The Photogrammetric Appendage Structural Dynamics Experiment

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Abstract

The Photogrammetric Appendage Structural Dynamics Experiment (PASDE) is a Hitchhiker payload scheduled to fly as part of the International Space Station (ISS) Phase-I flight program to the Russian Space Station Mir. The objective of the first flight of PASDE on STS-74 is to obtain video images of the Mir Kvant-II solar array response to various structural dynamic excitation events. This experiment will demonstrate the use of photogrammetric techniques for on-orbit structural dynamics measurements. Photogrammetric measurements will provide a low cost alternative to appendage mounted accelerometers to the ISS program. The PASDE experiment hardware consists of three instruments each containing two video cameras, two video tape recorders, a modified video signal time inserter, and associated avionics boxes. The instruments were designed and built at the NASA Langley Research Center, and are integrated into standard Hitchhiker canisters at the NASA Goddard Space Flight Center. The Hitchhiker canisters are then installed into the Space Shuttle cargo bay in locations selected to achieve good video coverage and photogrammetric geometry. The measurement resolution of the instruments is expected to be on the order of 0.25 cm (0.1 in.).

Introduction

The Photogrammetric Appendage Structural Dynamics Experiment (PASDE) is an experiment to mitigate technical risk and cost associated with passive, on-orbit, measurement of spacecraft appendage structural response for the International Space Station (ISS) program. The experiment will demonstrate a photogrammetric method for making appendage structural measurements, provide engineering data on solar arrays designs expected to be used on the ISS, and verify that routine on-orbit spacecraft operational events provide sufficient excitation for structural response testing.

On-orbit measurements of spacecraft structural response are often desired or necessary for structural verification and loads prediction validation. Typically, acceleration response time-history data is collected and processed on the ground. From this data, structural dynamic characteristics (structural mode frequencies, damping, and mode shapes) can be determined using parametric identification algorithms such as the Eigensystem Realization Algorithm (ERA) [1].

The use of photogrammetric measurements is a low cost alternative to dedicated accelerometer-based structural response measurement systems, especially when measurements are required for articulating or rotating spacecraft components such as solar arrays or thermal radiators. Elimination of accelerometers, wiring, signal conditioning and digital conversion electronics, etc., can greatly simplify the spacecraft electrical design and integration, with corresponding reduction in spacecraft cost.

For the International Space Station (ISS), Figure 1, on-orbit structural response measurements are required for loads validation and verification of structural mathematical models. Currently, accelerometer-based measurements of the US. primary truss and modules are being planned, however, accelerometer measurement of the US. solar arrays are not being considered because of cost and resource impacts. Since the current ISS design calls for numerous video

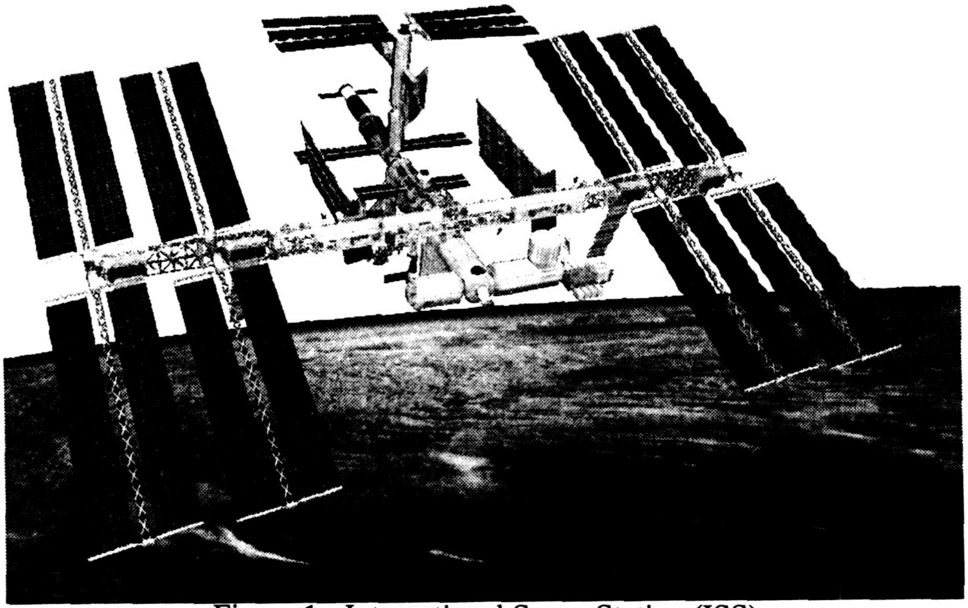


Figure 1 - International Space Station (ISS)

cameras mounted at various external points, photogrammetric measurements of solar array structural responses is a potential alternative.

