ISAG presented a historical review of the port FGB solar array, showing that the retracted state of the solar array had not detectably changed between October 25, 2007, (28 days after port FGB solar array retraction) and May 18, 2011 (last available nadir image of the FGB). In response, the Russians stated that when the limit switch that controlled the solar array retraction process was tripped and power was removed from the retraction drive motor, the solar array may have rebounded outward by some small amount. They stated that this rebound would have been no more than half a meter, although no documentation or measurements were presented to support this position.

In early January 2013, ISAG located on-orbit recorded video of the port FGB solar array retraction from September 2008. The video shows that when the array reached the point of maximum retraction, it rebounded outboard and oscillated several times before finally stabilizing in a configuration that was significantly less retracted than the minimum point. A similar rebound was seen during the retraction of the starboard FGB solar array. A copy of the port and starboard solar array wing retraction video was provided to the ISS Vehicle Configuration Office and the Structures and Mechanisms Group.

In response to the discovery of the retraction anomaly, the ISS Program Office abandoned efforts to relocate the PMM to the aft Node 3 CBM and has issued a change request to relocate it to the forward Node 3 CBM. The Shuttle Engineering Change Implementation Board (SECIB) has also requested that ISAG perform a photogrammetric analysis of the starboard FGB solar array to document its current configuration.

The image-based measurement techniques employed by ISAG identified and documented a major discrepancy in the as-built configuration of the ISS. Without this capability, any attempt to relocate the PMM to the Aft Node 3 CBM would have resulted in hard contact with the port FGB solar array.

## Clearance Analysis of CTC2 (on ELC4) to S-TRRJ HRS Radiator Rotation Envelope

*Donn Liddle*

In response to the planned retirement of the Space Shuttle Program, International Space Station (ISS) management began stockpiling spare parts on the ISS. Many of the larger orbital replacement units were stored on the Expedite the Processing of Experiments to Space Station (EXPRESS) Logistics Carriers (ELCs) mounted on the end of the S3 and P3 truss segments, immediately outboard of the Thermal Radiator Rotary Joints (TRRJs) and their attached radiators. In an August 2009 computer-aided design (CAD) assessment, it was determined that mounting the Cargo Transport Container (CTC) 2 on the inboard face of ELC4 as planned would create insufficient clearance between the CTC2 and the rotational envelope of the radiators when the TRRJs were rotated to a gamma angle of 35.0 degrees (see figure 1). The true clearance would depend on how the Unpressurized Cargo Carrier Attachment System (UCCAS) was mounted to the S3 truss and how the ELC4 was attached to it. If the plane of the UCCAS attachment points were tilted even slightly inboard, it would significantly change the clearance between CTC2 and the Starboard TRRJ (S-TRRJ) radiators. Additionally, since CTC2 would be covered in multilayer insulation (MLI), the true outer profile of CTC2 was not captured in the CAD models used for the clearance assessment. It was possible that, even if the S-TRRJ radiators cleared CTC2, they could snag the MLI covering. In the fall of 2010, the Image Science and Analysis Group (ISAG) was asked to perform an on-orbit clearance analysis to determine the location of CTC2 on ELC4 and the S-TRRJ radiators at the angle of closest approach so that a positive clearance could be assured.

