A Precision Deployable Aperture System Facility

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Abstract—Precision deployment is an enabling technology for future NASA large aperture missions. Possible concept missions include optical, infrared, sub-millimeter, or microwave apertures too large to fit unfolded in a launch shroud. Dimensional stability is the overriding structural design driver for these large deployable apertures. The stability is driven by constraints derived from the system's mass and structural stability and to thermal and dynamical loads. As the aperture size increases, and the systems mass density is correspondingly decreased, the ability to test the performance of these apertures in a 1-g environment requires both a unique facility and special testing methodologies.

This talk will describe a facility under development that includes an enclosure with extreme environmental control, a metrology systems for measuring deployment precision and aspects of an integrated modeling system that will be validated in the facility. Though built to the demanding specifications of deployed optical systems, this talk will focus on components of the facility specific to space-based microwave and millimeter wave antenna systems.

The first component of the facility is an enclosure with 10m x 5m x 3m (L x W x H) usable volume that is controlled under ambient temperature to thermal stability of < 0.01 C°/Hr, acoustic control of <35 dBA and seismic control of <10 µgs. The enclosure includes a gravity offload system and allows development of single and multi-petal test articles. Instrumentation in the facility includes three-dimensional videogrammetry system capable of absolute measurement accuracy less than 1 millimeter, and a laser vibrometer system for modal testing. The second component of the facility is the development of an optical metrology system for aligning and monitoring large, deployable structures and telescopes to a fraction of a wavelength. A six beam 'optical hexapod' metrology gauge is being built that will measure to 1 micron absolute accuracy with 1 nanometer relative accuracy over a 10m range. The final component of the facility is comprised of system architecture and modeling components using integrated modeling tools for predictive simulations of aperture systems under orbital loads. These models are being compared to controlled experiments completed in the facility.

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1. INTRODUCTION

A precision deployable aperture systems facility is under development at the Jet Propulsion Laboratory. The purpose of this project is to provide a unique integrated facility for deploying, characterizing and modeling large precision deployed structures. These structures will be an enabling technology for future NASA missions across the spectrum – from those in the visible to infrared, sub-millimeter, or microwave apertures too large to fit unfolded in a launch shroud. Dimensional stability is the overriding structural design driver for these large deployable apertures. The stability is driven by constraints derived from the system's mass and structural stability and to thermal and dynamical loads. As the aperture size increases, and the systems mass density is correspondingly decreased, the ability to test the performance of these apertures in a 1-g environment requires both a unique facility and special testing methodologies.

This paper describes an overview of the precision environment test enclosure for testing the structures, a metrology system for absolute measurement at the micron level and the formulation of a modeling methodology that integrates the measurement of aperture components or subsystems with models for direct validation.

2. A CONTROLLED ENVIRONMENT

Fundamental to the precision aperture deployable facility is a precision environment test enclosure that will allow controlled experiments to validate new technologies [1]. The enclosure operates in a controlled but ambient temperature and pressure environment. The driving requirements for the enclosure came from the range of concept missions and associated aperture needs. The most extreme requirements are driven by optical structures where the visible wavelengths dictate the amount of structural deformation allowed and hence vibration and thermal environment control. But also at longer wavelengths, into the millimeter and sub-millimeter wavelengths, control of the environment becomes important to meet error budgets at the aperture, and when using membrane systems even in the microwave, a controlled environment is advantageous.

The enclosure has a usable volume of 10m x 5m x 3m (L x W x H). It has been installed within a Class 100,000 clean room at the Jet Propulsion Laboratory and maintains this rating within the enclosure with the air handling equipment operational. A set of hard points on the ceiling and walls was designed to hold the range of envisioned structures and apertures. A set of compressed air drops, power, internet and phone ports was supplied. Feed-through holes to the external room are available for external test equipment, computers and data collection systems. A set of doors for moving the test articles and a viewing window is in place. Figure 1 shows both a CAD view of the facility as well as a picture of it nearing-completion.

Key thermal environmental requirements of the facility include

- Temperature setpoint: 22 C°.
- Temperature setpoint stability. ±2 C°.
- Temperature gradient (temporal): 0.01 C°/hr and 0.1 C°/12 hr and 0.1 C°/ 24 hr.
- Temperature gradient (spatial): 0.1 C°/m (vertical and horizontal).
- Equivalent heat load generated within test enclosure: 1 kW.

Key vibration requirements are specified in Table 1.

