Close-Range Photogrammetry & Next Generation Spacecraft

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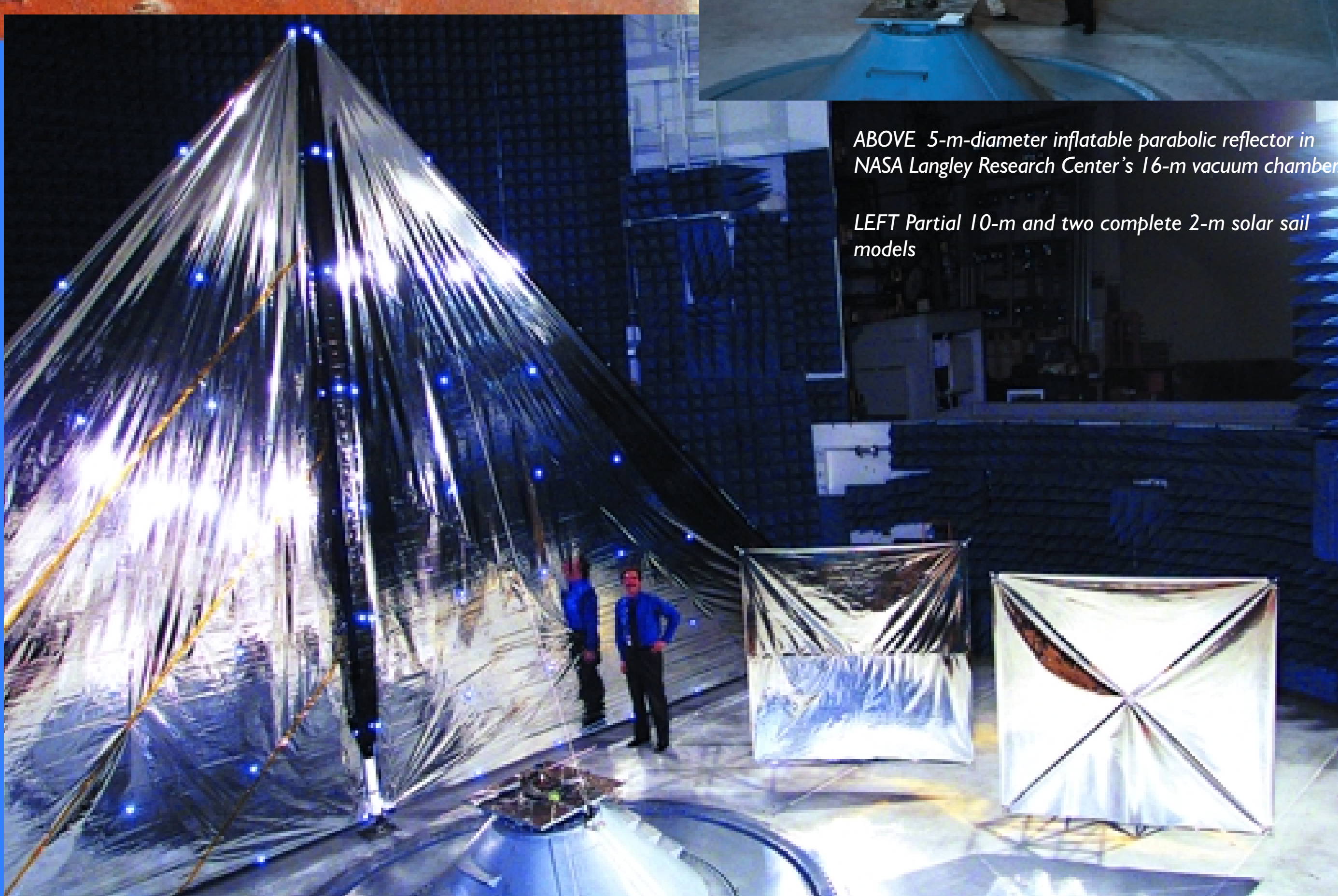


ABOVE 5-m-diameter inflatable parabolic reflector in NASA Langley Research Center's 16-m vacuum chamber.