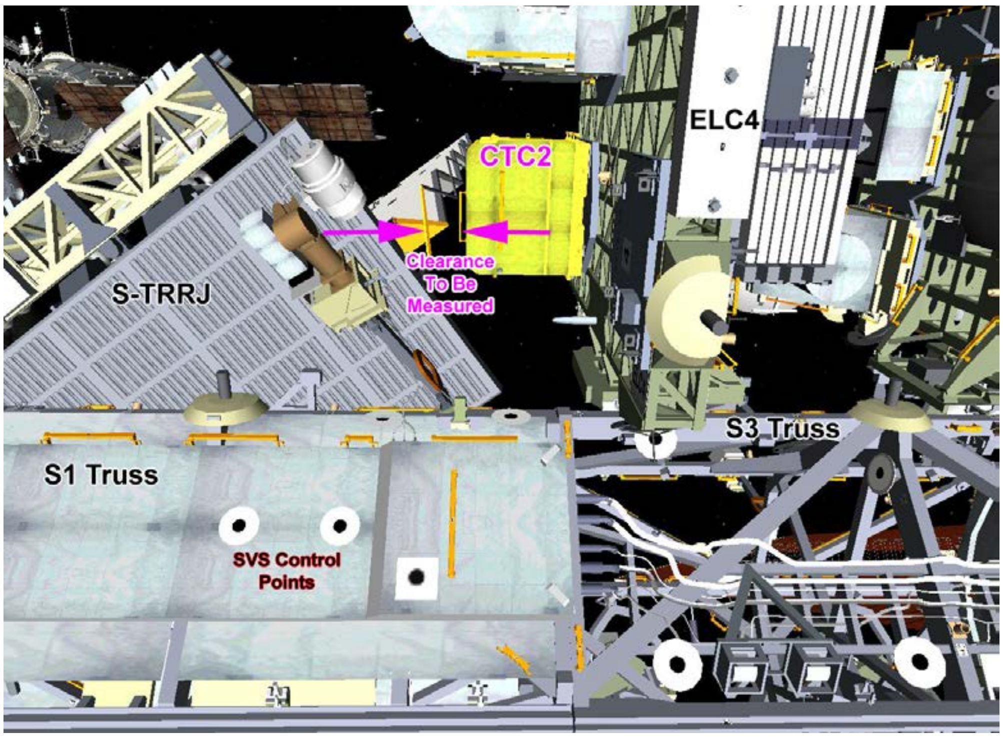


*Figure 1.– CTC2 to S-TRRJ radiator clearance.*

To provide the measurements as quickly as possible to aid in the assessment, it was decided that the clearance analysis would be broken into two phases.

**Phase I**

The location and orientation of the UCCAS fittings, which support and hold the ELC4 in place, would be measured relative to the ISS Analytical Coordinate System (ISSACS) as defined by nine preexisting Space Vision System (SVS) targets affixed to the forward/zenith side of the S1 and S3 truss segments (see figure 2). The location of the outboard edge of the S-TRRJ radiator would also be measured when positioned at the angle of closest approach to CTC2 (gamma = 35.0 degrees). This data would allow the Digital Pre-Assembly Group to predict how the ELC4 would sit on the UCCAS and how that would translate into the clearance between CTC2 and the S-TRRJ radiators.