Table 1. Required vibration levels inside test enclosure.

f (Hz)	S (g^2/Hz)	m (dB/oct)	a (mean sq)
20	2.08E-12		
31.5	2.00E-11	15.0	9.84E-11
50	2.00E-11	0.0	3.70E-10
60	8.06E-12	-15.0	1.30E-10
500	8.06E-12	0.0	3.55E-09
		grms=	**6.44E-05**

Key acoustic requirements are specified in Table 2.

Table 2: Ambient and required sound pressure levels.

One-Third-Octave Band Center Frequency (Hz)	Ambient Sound Pressure Level (dB re 20 mPa)	Required Sound Pressure Level (dB re 20 mPa)
16	64.9	40
20	63.5	40
25	62.6	40
31.5	60.7	40
40	62.8	40
50	59.4	40
63	72.3	40
80	70.9	40
100	53.8	30
125	53.8	30
160	54.4	30
200	57.1	30
250	55.9	30
315	53.3	30
400	54.8	30
500	53.5	30
630	51.1	30
800	49.9	30
1000	49.1	30
Overall	**76**	**50**

These requirements were driven by the measurement of structures for optical systems. It is not expected to generally operate and test complete operational optical systems in this ambient facility, but be a development facility leading to the use of thermally controlled vacuum chambers.

Gravity Offload System

In addition to the enclosure a gravity offload system is being constructed to provide a constant gravity compensation force for a test article while following the free motion of the article both vertically and in one horizontal direction. The system will accommodate a 1m by 1m cantilevered test article, be able to follow motions from vertical to horizontal at speeds up to 0.1 m/s and allow time scales of tens of minutes to simulate deployment. The frequency range of interest for the modal testing is from 0.1 Hz to 200 Hz. The offload system is designed to operate without affecting the modes of the test article in this frequency range.

There are a number of different types of gravity offload systems being considered to accommodate a range of experiments. The driving requirements for this system are the need to allow large displacements, on the order of meters, and the need to allow motion in both the vertical and horizontal directions.

A literature survey and trade study was conducted. Candidate systems included:

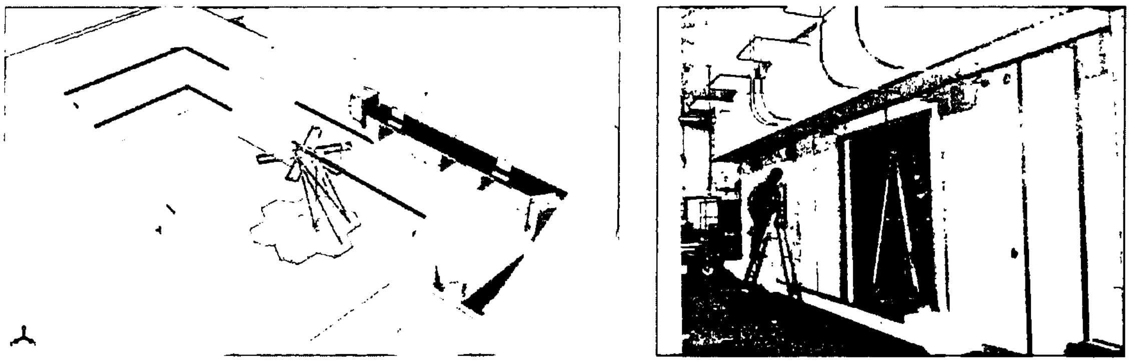

Figure 1. CAD representation of precision environment test enclosure and facility nearing completion.

- Freefall systems have the obvious limitation of very short durations and are not suitable for studying deployments that take place on minute timescales.
- Air bearings have freedom in the horizontal direction, but do not provide it in the vertical direction.
- Although buoyancy systems have the required freedom of motion, they also have a high level of viscous damping. This would drastically change the mode frequencies of the test article, so they are not appropriate for this system.
- Suspension cable systems need to be long enough so that the horizontal restoring forces from cable pendulum motions are negligible for the needed horizontal excursions. They also need to be long enough so that they appear as a soft spring in the vertical direction. This makes suspension cable systems only practical for vertical displacements on the scale of inches, which is inadequate for deployment testing.
- Trolley systems either actively or passively adjust the suspension point so that it remains over the center of gravity of the test article. This allows for large range of motion in one horizontal direction without the complication of an active gantry system.
- Counterweights have the advantage of the stiffness in the system and the damping forces coming entirely from the pulley. The disadvantage to counterweights is that the inertia of the test article is doubled. Since this is an entirely passive system, it is a good initial testing of the mechanics of the system without the added complication of active control.
- Zero Rate Spring Mechanism (ZSRM) provides a very soft equivalent spring constant over a limited throw.