The PASDE experiment will verify that photogrammetric measurements can provide measurement resolution and accuracy sufficient for ISS structural verification purposes. It is manifested as part of the ISS Phase I Risk Mitigation Program. ISS Phase I involves seven flights of the U. S. Space Shuttle to the orbiting Russian Space Agency Mir space station. Current plans call for PASDE to fly twice as part of the Phase I program.

NASA Langley Research Center (LaRC) is funded by NASA Headquarters Code X for development and first flight of PASDE. PASDE hardware will be flown as a Class D, NASA Goddard Space Flight Center (GSFC) Hitchhiker payload. On STS-74, the second Space Shuttle flight to Mir, PASDE will fly along with the Glo-4 experiment [2] as the Hitchhiker Glo-4/PASDE or GPP payload. On STS-86, the seventh mission of Shuttle to Mir, PASDE hardware will be used to obtain measurements as part of the Mir Structural Dynamics Experiment (MiSDE) Risk Mitigation Experiment. Funding for the STS-86 flight of PASDE is provided by the ISS Phase-I program.

The remainder of this paper is organized as follows. The concept of photogrammetric structural response measurements is discussed first, followed by specific measurement requirements for the PASDE experiment. The design and fabrication of hardware to meet the measurement requirements is covered next, followed by the STS-74 mission science objectives and planned operations.

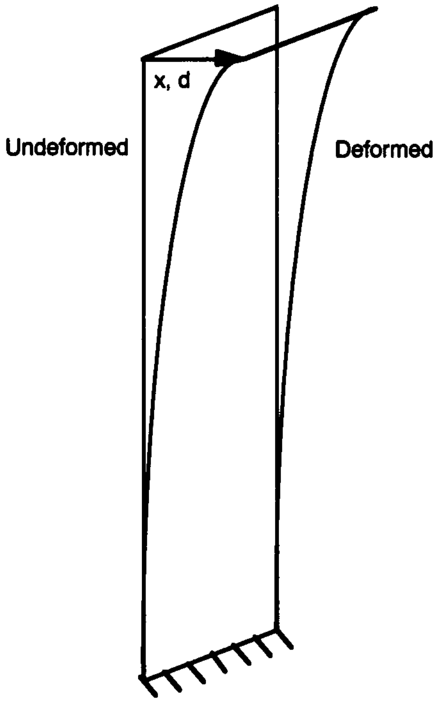
Photogrammetric Structural Response Measurement

Photogrammetry is defined as "the science of making reliable measurements by the use of photographs..." [3]. In the case of a single photograph or image, certain precise measurements of an object in the image, such as geometrical size, can be made under appropriate conditions. With several images of an object, again under appropriate conditions, the orientation and/or position of the object with respect to the positions of the cameras can be determined using a triangulation process [4]. The precision of the position or orientation determination is dependent on the quality and number of images. At least two independent images are required for triangulation, with more images leading to higher precision. If the object of interest is moving, determination of the position or orientation as a function of time requires a sequence or series of images from each camera location and triangulation at each time of interest. Measurement of time-varying structural response, which is of interest here, is an example of this third type of photogrammetric measurement.

The measurement of structural dynamic response using photographic cameras has previously been limited by costs of film and film processing, alignment of photographic frames in time, and the significant manual processing inherent in using photographs for triangulation. The recent advent of low-cost, charge-coupled-device (CCD) video cameras, video recorder systems, and digital image processing techniques have eliminated most of these limitations.

