is most relevant to optical telescopes and instruments, where the center of a silicon detector (usually equivalent to a boresight) can be seen through a theodolite and mapped into a reference cube. The output of this boresighting operation is a unit vector defined along axes determined by the orthogonal mirrored surfaces of the reference optical cube. Knowledge of the boresight vector

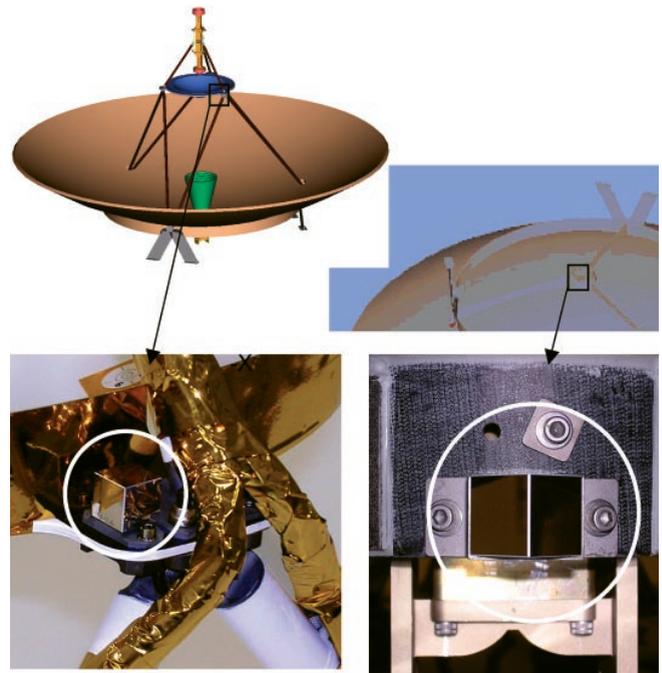


Figure 10. Subreflector cube, lower left; Primary reflector cube, lower right.

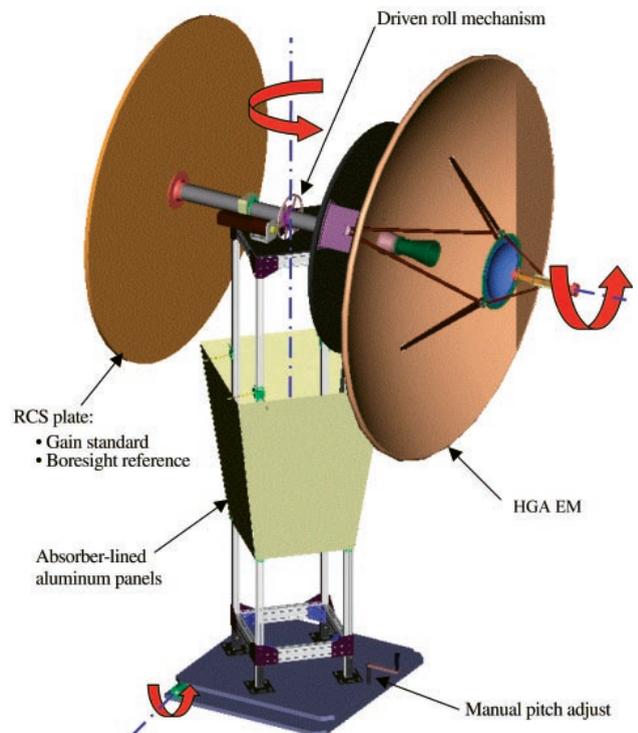


Figure 11. RF test stand for measuring antenna performance and boresight. Facing front right is the HGA. Facing back left is the reference control surface (RCS) plate.

allows the boresight to be accurately aligned on some larger structure or to the boresights of other devices. Figure 9 shows examples of a theodolite and optical cubes used for vector metrology.

Placement of an optical reference onto the HGA was complicated by the lack of suitable mounting spots. The reference for the primary reflector dish was mounted onto a bracket at the central ring of the backing structure. (See figure 6.) A second reference, to serve as a measure of internal misalignment or a backup cube, was mounted to the subreflector. Figure 10 shows the actual cubes as mounted. Because the subreflector angle was not directly tied into the boresight direction (a factor of 1:10), the primary reflector dish cube served as the primary optical reference for the dish.