LEFT Partial 10-m and two complete 2-m solar sail models

NASA is focusing renewed attention on the topic of large, ultra-lightweight space structures, also known as "Gossamer" spacecraft. New materials and new structural concepts including inflatables offer the possibility of creating space structures that are orders of magnitude larger and/or lighter than existing ones. This technology can enable many new classes of missions within the next 5-30 years, such as:

- **Space observatories with collectors of 30 m or larger in size with sub-millimeter surface accuracy**
- **Solar sails of 100 m or larger in size with areal densities of less than 5 g/m^2**
- **Orbital transfer vehicles with large inflatable concentrators for solar thermal propulsion**
- **Next-generation space telescopes with large membrane sunshields for passive cooling**
- **Space solar power collectors and transmitters that are hundreds or even thousands of meters in size**
- **Inflatable habitats for the International Space Station or for future lunar and planetary exploration**

Equipment for photogrammetry of 2-m solar sail model using projected dots.

Nearly all of the details of the giant spacecraft are still to be worked out. But it's already clear that one of the most challenging aspects will be developing techniques to align and control these systems after they are deployed in space. A crucial part of this process is creating new ground test methods to measure gossamer structures under stationary, deploying, and vibrating conditions for validation of corresponding analytical predictions. Validated structural models are required in order for NASA and the aerospace industry to gain sufficient pre-launch confidence that these revolutionary systems will work as planned in space. Stationary measurements are required because the shape and size of the deployed gossamer must closely match the theoretical dimensions in order to provide good performance. Time sequences of measurements of the gossamer deployment are needed to validate and fine-tune deployment systems. Finally, vibration measurements are needed in order to evaluate the ability of a design to perform under both expected and unexpected dynamic loads.

In addressing this problem, I considered, first of all, the possibility of simply using conventional displacement or vibration sensors that could provide spatial measurements. The main problem with this approach is that the gossamer structures are so light and flexible that attached sensors and their cabling can greatly interfere with deployment and change the static shape and dynamic characteristics. I also considered the use of laser scanners that work by measuring the 3D shape of opaque objects by scanning a laser in a grid pattern over the structure. But this method is so slow (typically at least 10 minutes are required) it is difficult to guarantee that the shape of these extremely flexible structures remains constant during the scan.

Procedure for Close-Range Photogrammetry

Next, I turned my attention to photogrammetry, a method of determining the spatial coordinates of objects using photographs. Three-dimensional coordinates of objects are determined by calculating the intersection of light rays based on known camera locations and orientations. An important aspect of photogrammetry is that the software calculates the camera locations and orientations from the images (*i.e.*, they do not need to be measured by the user). Each point of interest on the object typically must appear in at least two photographs, although three or more photographs are preferable for improved accuracy and reliability. Photogrammetry is already widely used for creating electronic computer-aided design (CAD) models of objects that are inconvenient to measure by other methods such as buildings, archeological discoveries, machinery, civil engineering projects, etc.

Photogrammetry typically requires the following nine steps: 1) Establish measurement objectives and accuracy requirements, 2) Design the photogrammetric geometry and select suitable cameras and lenses, 3) Calibrate the cameras and lenses, 4) Take the photographs, 5) Import the images into the data analysis program, 6) Mark the target locations on each image (this can be automatic in many cases), 7) Identify which points in each image are the same physical point (this can also be automatic in many cases), 8) Process the data to obtain 3D results, and 9) Export the 3D coordinates to a CAD program for viewing or comparison with analytical predictions.

I investigated several different photogrammetric software packages. One class of programs that I considered, designed for high-end industrial applications, costs in the neighborhood of $150,000 including one high-precision camera. Because some fu-