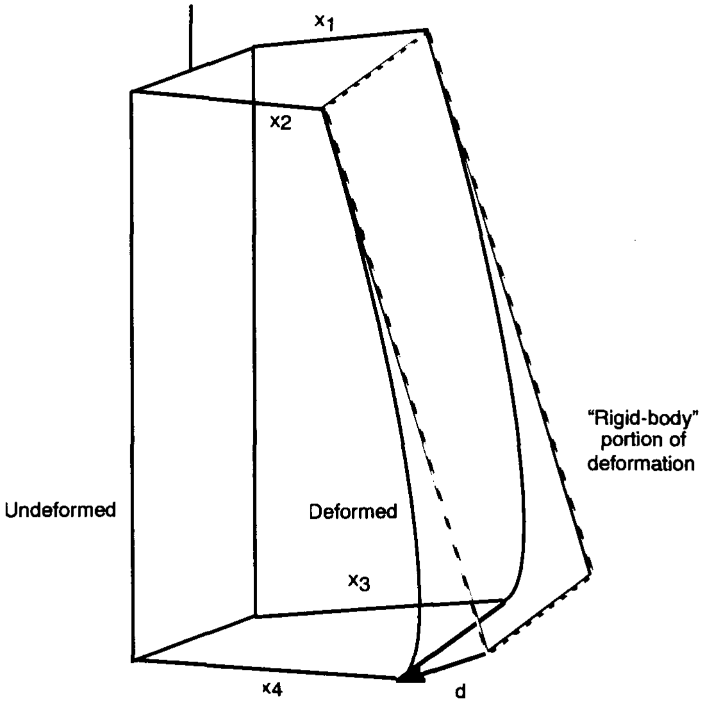
Several efforts at measuring structural response by photogrammetric methods have been made [e.g. 5,6]. In the 1984 Solar Array Flight Experiment (SAFE) for example, photogrammetric measurements of a solar array cantilevered from the cargo bay of the Space Shuttle were made from video recorded by the Shuttle's on-board camera systems. The position of the array in the cargo bay was fixed with respect to the Shuttle camera system in this experiment. As shown in Figure 2, the motion recorded in the SAFE video images was directly proportional to the structural deformation of the array as it responded to various structural excitation sources.

For the case of the International Space Station solar arrays, there will be relative, rigid-body motion of the solar array with respect to the positions of the photogrammetric cameras. This motion is due to articulation and/or rotation of the array as it tracks the sun in Earth orbit. Thus the motion measured by a photogrammetric system for ISS solar arrays will consist of combined rigid-



x = photogrammetric measurement
d = desired structural measurement

Figure 2 - Solar Array Flight Experiment (SAFE) structural measurement.



x = photogrammetric measurement
d = desired structural measurement

Figure 3 - Relative motion case structural measurement.

body and structural deformations, as shown in Figure 3. To extract the structural motion from the combined motion, the apparent "rigid-body" motion component must be determined. This can be accomplished by determining the motion of points on the solar array which can reasonably be expected to have little structural deformation (such as near the root), and using this measurement to predict a "rigid-body" orientation and position of the array from known array geometry. Subtracting the predicted "rigid-body" motion from the total measured motion leaves an estimate for the structural deformation.

The PASDE experiment was designed to make relative motion structural measurements as defined in Figure 3. Use of the latest technologies in CCD cameras and digital image processing enables the extraction of minute structural motions from video images of spacecraft solar arrays and other flexible, articulating components. The hardware requirements to make these measurements are described in the next section.

PASDE Measurement Requirements

The hardware requirements for on-orbit photogrammetric spacecraft structural response measurements are dependent on the size and orientation of the appendage(s) of interest, the lighting conditions, the distances and three dimensional relationship of the imaging devices, and the number of desired mode parameter sets (frequencies, damping, and shapes) desired.

For the PASDE hardware development, a general sense of potential flight opportunities and possible targets and geometry was used to generate a set of design requirements. These potential flight opportunities involved imaging solar arrays on the Russian Mir space station during Space Shuttle docking flights. For these opportunities, photogrammetric distances ranging from 10 to 20 meters (30 to 60 feet) were expected, measuring from 2 or 3 Shuttle cargo bay locations. Identification of the first 3 or 4 solar array mode parameter sets was desired, leading to the hardware design requirements listed in Table 1.

Table 1 - PASDE hardware design requirements.