Boresighting an RF antenna utilizing optical references is more complicated than boresighting an optical instrument. Because of the tight requirement for measuring boresight (0.05°) and the size of the HGA main reflector, testing was performed at The Ohio State University Electroscience Laboratory Compact Test Facility. This facility provided a fixed-direction, plane-wave RF signal across the *New Horizons* HGA reflector in a stable indoor environment

To probe the response of the HGA and derive the direction of peak response, an actuated test stand was developed to provide precision positioning of the antenna with three angular degrees of freedom. Figure 11 shows the modeled RF test stand with the HGA installed.

Mapping the HGA boresight required that two measurements be combined, relating the HGA peak energy direction to the HGA optical references: (1) the incident plane wave direction relative to an external reference and (2) the HGA optical reference direction while “peaked up,” measured to the same external reference as in step 1. The difference between (2) and (1) is the desired HGA boresight mapped into the optical reference coordinate system.

In addition to serving as references for the boresight knowledge, the HGA cubes allowed measurements of internal misalignment (i.e. between the subreflector and primary dish). In the next subsystem test step (thermal vacuum testing), only initial and final relative cube checks were possible, with periodic checks made during the test with photogrammetry. Further measurements

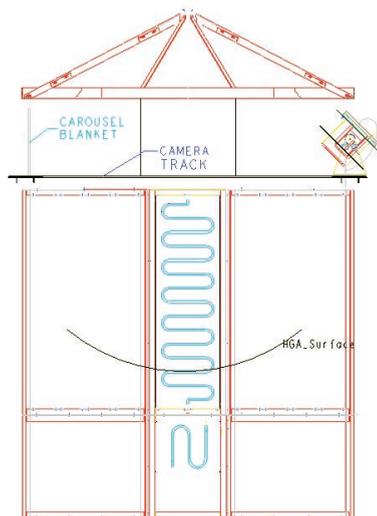


Figure 12. Helium shroud with camera carousel and canister (top right).

utilizing the optical references are discussed in the “Multiple-theodolite triangulation of dimensional coordinates” section.

Photogrammetry of the HGA during thermal vacuum testing

Because of the importance of the HGA function to overall mission success, testing of the HGA surface profile at operational temperature was necessary. The difficulty and cost of this test originally led our team to verify this performance through analysis and coupon-level testing. However, the *New Horizons* program was requested to mitigate this risk further with a subsystem-level thermal vacuum test of the HGA.

After examining available options that could meet the HGA size, temperature and measurement requirements, the NASA Goddard environmental test facility in Greenbelt, Maryland, was selected. Here, NASA engineers had previously developed an



Figure 13. Photogrammetry targets originally applied to Kapton tape did not remain in place (uppermost target did remain on Kapton, but no others in this picture).

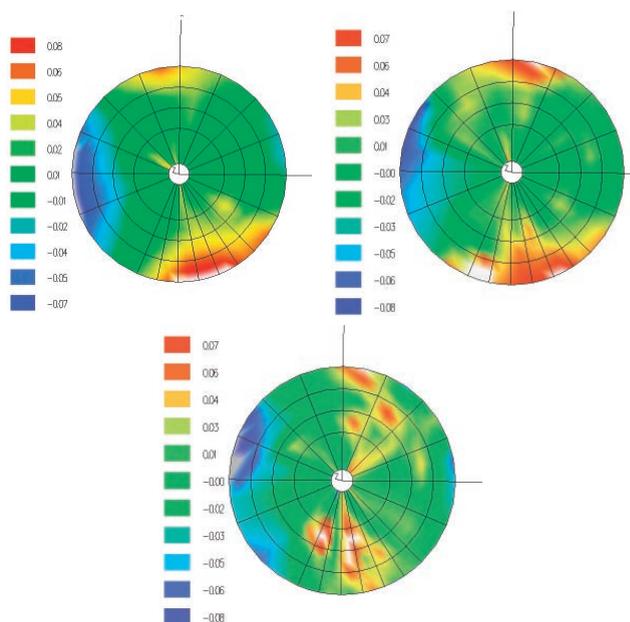


Figure 14. Deviation of HGA from ideal shape: initial room temperature (upper left), coldest temperature (lower), and final room temperature (upper right).