Since no acceptable system was found, a hybrid system was selected that is a combination of an active ZSRM and a trolley system. This system will be capable of supporting the test article's mass, as well as allow large changes in the length of the offload cables to allow deployment of the test article. This allows for large excursions in both the vertical and horizontal directions while being limited to a single plane. Components were fabricated and procured for this system in and testing is underway.

Test Instrumentation

Instrumentation in the facility includes three-dimensional videogrammetry system capable of absolute measurement accuracy less than 1 millimeter, and a laser vibrometer system for modal testing. Both measurement sets have been used in shakeout experiments to validate their accuracy on test structures. This included a range of data collection equipment and computational resources.

Test Article

To validate the ability to perform a rage of tests, a representative test article was required. A six-petal, three meter diameter test article will be constructed and tested. Initially however, a single-petal test article was designed and constructed. An overview of the test article is shown in Figure 2.

3. A Precision Metrology System

To provide precision distance measurements in the facility, a laser metrology system that uses a common-path heterodyne interferometer with a calibrated delay-line as a reference for absolute distance measurement is being constructed [2]. The reference delay-line is the only absolute reference needed in the metrology system and can be made of ultra-low thermal expansion materials such as Zerodur and ULE to provide a ultra-stable reference. A highly accurate calibration approach for calibrating the reference delay-line was developed in this project.

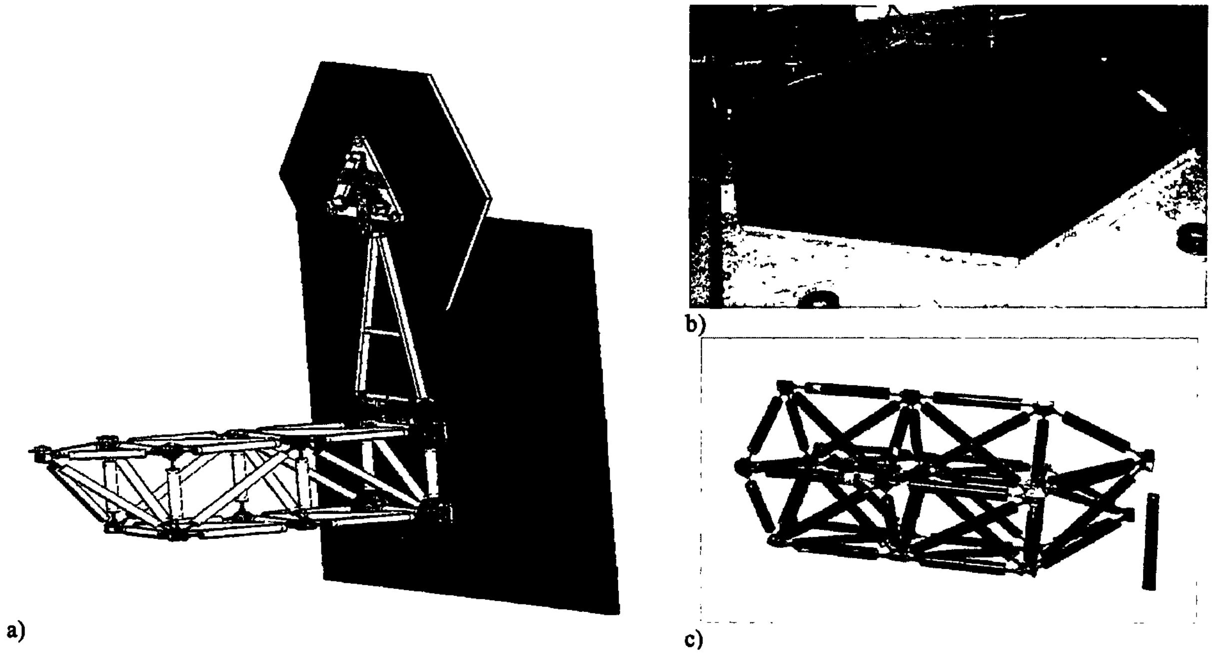

Figure 2: Single petal test article (a) will deploy a 0.85 meter composite "optical" hex panel (b) onto a precision, separately deployed backing truss (c).