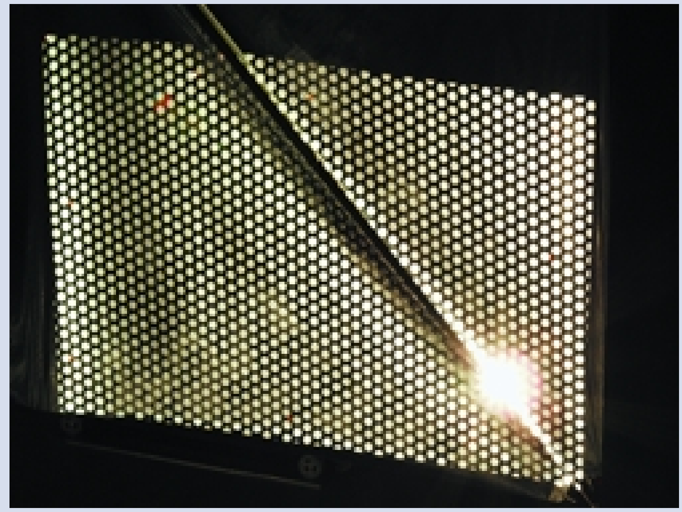
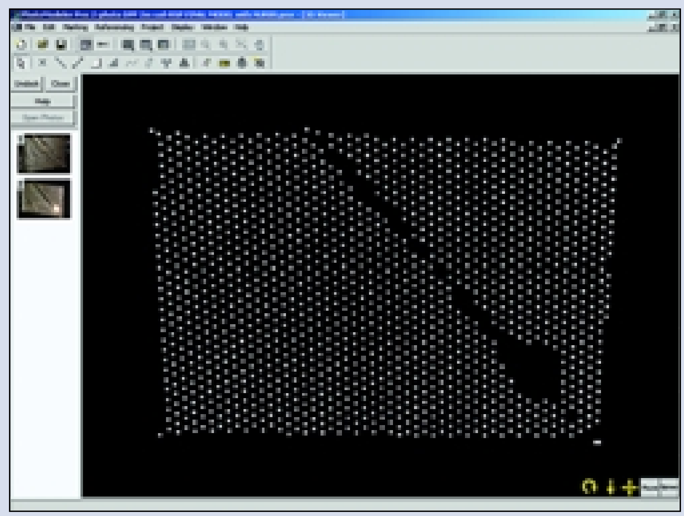
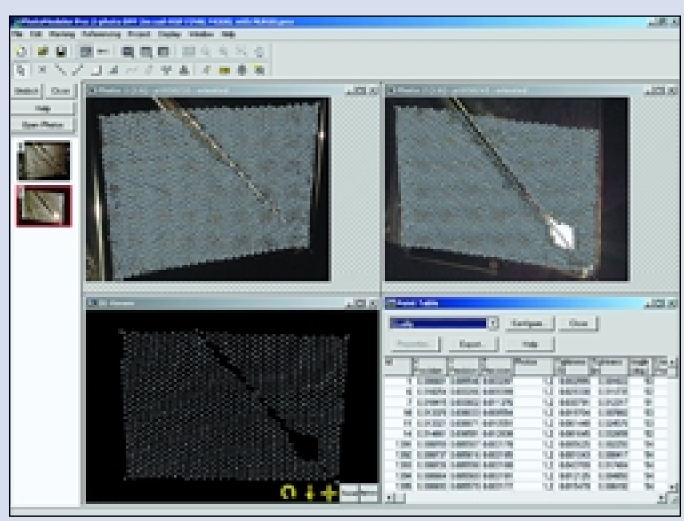


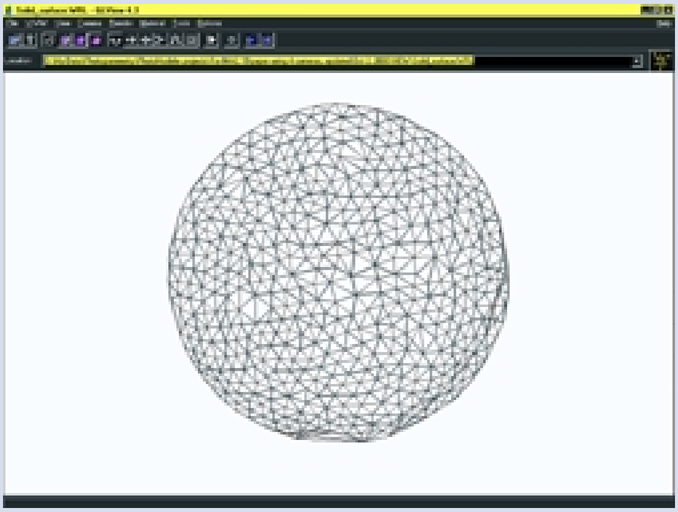
Image from right-hand camera in 2-m solar sail test.