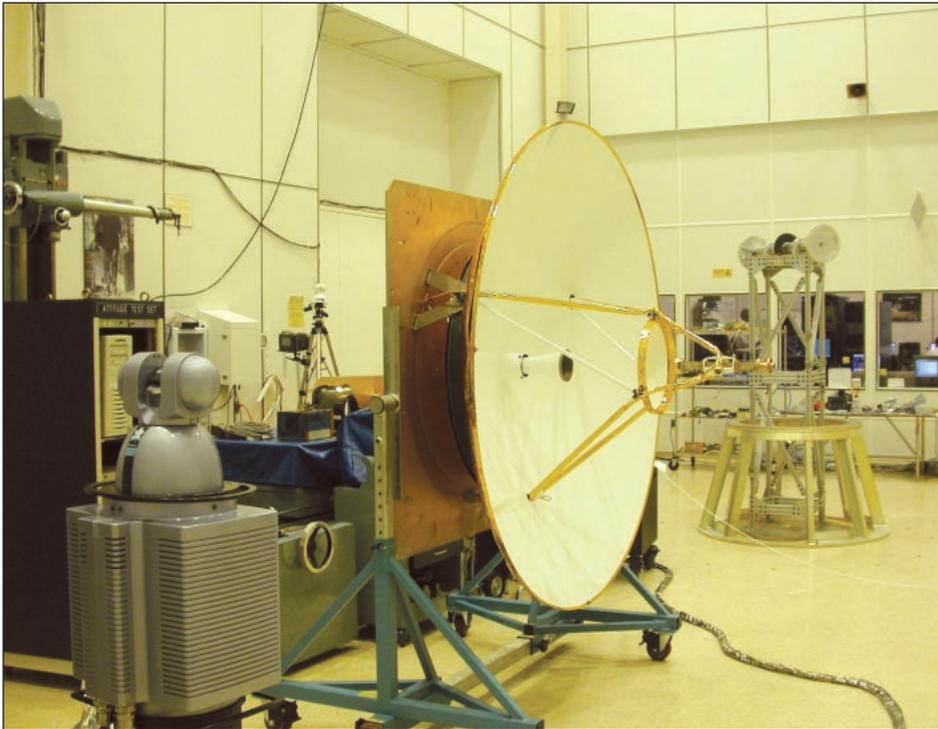


Figure 15. Mapping of the subreflector with the coherent laser (front left).

automated close-range digital photogrammetry system for measuring the mechanical thermal distortion of the NASA Wilkinson Microwave Anisotropy Probe (MAP) spacecraft⁴. In this system, the camera was placed within a sealed canister that traveled on a circular track via a geared drive/chain system. During a measurement sequence, the camera canister is moved and rotated to acquire digital pictures. Figure 12 shows a drawing of the helium shroud with the camera canister/track on top.

Targets made from retroreflective tape were placed on the dish surface and on the edges of the subreflector attachment bracket. Retroreflective tooling balls were placed on the dish ears (figure 8) and at the dish flexure bases. This targeting scheme allowed

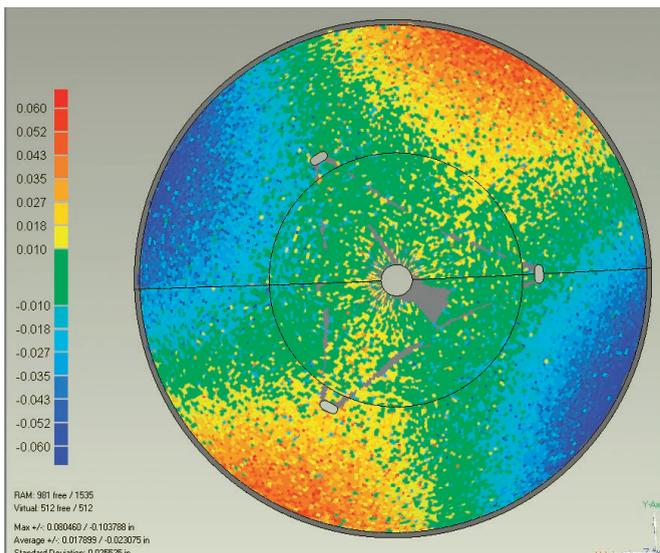


Figure 16. High-density HGA scan using the coherent laser radar.

for measurement of the base, the dish surface and a plane approximating the subreflector.

Once targeted and instrumented with temperature sensors, the HGA was ready for thermal vacuum testing. At the outset of testing, a problem was encountered with the photogrammetry self-adhesive targets: they came loose from the Kapton tape between them and the dish surface. In some cases, the targets were violently projected from the dish surface, as seen in figure 13.