Item	Requirement
Resolution	Measure 0.1" motions of the array tip
# of Array Measurements	Minimum of 6 needed to extract motion and determine modes shapes
Data Recording	1-2 minutes prior/during excitation 3-5 minutes following excitation
Time Correlation	Video data time tagged to Shuttle events consistently for all events
Sample Rate	10 Hz. or greater

From analytical finite element structural models of the coupled (docked) Shuttle/Mir spacecraft, solar array responses to expected on-orbit excitation events were computed. These results in conjunction with solid-body viewing models and likely Shuttle payload bay locations led to the PASDE requirement to resolve 0.25 cm (0.1 inch) motions at the expected viewing distances. To identify both bending and torsion mode parameters while extracting relative array motions, a minimum of six time history data points are required. Desired ranges of locations for the six minimum points were defined, and target regions for pointing the cameras were established, as illustrated in Figure 4. In Figure 4, the arrows and dimensions establish the six approximate locations, indicated by small circles, with respect to the length and width of the array. The larger viewing circles indicate the desired viewing areas for the cameras, which encompass the minimum number of time history points. Actual data points for flight data analysis will be determined after the flight based on the obtained images, contrast, identifiable features, etc. It is expected that time history data will be obtained for more than the minimum number of points.

The other requirements listed in Table 1 were defined qualitatively, accounting for the typical types of data characteristics needed for good identification of structural modes. These included the amount of free decay response following excitation, the time correlation of the video

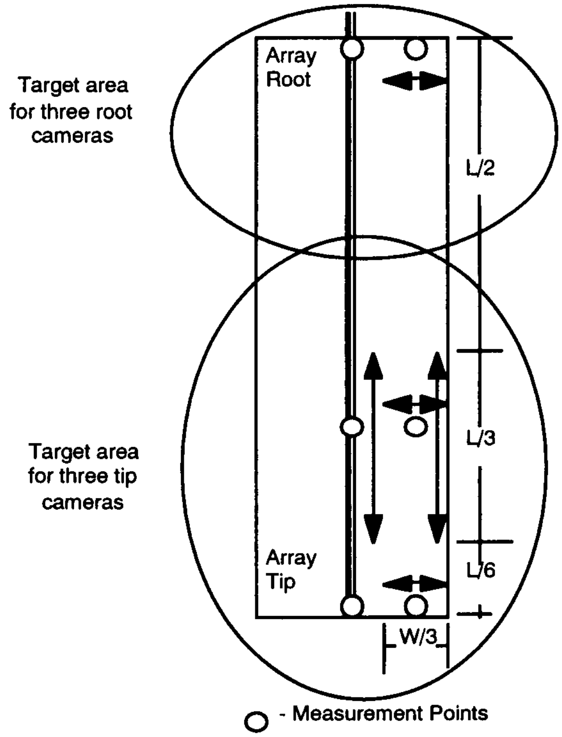


Figure 4 - Definition of minimum number and location of measurement points.

images with each other, and the sampling rate. The minimum 10 Hertz sampling rate provides a 10 to 1 frequency ratio with respect to the highest frequency mode that can reasonably be expected to be identified. Standard video data is 30 Hertz.

Hardware Design

Based on the length of the Mir solar arrays and the viewing geometries possible in the Shuttle payload bay, a PASDE design incorporating six video cameras in three Hitchhiker canisters located in the Shuttle payload bay was selected. Two cameras are in each Hitchhiker canister, one aimed and focused at the root of the array, and the other at the tip of the array. It was also decided that the PASDE hardware for each canister would be identical, with adjustable mounting arrangements for the cameras to allow for individual pointing. A photo of an assembled flight unit is shown in Figure 5, prior to installation into a Hitchhiker canister.