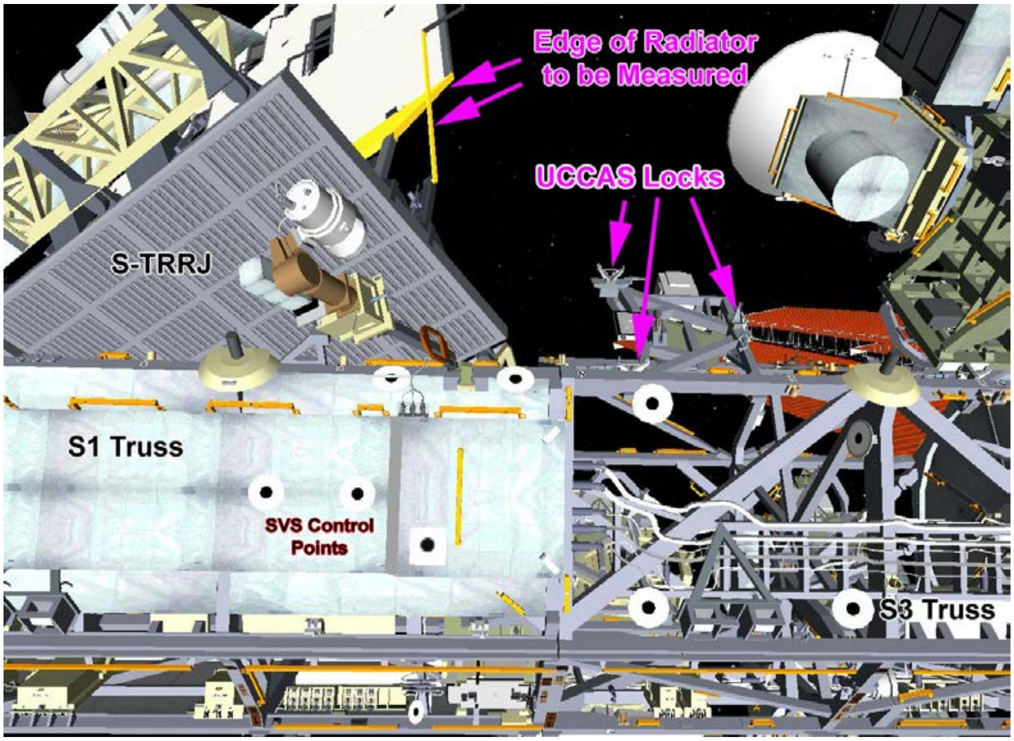


*Figure 2.– Phase I measurements.*

**Phase II**

After the ELC4 was delivered and installed into the UCCAS, the position of the CTC2 mounting plate on the inboard face of ELC4, would be measured in the ISSACS coordinate system relative to the SVS control points used in Phase I. Although CTC2 would not yet be mounted on ELC4, the working envelope of CTC2 could be mathematically added to the measured position of ELC4 to produce a best estimate for CTC2's mounted location. Comparing CTC2's best estimated location to the S-TRRJ radiator (measured in Phase I); relative to the ISSACS coordinate system, would provide a direct measurement of the expected clearance.

Due to the impending delivery of ELC4 (scheduled for January 2011), planning for the Phase I clearance analysis began immediately. Using the Dynamic Onboard Ubiquitous Graphics (DOUG) program, ISAG designed a way to acquire images of the SVS control points on truss segments S1 and S3, the aft facing edge of the S-TRRJ Heat Rejection Subsystem (HRS) radiator, and the three UCCAS latch mechanisms mounted on the zenith face of the S3 truss using the Space Station Remote Manipulator System (SSRMS). To minimize the number of SSRMS movements, the Special Purpose Dexterous Manipulator (SPDM) would be attached to the SSRMS. This would make it possible to park the SPDM in one position and acquire multiple images by changing the viewing orientation of the SPDM body cameras using the pan/tilt units on which they are mounted. Using this implementation concept, ISAG identified four SSRMS/SPDM positions from which the majority of the needed imagery could be acquired. Five additional images would be acquired using the CP-3 external ISS camera mounted on the S1 truss immediately inboard of ELC4. Based on a photogrammetric simulation, it was estimated that the measured location of the HRS radiator and UCCAS latch points would be accurate to about 0.3 in. in each of the three axes relative to ISSACS.