The test was halted and the targets were replaced with a new scheme. In the first trial, the targets were applied to Kapton tape and then attached to the dish surface. Re-examining the target attachment scheme from the MAP program, the targets were first adhered to a small section of paper with the paper taped to the dish using Kapton. It was speculated that this would allow any trapped air behind the target to be removed without

disrupting the target bondline. This approach was relatively successful and testing commenced after the chamber was cooled to cryogenic operational temperatures, requiring several days.

Photo sequences were taken at the test outset, at test completion and roughly once per day during testing. Figure 14 shows the surface deviation from nominal at the test beginning (room temperature), coldest temperature reached (-174° C) and test completion (room temperature).

Though the targets adhered much better the second time, there were apparent problems with motion and bundling for some individual targets. This made interpretation of the surface profile data difficult. Generally, the mode of dish distortion appeared “taco-”

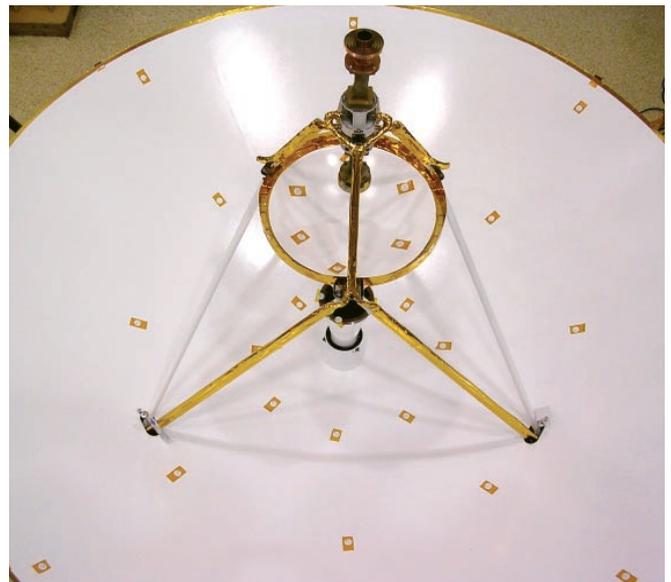


Figure 17. HGA targeted with “bull’s-eye” targets.

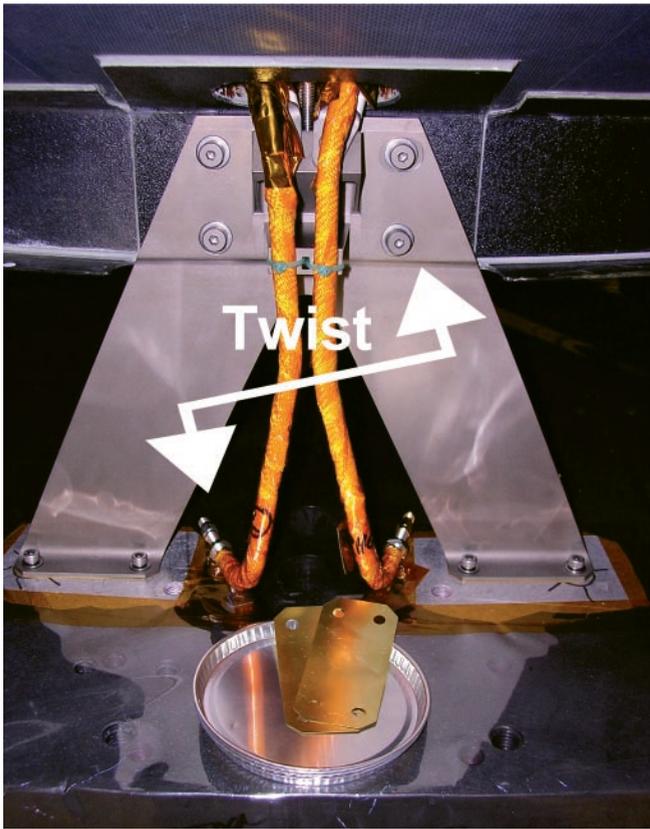


Figure 18. Flexure twist causing distortion within the HGA, the result of uneven mounting surfaces.