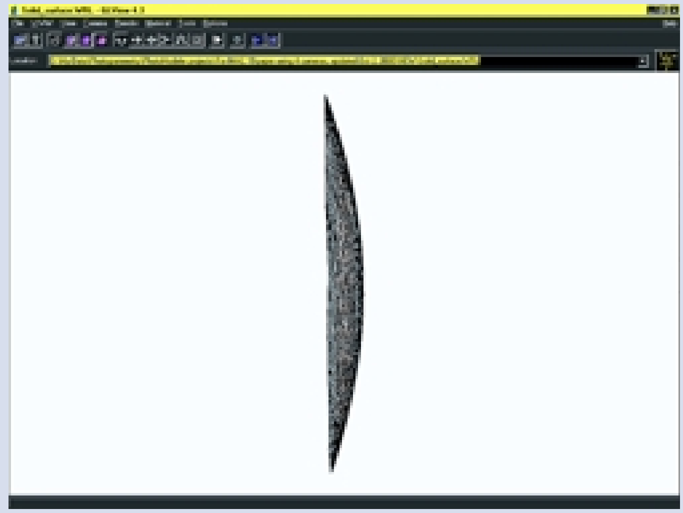


3D point model calculated by PhotoModeler software.



Multiple analysis windows in PhotoModeler.





Front and side views of photogrammetrically determined 3D model of inflatable reflector.

ture deployment tests in the large 16 m vacuum chamber at NASA Langley may require using up to eight or more cameras simultaneously, I naturally had a preference for the two programs that I identified that are designed for a wider audience and cost only several hundred dollars. These packages come without a camera but can work with any of the new generation of consumer digital cameras. After testing the two programs, I chose PhotoModeler Pro from Eos Systems Inc., of Vancouver, Canada. It proved to be easy to use and well documented. The program has worked very well from day one, and I have been very pleased with its accuracy, reliability, and user friendliness.

I began by calibrating each digital camera (I have several different models that I am comparing) using the software's calibrator program, which computes the camera's parameters, including focal length, lens distortion, image aspect ratio, and principal point. The program measures the deviation of the camera from ideal characteristics, and subsequent images are corrected by these measured deviations. In one of my first applications, I then used the camera to measure a prototype inflatable gossamer space structure consisting of a 5-meter diameter inflatable parabolic reflector attached with thin cords at its perimeter to an inflatable Kapton torus with outer diameter of 6.5 m and cross-sectional diameter of 0.6 m. The total weight of this large reflector is only 4 kg.

Accuracies of One-tenth Pixel

I used retroreflective targets to mark a grid of points on the structure and took pictures of it from various angles. Setting the camera flash intensity fully on and turning the room lights off maximized the contrast of the targets in the images. The targets appear as bright ellipses on a dark background, which is ideal for automated measurements. The next steps are marking and referencing the targets and then processing the data. Marking and referencing is mostly automatic, and processing is just a matter of clicking the Process button to do a bundle adjustment. An important part of these computations is the software's sub-pixel interpolation algorithms that can find the center of ellipses in images to an accuracy of one-tenth of a pixel or less. The 3D spatial measurement precision of photogrammetry is directly related to this sub-pixel measurement factor. By least-squares analysis, the best parabolic surface representing the complete set of antenna measurements was calculated. The focal length of the calculated parabolic surface was 3.050 m, which closely correlated with the design focal length of 3.048 m. The root-mean square deviation over the reflector surface from an ideal parabolic shape was approximately 1.5 mm.

Experiments with Projected Targets

I have also experimentally demonstrated the ability to make accurate photogrammetric measurements in some applications by projecting dots on the gossamer structure, making it possible to eliminate the targets. This avoids the time and manpower needed to install the targets as well as the risk of tearing delicate membranes if the targets must be removed afterwards. I have successfully used this approach on a 2-m square solar sail model with approximately 1,500 projected white dots. Although the sail's aluminized membrane surface was quite shiny, there was sufficient contrast to measure its 3D static shape and obtain suitable results.

The success of this research and development has convinced me that photogrammetry is the most suitable method to solve the gossamer measurement problem. Since I started the project three years ago, PhotoModeler has been only capable of processing still pictures, but NASA has made an agreement with the program's developer under which the ability to process time sequences is being developed and will be available soon. In my opinion, photogrammetry will play an important role in our efforts to achieve breakthroughs in mission capability and cost with future gossamer structures.

For more information about PhotoModeler visit the Eos website at www.photomodeler.com.

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