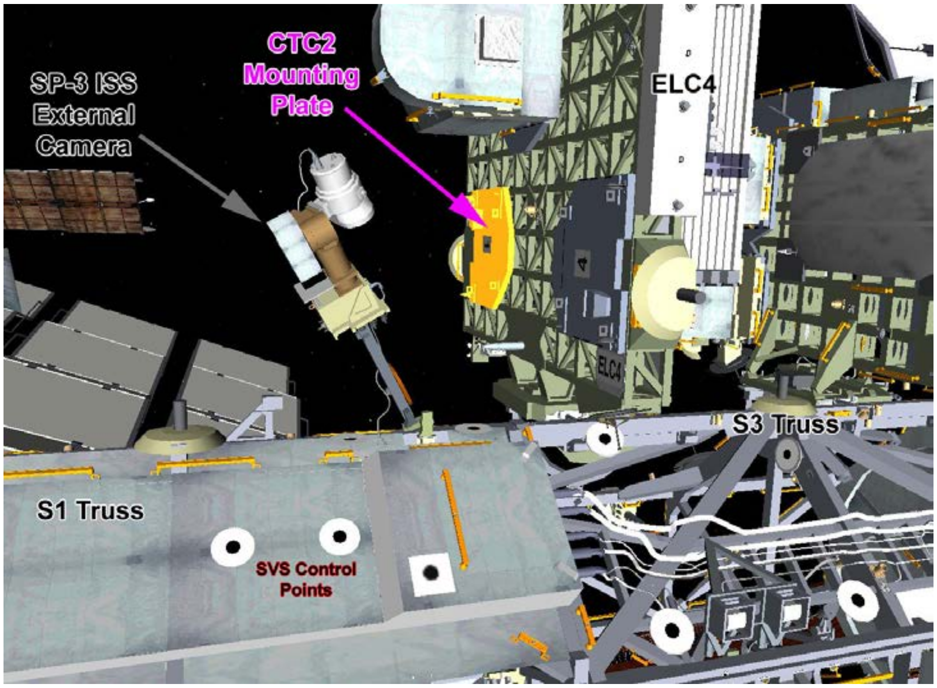


*Figure 3.– Phase II measurements.*

Working with ROBO, ISAG collected 78 images of the ISS December 29, 2010. From this imagery, the best 40 were selected for use in the analysis process. The images were radiometrically enhanced to improve color and contrast and loaded into the FotoG analysis software along with the camera parameters and control data, which consisted of the coordinates for the nine SVS targets on the S1 and S3 trusses in the ISSACS coordinate system.

The results of this analysis produced the coordinates of 11 points distributed across the outboard face of the S-TRRJ radiator panel and 4 points on each of the three UCCAS latch mechanisms in the ISSACS coordinate system with propagated uncertainty estimates in each coordinate axis. These results were delivered to the ISS Digital Pre-Assembly Group, which used the UCCAS latch mechanism points to estimate the installed position of ELC4/CTC2. This position was then compared to the measured location of the S-TRRJ radiator. This analysis suggested that even with the worst case dynamic scenario, there would still be at least 1.63 in. positive clearance between the S-TRRJ radiator and the CTC2. With the best available analysis showing adequate clearance, the ISS program continued to plan for the installation of CTC2 on ELC4.

The ELC4 was launched January 24 aboard STS-133, arrived at the ISS January 26, and was installed on the S3 UCCAS January 27, 2011. After installation, ROBO released the SSRMS joint locks and allowed the ELC4 to settle into its natural position. They then measured that position using the SSRMS joint angles. This showed that the ELC4 was within the tolerance bands of the predicted location computed from ISAG's UCCAS measurements, thereby validating the structural models. With these results, ISS program management became confident that there would be a sufficient (although small) positive clearance, and in early February 2011, they dropped the requirement for the Phase II analysis. In early April 2011, ISAG was informed by Structures and Mechanisms that ISS program management now wanted to perform the Phase II measurements.

Since its arrival on H-II Transfer Vehicle #2 (HTV2) early in January 2011, CTC2 had been stored on the SPDM attached to the mobile transporter (MT). The new plan was to measure the location of the CTC2 immediately after it was installed on ELC4, which was scheduled for August 2011. ISAG developed the SSRMS joint angles to position the SPDM body cameras so that imagery of the SVS control points and the inboard face of ELC4/CTC2 could be obtained. After much negotiation with ROBO, an image acquisition plan was released July 1, 2012.

CTC2 was installed on ELC4, and the images required to support the photogrammetric clearance analysis were acquired on September 9, 2011. Additionally, an edge-on image of CTC2 and the S-TRRJ radiator at the angle of closest approach was obtained to immediately prove positive clearance (see figure 4).