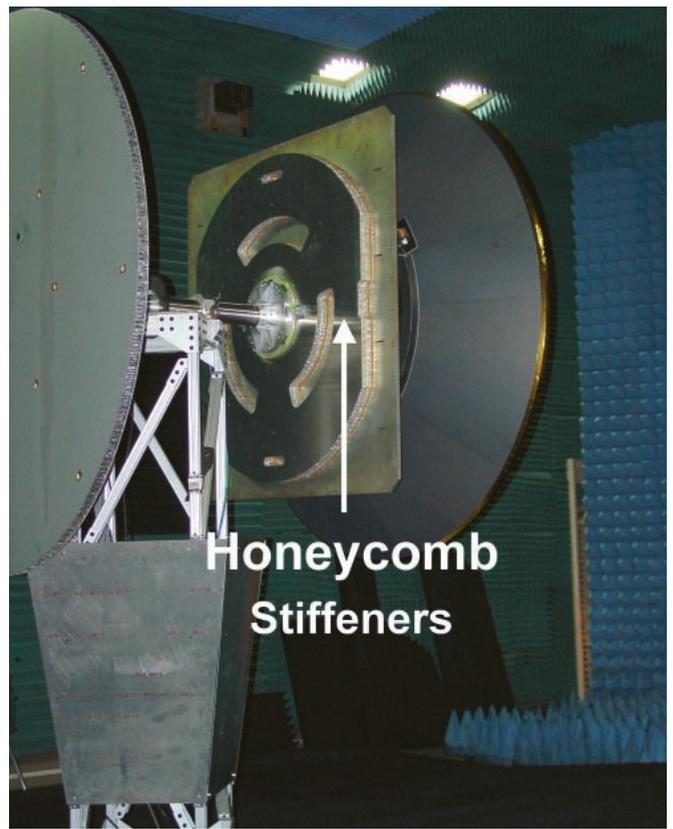


Figure 20. RF test stand with stiffened backing plate.

shaped. An increase in total surface root mean square (RMS) of about 0.012 in. was evident at operational temperature. When examining rigid body fits to the test data, it was clear that the HGA subsystem maintained its alignment very accurately over temperature (a total effect on boresight of less than 0.008°).

Coherent laser radar

Questions were raised during the subsystem thermal vacuum test as to what the real surface shape was and how much of the apparent deviation was actually due to measurement error. To address these concerns and present additional useful information for RF modeling, a higher density measurement was per-

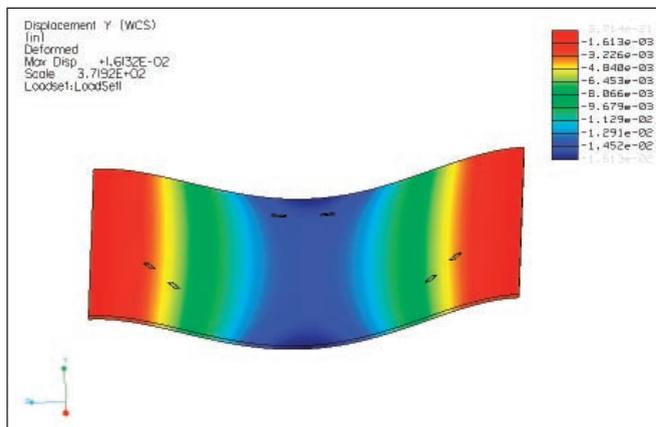


Figure 19. Self-deflection of the original HGA backing plate on its stand, with mounting spots shown.

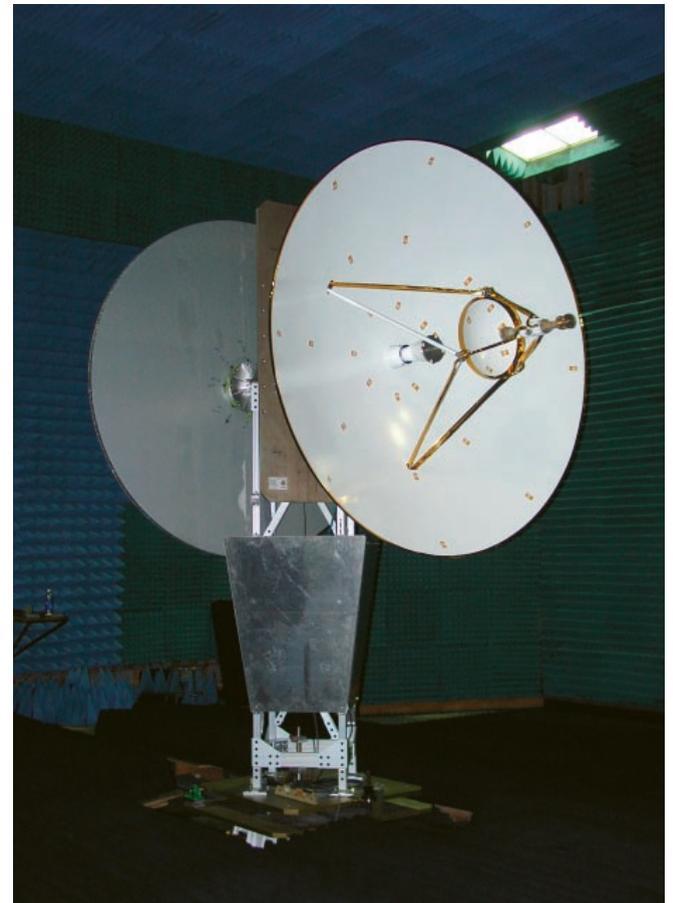


Figure 21. RF test stand with targeted HGA.