Pulnix Model TM-9701 monochrome video cameras with CCD array sizes of 764 x 486 pixels were selected. Each camera has a Schneider 50 millimeter focal length lens with a motor driven iris to adjust for lighting conditions. Lens focus is adjusted on the ground prior to flight and cannot be changed on-orbit. The camera/lens combination has a ± 5 degree field-of-view. Associated with each camera is a Teac Model V-80AB-F Hi8 video tape recorder providing two hours of video recording time. A single modified IRIG-B time inserter from Sekai, a single Power Conversion and Distribution Unit (PCDU) from Vicor, and a single Langley designed and built Interface and Control Unit (ICU) were used for each set of flight hardware. The IRIG-B time inserters convert time code from the Shuttle into a video format and add the result to the video signal prior to recording. This ensures that the six recorded video signals can be time correlated to within a single video frame. The ICU provides the interface between the PASDE hardware and the

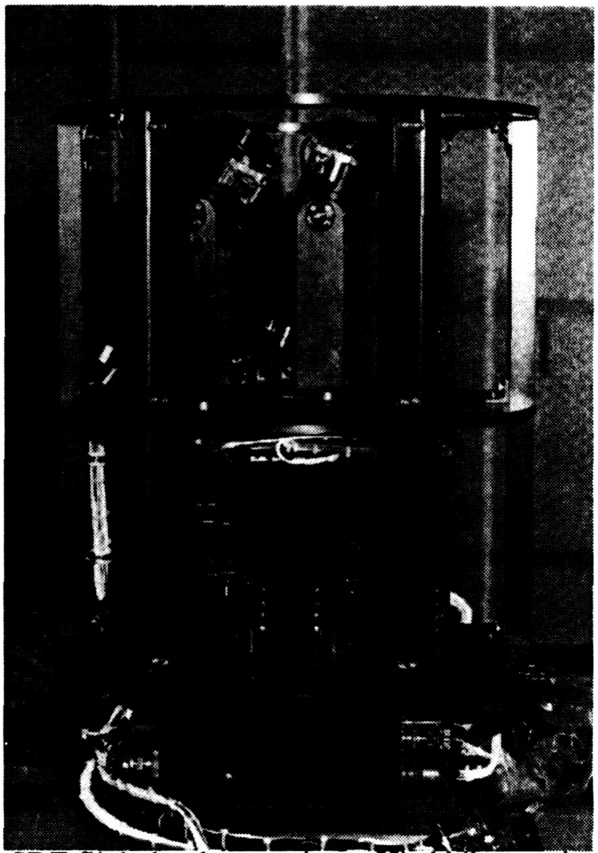


Figure 5 - PASDE flight hardware prior to Hitchhiker canister integration.

standard Hitchhiker avionics. It processes 8 different bi-level commands from the Hitchhiker to activate the hardware, initiate and stop recording, and to establish lens iris positions.

A supporting structure to mount two cameras, two recorders, and the avionics boxes to fit inside a standard Hitchhiker payload canister was designed. In addition, a 3 degree-of-freedom camera/lens mount gimbal was designed to allow each camera to be individually pointed. The gimbal is fixed prior to flight and is not adjustable on on-orbit.

Three sets of identical flight hardware were fabricated, assembled, and tested at the NASA Langley Research Center. Each unit was subjected to acceptance level vibration, EMI, thermal-vacuum, and functional tests. The units were then shipped to GSFC for integration with the Hitchhiker canisters and further EMI testing. Once integrated, the canisters were sealed with a large aperture window upper endplate and pressurized with dry nitrogen.

STS-74 Mission Science Objectives

The measurement objective for the PASDE experiment on the STS-74 mission is the lower, Kvant-II solar array as shown in Figure 6. During the docked portions of the combined Shuttle/Mir mission, this array will be outboard on the port side of the Shuttle, slightly ahead of the wing. The three Hitchhiker canisters containing the PASDE flight hardware will be located aft of the Kvant-II array in Shuttle cargo bays 6 (port side), bay 7 (starboard side), and bay 13 (port side). The expected camera images (for one orientation of the array with respect to Mir) for each PASDE canister tip and root camera are shown in Figures 7 and 8 respectively.

Excitation and structural deformation of the lower Kvant-II array is expected from a variety of events planned for the mission. These include the actual docking, a series of Shuttle Primary Reaction Control System (PRCS) jet firings, day/night and night/day orbital transitions, and solar array rotational slews for sun tracking. Data for each of these events will be collected (i.e. tape recorded) and stored for post-flight analysis.