Principle of operation

A functional block diagram of the metrology system is shown in Figure 3, where a widely tuneable, swept-frequency laser is used to perform absolute ranging measurement. The laser output is split and fed into two acousto-optic modulators (AOM) to produce two heterodyne laser beams. Then the heterodyne beams after the AOM's are split to a number of interferometers using 1×N fiber optic splitters. The interferometer heads are referred to as "beam launchers", which launch free-space laser beams to metrology fiducials. Heterodyne fringes generated from reflections off the fiducials are then detected by the photodiodes. Phase meters are used to measure phase between the fringes in each interferometer.

Figure 4 shows the optical layout of common-path heterodyne interferometer (COPHI). The interferometer is also referred to as "beam launcher". Two optical frequencies in from the metrology source are delivered with two optical fibers to the beam launcher. The two optical beams are then collimated and denoted as measurement (MEAS) and local oscillator (LO), respectively. The MEAS beam is pointed to the fiducials. The first fiducial (CC1) is a holey corner cube which core is drilled out to let the center portion of the MEAS beam to pass through to hit the second corner cube (CC2).

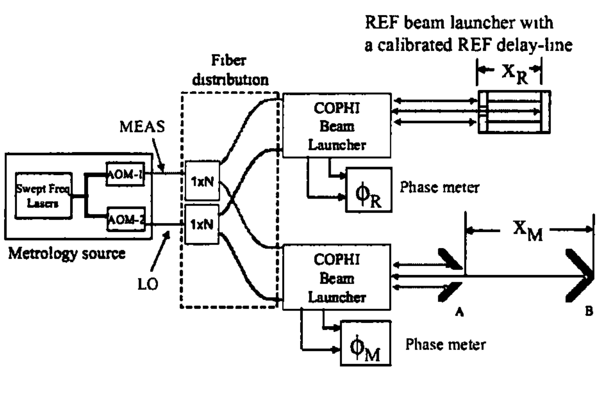

Figure 3. Block diagram of the heterodyne laser metrology system using a calibrated reference delay-line.

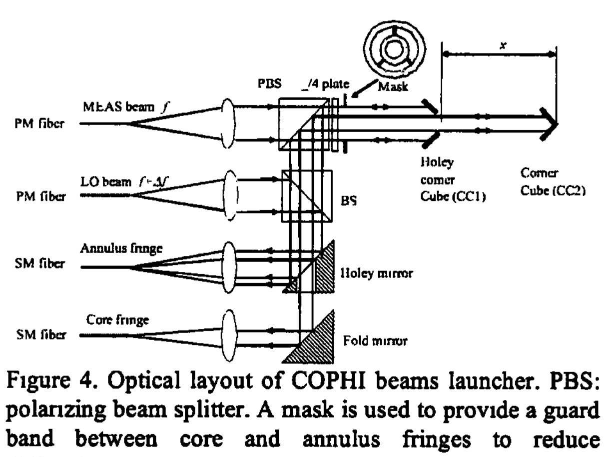

Figure 4. Optical layout of COPHI beams launcher. PBS: polarizing beam splitter. A mask is used to provide a guard band between core and annulus fringes to reduce diffraction leakage.

The two reflected beams, annulus beam from CC1 and core beam from CC2, then return to the COPHI beam launcher Both returned beams interfere with the second frequency, the LO beam to produce an annulus fringe and a core fringe. The interference fringes are then spatially separated and focused into two receiving optical fibers that are connected to photo detectors for the detection of the heterodyne signal phases.

The fringe phase detected in the COPHI beam launcher can be written as,

$$\phi = \phi_1 - \phi_2 = \frac{4\pi}{\lambda} x = \frac{4\pi}{c} f_o x, \qquad (1)$$

where x is the distance between the fiducials, λ and f_0 are the laser wavelength and frequency, respectively. If a tunable laser is used, as illustrated in Figure (3), then the phase changes due to frequency sweep Δf_0 in both the reference (REF) and unknown (UNK) beam launchers are:

$$\Delta\phi_R = \frac{4\pi}{c} x_R \Delta f_o, \qquad (2)$$

$$\Delta\phi_M = \frac{4\pi}{c} x_M \Delta f_o, \qquad (3)$$

where x_R is the reference delay-line length, x_M is the unknown distance, and $\Delta\phi_M$ and $\Delta\phi_R$ are the measured phase changes resulted from the laser frequency swept. Note the phase change resulted from frequency sweep is proportional to the length between the two fiducials.

The unknown distance x_M can be calculated by taking the ratio of (2) and (3).

$$x_M = x_R \frac{\Delta\phi_M}{\Delta\phi_R}, \qquad (4)$$

From Equation (4), it is obvious that x_R is the only quantity need to be calibrated in the metrology system.