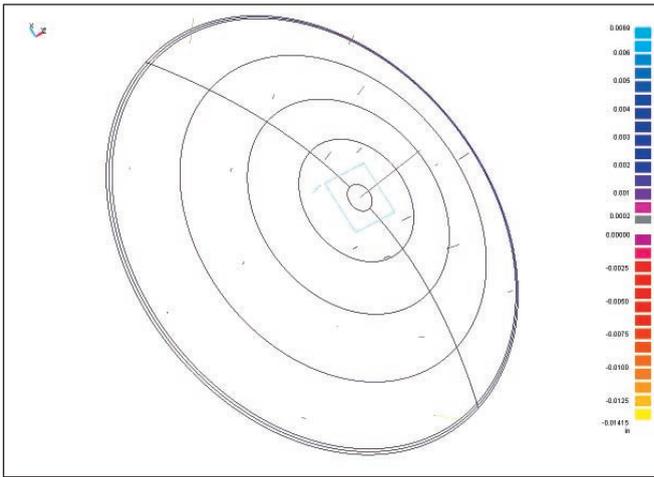


Figure 22. Fit of nominal dish shape (and axis of symmetry) to the measured dish coordinate points.

formed using the Metricvision (now Metris) coherent laser radar metrology station. The mapping was performed by Bill Griffin, Jr., of IAM Systems in Tipp City, Ohio, at a density of 1 point for every 0.25 in. to an accuracy⁵ of 0.004 in. Figure 15 shows the laser radar being used to map the subreflector from the side.

Mapping results (figure 16) clarified the taco shape of the primary reflector and definitively verified the extent of surface deviation. Generally, the photogrammetry and laser radar mappings also agreed in the magnitude of shape deviation (over a +/- 0.060 in.-range). The laser radar scans, though time-consuming, were very easy to set up and interpret.

Multiple-theodolite triangulation of dimensional coordinates

Relative cube checks (from the dish cube to the subreflector cube) continued to be taken, before and after thermal vacuum testing, and before and after each shipment of the HGA. The final

relative cube check after thermal vacuum indicated that motion, unconfirmed by photogrammetry, occurred between the cubes. At the time, this result was treated as an anomaly to be closely tracked.

As additional relative cube measurements were performed (pre-ship, post-ship, etc.), changes in the cube orientations continued to occur. Investigation of the root cause and the development of a backup plan to the optical cubes as boresight references became important.

To sort through the issues surrounding this mysterious cube motion, some measure of the actual reflector surface was needed. For this measurement, 24 Kapton-tape-backed bull's-eye targets were applied across the surface of the HGA, as shown in figure 17. A multiple-theodolite system (running ManCAT software) was used to measure the locations of the 24 targets to an accuracy of approximately 0.002 in.

With a new tool employed to understand the source of the cube motion, it became apparent that mounting (boundary) conditions were affecting the HGA surface shape and cube correlation. The largest effect came from a twist within any one individual flexure, as depicted in figure 18.

Once the root cause behind the cube motion was understood, doubts were also cast upon previously measured boresighting data relative to the HGA dish cube. This was because of the apparent cube instability and also the uncontrolled mounting conditions of the HGA flexures at the time of boresighting. In mounting the HGA to the RF test stand (figure 11), the HGA was first mounted to a backing plate with the plate lying in a horizontal plane. Examining the stiffness of this aluminum backing plate, substantial self-deflection in the plate (from its weight) was modeled (figure 19). This deflection, along with any gapping due to assembly tolerances, would transmit distortion into the HGA subsystem as the dish was lifted from horizontal (as mounted) to vertical (on the RF test stand). Therefore, substantial offsets in the cube orientation may have occurred at the time of boresighting, leading to boresight knowledge errors as high as $\pm 0.13^\circ$ on a budget of $\pm 0.05^\circ$.