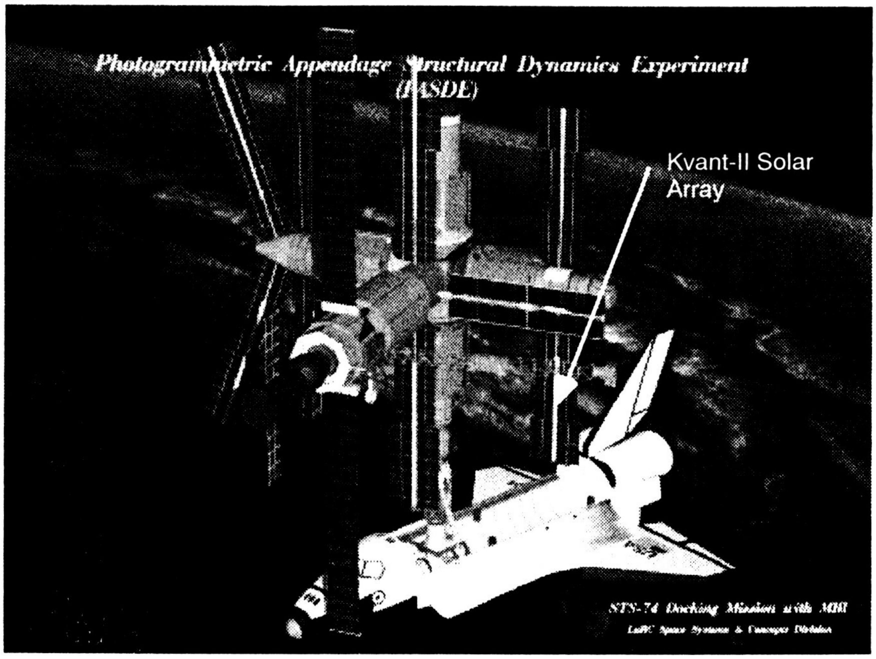


Figure 6 - STS-74 Shuttle/Mir configuration.

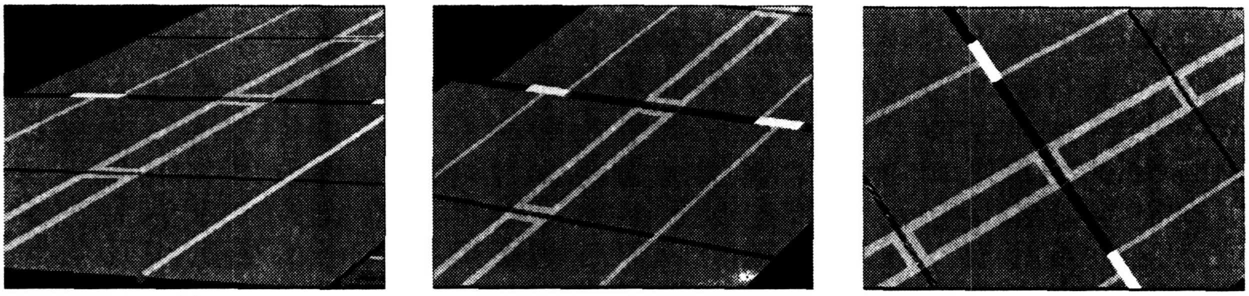

(a) (b) (c)

Figure 7 - Tip camera views of Kvant-II solar array: (a) Bay 6, (b) Bay 7, and (c) Bay 13

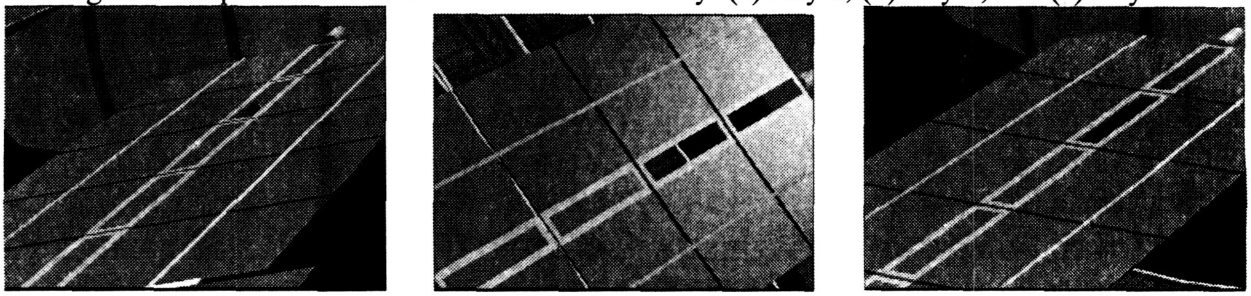

(a) (b) (c)