One apparent advantage of the proposed metrology system is that it does not have ambiguity in its distance measurement. This is because the measured phase change is directly proportional to the distance under measurement (Equations (1) and (2)). Additional advantage includes that the system can be used in both absolute mode and relative (displacement measuring) mode. The former is achieved by tuning the laser frequency; the latter is accomplished by using the laser in stationary mode. In the relative mode, since the REF delay-line is constant in length, the measured phase from the REF channel can be used to calculate the laser frequency drift, as shown in Equation (2). The measured frequency drift can then be applied to the UNK channel to correct for the phase errors resulted from the frequency drift. Figure 5 shows the bam launcher and reference path of the system. Complete results will be presented at the conference.

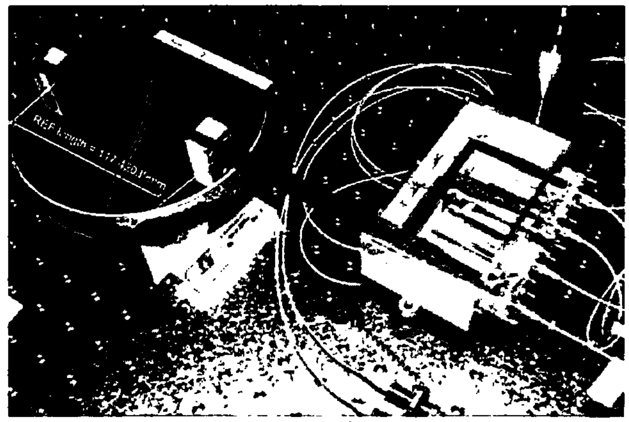

Figure 5. Beam launcher and reference path components of metrology system.

4. An Integrated Modeling Methodology

The third component of the facility is the definition of requirements used in designing the facility and an integrated modeling methodology to be validated using the measurement equipment in the precision environment test enclosure.

In the requirements definition phase of this task, a set of concept space missions were examined to assess technology needs for spaceborne precision apertures. These concepts ranged from collecting apertures in the visible spectrum to those needed for future missions in the microwave operating at frequencies as low as L-Band (1.2 GHz). Required aperture size, deployed precision and ranges on the space-operating environment, among other needs, were surveyed to provide a set of defining requirements for the facility. This led to the enclosure requirements outlined in Section 2 as well as focusing the range of instrumentation needed.

The integrated modeling methodology is a component of the project currently under formulation. Generally, systematic methods in establishing requirements for our models and tests, specifying margins, rolling-up all the associated uncertainties and demonstrating validation of the models based on establishing that the uncertainties fit within the margins are being explored. This methodology is critically important as systems that are difficult to test because of size, the need for a high-fidelity gravity off-load environment or stressing thermal or dynamical conditions are proposed and developed.

For the optical and IR precision deployed apertures considered, the goal is to validate 3-4 meter class deployed structures with nanometer metrology, deploying to within the capture range of demonstrated alignment mechanisms and processes. An important capability to be developed is the scalable modeling of deployed structures. One goal is to validate a modeling process via experiments on our test articles so the extension from models of devices with scales testable in the facility to full scale flight devices will be sufficiently reliable.

For the RF precision deployed apertures considered, the goal is to conduct simulations in the following areas:

- Thermal modeling: This involves orbit selection (i.e. a MEO sun-synchronous orbit) and preliminary thermal modeling of the antenna. This would allow the determination of the thermal loads on the structure that effects the deformation of the structure.
- Structures: Using available mechanical modeling tools simulate a MEO SAR radar (i.e. 2mx50m) and determine the mechanical changes of the system under thermal loading. We will also model antenna panels or the membrane on the antenna.
- Antenna Modeling: Available antenna simulation tools are used to determine the antenna performance with regard to structural and thermal changes.
- Radar Simulation: Ultimately, a range of radar system analysis tools is used to determine the effects of structural and thermal changes on the radar performance.

Essential to the modeling methodology is the direct validation of the modeling tools with measurements of components and subsystems in the facility. A process is underway to match results of modeling of components or subsystems (such as dynamical modes or structural deformations) to well-defined measurements of these components or subsystems using the instrumentation and metrology system in the precision environment test enclosure.

5. Summary

An overview of the Precision Deployable Aperture Systems facility at JPL has been presented As of the writing of this paper, the precision environment test enclosure is being certified to meet the requirements outlined in Section 2. The precision metrology system is becoming operational with a single measurement path, and the six path optical hexapod is under development. The integrated modeling system is under development, with initial models and tests being performed. Complete results will be presented at the conference.