A final boresighting step would be needed, during which a stiffer HGA backing plate was used, careful shimming was implemented to prevent HGA flexure twist and the coordinate mapping technique was employed to generate a boresight reference (in addition to the optical cube measurements). The implementation of these corrective actions is shown in figures 20 through 22. Two 1-in. aluminum honeycomb panels were bonded to the HGA backing plate, reducing maximum deflection by a factor of 8 (figure 20).

Figure 21 shows the HGA mounted on the improved RF test stand, with 24 coordinate targets located across its surface. The reference control surface (RCS)

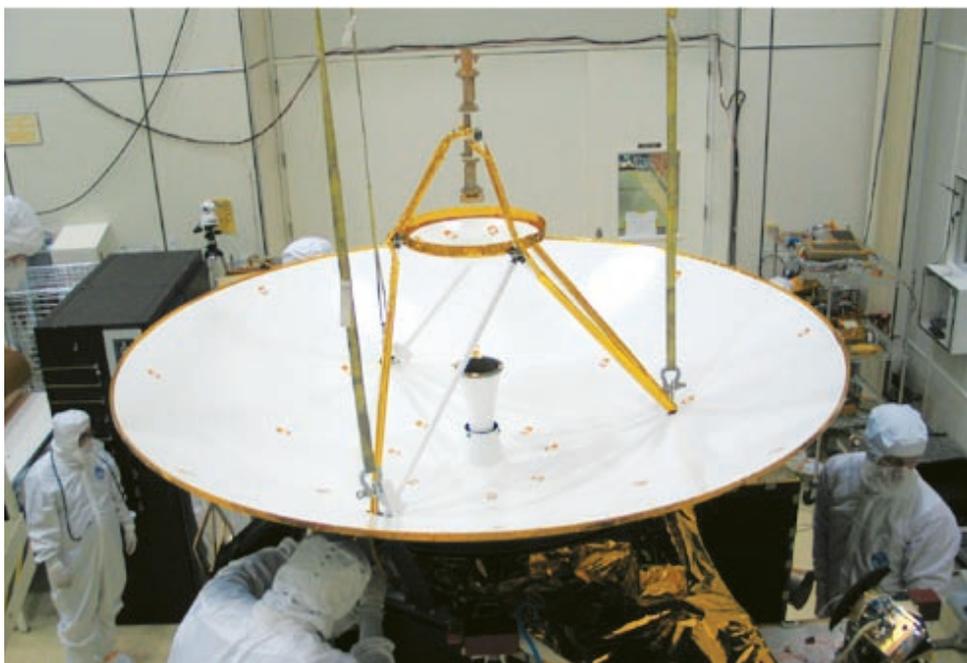


Figure 23. Mounting the successfully tested HGA to the New Horizons spacecraft.

plate used in the boresight test setup was also targeted with 17 targets for use with the coordinate mapping technique.

To utilize the set of coordinate targets on the surface of the HGA as a known reference for measuring the boresight, a coordinate system had to be consistently identified from the raw point data. This was achieved by fitting the nominal dish shape to the measured targets, defining an HGA axis of symmetry (figure 22). In many ways, this was a superior reference to the optical cube surfaces because of its tight correlation with the actual surface of the HGA.

Mapping the boresight of the HGA then required the same two measurements as with the optical reference method: (1) the test range incident plane wave direction (i.e., the RCS plate plane when peaked up) and (2) the fitted HGA symmetry axis direction with the HGA in its peaked-up position. The theodolites were left in place between measurements, providing a common reference coordinate system for each measurement.

With the boresight vector known relative to the dish surface shape, the HGA performance characterized and subsystem qualification completed, the HGA was prepared for installation and alignment to the *New Horizons* spacecraft (figure 23). First, shims were used to fill gaps between the HGA flexures and the spacecraft deck. After that, an iterative process of shimming and surface measurement was used to bring the HGA boresight into alignment with the spacecraft coordinate system (to 0.008°).

LESSONS LEARNED

Question assumptions

Certain assumptions were initially made about the HGA that contributed to “surprises” during its verification process. These bad assumptions were:

- A kinematic mechanical interface is easy to implement.
- Because of the stiff composite materials used, the HGA is a rigid body.
- Handling is the same regardless of dish size.