Figure 8 - Root camera views of Kvant-II solar array: (a) Bay 6, (b) Bay 7, and (c) Bay 13

Post-flight, the recorded video data will be digitized frame-by-frame and high contrast features in the images will be identified. Advanced digital image processing algorithms will be applied to precisely locate the high contrast features with respect to the focal planes of the individual cameras. A triangulation process will then be used to determine the three dimensional position of features appearing in multiple views with respect to the Shuttle coordinate system. Processing of the images in sequential time order will provide a three-dimensional time history record of motion at various points on the array.

The time history data describing the motion of points on the array will be further processed to determine the relative "rigid-body" motion of the array with respect to the camera system. With this information, the structural deformation and modal parameters can be determined. The final data will satisfy the following three science objectives:

1) Verification that photogrammetric measurements techniques can be used for passive on-orbit measurement of structural response sufficient to determine structural mode parameter sets for appendages which may have non-structural relative motion with respect to the cameras.

2) Direct determination of the response of Mir Kvant-II solar arrays to day/night and night/day thermal transitions.

3) Verification that normal on-orbit dynamic events provide sufficient excitation for determination of structural mode parameters.

Satisfaction of objective 1) will be enhanced by accelerometer data collected on the Mir space station and from the Inertial Measurement Units (IMU) on the Space Station. Mir has 22 accelerometers located at various points inside the modules which will collect data during some of the expected on-orbit events.

STS-74 Mission Operations

PASDE mission operations will conducted during the STS-74 mission from the Hitchhiker Payload Operations Control Center (POCC) at NASA Goddard. The PASDE hardware will be commanded to set camera iris positions and start and stop recording directly from the POCC. Within the POCC, PASDE will have a limited capability to downlink a video signal from any one of the six cameras in real or near-real time.

During the mission, the first PASDE operations will occur prior to docking when a calibration of the camera iris settings is undertaken. The Shuttle Remote Manipulator System (RMS) end effector will be positioned in the approximate location of the tip of the Kvant-II solar array, and the Shuttle attitude will correspond to an expected post-docking orientation. Direct downlink of video images from the tip cameras for various lens iris settings will be compared with ground based data to update iris settings for later data collection activities.

The first actual data collection event will be the Shuttle/Mir docking. Table 2 lists the expected recording time and solar array motion for this event. Based on current mission timelines, several hours following the docking the Shuttle will undertake a series of PRCS jet firings for confirmation of Shuttle flight control system parameters. The solar array response to each of these jet firings will also be recorded. A second iris calibration period and a second PRCS jet firing sequence may be scheduled following the first jet firings events. Recording of day/night and night/day transitions will occur later in the docked portion of the mission, with several different lens iris settings. Multiple recordings will be made, dependent on remaining available tape, to mitigate the effects of the rapidly changing lighting conditions for these events. Of the 120 minutes of available tape recording time, 100 minutes is currently scheduled so as to provide tape margin for contingencies and "event-of-opportunity" data collection.

Table 2 - STS-74 excitation events and data collection periods.

Event	Time	Expected Motion (0-Peak)
STS/Mir Docking	30	> 2"
PRCS Jet Firings	40	≤ 0.8"
Day/Night	15	?
Night/Day	15	?

Concluding Remarks

The ISS Phase-I PASDE Risk Mitigation experiment is being developed by NASA Langley Research Center and flown as a NASA Goddard Space Flight Center Hitchhiker attached payload. The PASDE flight hardware has been fabricated, assembled, tested, and integrated for first flight on STS-74, currently scheduled for launch in October 1995. Planning and operational training for the first flight is underway. Data from the experiment will provide confidence to the ISS program that photogrammetric measurement methods can provide sufficient resolution and accuracy to meet appendage structural verification measurement requirements.

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