6. Acknowledgement

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References

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Biography

Tom Cwik manages NASA JPL's office of instrument and technology development for Earth remote sensing, and the development of new Earth observing mission concepts. Prior to this position he was Technical Group Supervisor of JPL's High Performance Computing Group. His work has included the development and use of integrated electromagnetic design tools for instrument design at proposal and build stages; the invention and analysis of microdevice components for electromagnetic coupling and filtering in remote sensing instruments; and algorithm development for high performance computational electromagnetic applications. He has made contributions to frequency selective surface design and analysis, and asymptotic analysis in reflector antenna systems. He has led the team that proposed and was awarded the NASA flight mission *Aquarius*, a mission to be launched in 2009 to measure sea surface salinity from space.

Tom has worked at the Very Large Array, National Radio Astronomy Laboratory in Socorro N.M, worked as a research assistant at the Joint Institute for Laboratory Astrophysics, National Bureau of Standards (Now NIST) in Boulder CO and upon completion of his Ph.D. degree, he was awarded a postdoctoral fellowship at the Electronics Research Laboratory, Norwegian Institute of Technology in

Trondheim Norway. He is a graduate of the University of Illinois, Urbana-Champaign.

Tom is a Fellow of the IEEE, Affiliate professor in the Department of Electrical Engineering, University of Washington, Seattle and a Principal Member of the Laboratory at JPL. He was a Fellow at the Texas Institute for Computational and Applied Mathematics in 1997, and received the IEEE Gordon Bell Award Finalist award in 1992 for parallel processing research. Dr. Cwik has edited 1 book and 1 journal special issue, published 7 book chapters, over 30 refereed journal papers and over 110 conference papers. He has 1 patent with Dr. Cavour Yeh, *Efficient Radiation Coupling to Quantum-Well Radiation-Sensing Array via Evanescent Waves.*

Greg Agnes is a senior member of the JPL Instrument Mechanical Engineering technical staff. He earned his B.S in aeronautical engineering from Rensselaer, his M.S in aerospace engineering from Univ of MD, and his Ph.D. in Engineering Mechanics from Virginia Tech. Prior to coming to JPL he served 11 years in the USAF, working at both the Wright Laboratory and the Air Force Institute of Technology. He is an associate fellow of the AIAA. His research interests include precision deployable structures, adaptive structures and nonlinear dynamics.

Alina Moussessian received her Ph.D. in Electrical Engineering from Caltech in 1997. At Caltech she worked on microwave and millimeter-wave power combining, beam-steering, computer-aided design and microwave circuits. After graduation she joined the Radar Science and Engineering Section at JPL where she worked on Shuttle Radar Topography Mission (SRTM) radar testing and the development of a testbed airborne radar sounder for the Europa Orbiter Radar Sounder. She worked in industry from 2000 to 2001, developing optical telecommunication components. Since returning to JPL in 2002 she has been involved in technology development projects for very large aperture phased arrays. She is currently working on membrane radar systems for future NASA missions and advanced components technology for membrane-based phased arrays. She is currently the supervisor of the Radar Technology & Hardware Implementation Group.

Charles D. Norton is a Principal Member of Technical Staff on the Modeling and Data Management Systems Section Staff at the Jet Propulsion Laboratory, California Institute of Technology. He is also the modeling and simulation representative (AD) to the Earth Science and Technology Directorate at JPL. Norton has also been a

member of the Center for Space Mission Information and Software Systems where he managed the Software Engineering Technology Program. Prior to joining JPL in 1998 he was a National Research Council resident scientist at the lab from 1996-1998.

His work covers research, development, guidance, infusion, and consulting on advanced scientific software modernization techniques, parallel/cluster computing technologies, and modeling/simulation applied to finite element parallel adaptive mesh refinement as well as other areas that have impacted numerous projects throughout multiple divisions at JPL. He received his B.S.E. in Electrical Engineering and Computer Science from Princeton University and his M.S. and Ph.D in Computer Science from Rensselaer Polytechnic Institute. His work has appeared in numerous journals, conference proceedings, and book chapters as well as NASA Tech Briefs. He is a member of the editorial board of the journal Scientific Programming, the IEEE Technical Committee on Parallel Processing, and a Senior Member of IEEE.

Feng Zhao is supervisor of the Interferometry Metrology & Optics Group at JPL. His interest includes primarily research, development and validation of precision metrology and optics technologies for interferometer systems.

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