It was initially assumed that the HGA shape would be insensitive to mounting conditions, because it was mounted on flexures. (Figure 24 shows the flawed initial understanding of the flexure capabilities.) In actuality, the flexures did not offer a kinematic mount to the spacecraft. This is most easily seen in the flexure twist direction (figure 18), in which the flexures are exceedingly stiff. In twist, most of the deck deflection is passed along to the HGA backing structure as distortion.

Regarding the treatment of the HGA as a rigid body, it was found that the dish could be deformed with changing boundary conditions at the flexures. Though stiff materials were used, the thin facesheets and supports could be distorted. Because the flexures and the dish optical cube were all mounted on the HGA support structure (figure 6), deformation caused in the support by the flexures also manifested as instability in the cube. More

- **Annealed TI-6AL-4V ELI grade**
 - high stiffness
 - high strength
 - high toughness
- **Kinematic mount between reflector/SC**
 - 3 bipod blades at 120 degree apart
 - allow cte mismatch: Gr dish vs. AL SC
 - allow DT: -200°C dish vs. -3°C SC
 - isolate HGA from SC to reduce load transfer
- **Kinematic mount between flexure/backing ring**
 - 1 close-fit, 1 slotted and 2 sloppy holes
 - allow cte mismatch between Gr dish vs. Ti flexure

Figure 24. Initial (incorrect) understanding of the HGA flexure behavior.

extensive early testing could have been conducted in advance to study this assumption.

Physical limitations

In hindsight, it should have been evident that a 2.1-meter-diameter surface should not be correlated to an optical cube mounted on one small portion of the support structure. This is a physical limitation on the use of vector metrology to large, lightweight structures. Were the dish smaller, stiffer or supported differently, this issue may not have been a problem.

Similarly, it was difficult to develop fixtures and plates to properly handle the HGA because of its size. In fact, the original backing plate was a source of HGA distortion (figure 19). A stiffer plate was needed so that it could be turned from horizontal to vertical (changing gravity conditions) without significant flex. The mounting of large optical components encounters this same issue, where specific stiffness (not strength) must be the driving consideration.

Another recommendation is that in using vector metrology, the optical reference should be placed where it is most closely tied to the boresight or vector it represents. For instance, there should not be a large distance between the cube and the component controlling boresight; this could allow deformation to occur in-between, ruining the desired “fixed” relationship. In the case of this HGA, there was seemingly no good place for the reference cube on the primary reflector.

While not necessarily a physical limitation, the adhesion of photogrammetry targets during thermal vacuum was a problem that affected measurement results (and the perception of their accuracy). Better initial planning into the target construction (how to layout the Kapton tape, paper and retroreflective tape) would have been useful.

Have a backup plan

Once a problem arises, it may be too late to solve it. While some of the techniques discussed in this article were added to the measurement plan in a reactive fashion, proactive planning for



Vector metrology between optical references was initially used for boresighting and alignment to the spacecraft. But after discovering that the optical reference did not remain stable, a new technique had to be selected. Henceforth, multiple-theodolite coordinate triangulation was used to map the HGA surface during boresighting and alignment, providing a reference that was closely tied to the HGA boresight. Had certain physical limitations about the HGA mechanics been better understood via analysis, this selection would have been made at the outset.

Close-range digital photogrammetry was successfully used within thermal vacuum testing (to -174°C) to verify shape and component alignment at temperature. Subsequent coherent laser radar measurements of the HGA surface supported the photogrammetry results by providing a dense set of accurate dimensional measurements.

ACKNOWLEDGEMENTS

The authors wish to acknowledge The JHU/APL *New Horizons* Antenna Team, including Jeff Will, Mike Lynch, Jeff Kelley, Stuart Hill, Doug Mehoke, Steve Vernon and Ed Schaefer. Recognition for this work also goes to Mike Hill at NASA GSFC for his photogrammetry and measurement work, The Ohio State University Electroscience Laboratory (especially Willy Theunissen) for the use of their compact range, Bill Griffin of IAM Systems for his laser radar measurements, Direct Dimensions of Owings Mills, Maryland, for their point/shape fitting efforts, and the JHU/APL *New Horizons* Project Office for their support in this work and preparation of this paper.

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a measurement failure is a better practice. Fortunately, the HGA measurement plan did have some common-sense checks built into its test procedure. In the future, utilizing dual path alignment methods (i.e. two different methods) at each step would increase the probability of overall qualification success.

CONCLUSIONS

Measurements utilizing various techniques were made to verify the performance of a 2.1-meter high gain antenna that launched aboard NASA’s *New Horizons* Pluto-bound spacecraft.