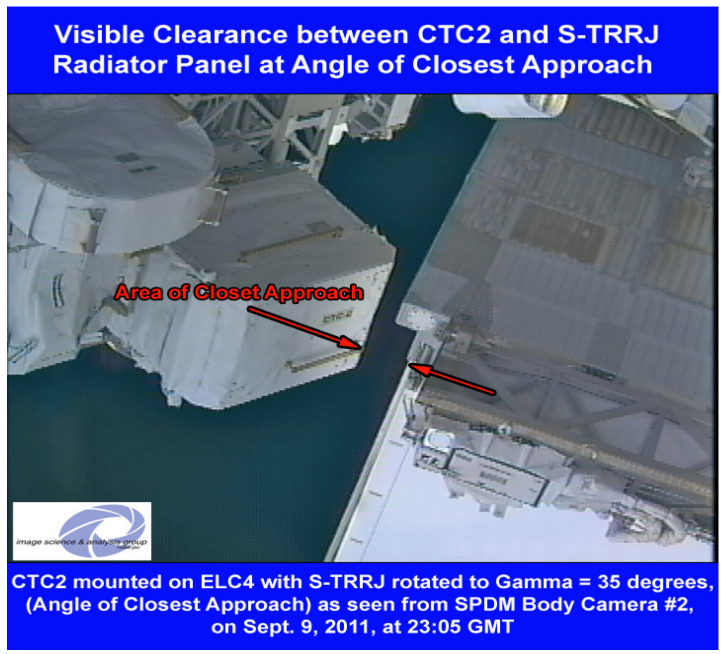


*Figure 4.– Clearance between CTC2 and S-TRRJ Radiator*

Out of about 86 images collected, the best 50 were selected for use in the analysis process. These images, the camera parameters, and 9 SVS control targets were used to compute coordinates for 20 points distributed across the inboard and forward face of CTC2, as shown in figures 5 and 6.

Coordinates for 50 additional points on the inboard surface of ELC4 were also computed and delivered to the ISS Digital Pre-Assembly Group along with uncertainty estimates in each axis.

The results were delivered to the ISS Structures and Mechanisms Group, which combined them with the S-TRRJ radiator measurements computed in Phase I to compute the final clearance results, as stated below:

> *"The combined measurement showed a clearance of 10.84" between the radiator and the CTC-2 (a bit better than expected). When we account for worst case conditions (worst possible thermal effects + worst on-orbit loads + uncertainty in our measurements & models) we still show an analyzed clearance of 7.89" (again, the best clearance we've seen)."*

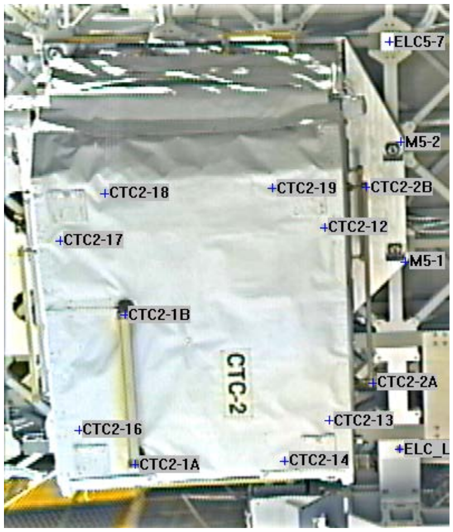


*Figure 5.– Point measured on the inboard face of CTC2.*

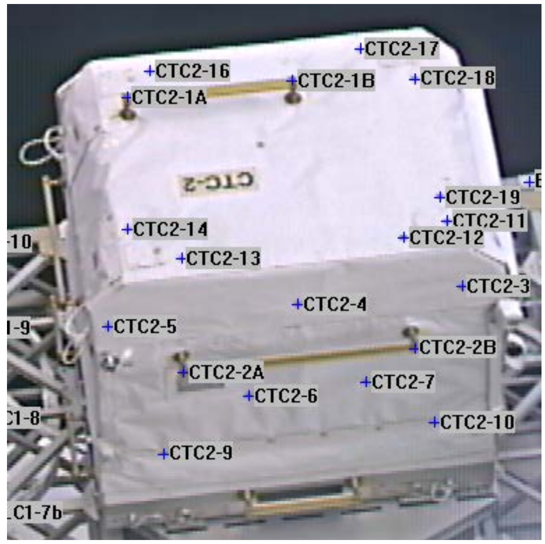


*Figure 6.– Point measured on the forward face of CTC2.*

The image-based measurement techniques employed by ISAG provided measurements of the as-assembled, on-orbit hardware configuration, which verified positive clearance both in static and dynamic modes. This measurement capability reduces the overall risk of ISS operation for both NASA and its partner nations.

## *Analyzing an Aging ISS*

*R. Scharf*

The ISS External Survey integrates the requirements for photographic and video imagery of the International Space Station (ISS) for the engineering, operations, and science communities. An extensive photographic survey was performed on all Space Shuttle flights to the ISS and continues to be performed daily, though on a level much reduced by the limited available imagery. The acquired video and photo imagery is used for both qualitative and quantitative assessments of external deposition and contamination, surface degradation, dynamic events, and MMOD strikes. Many of these assessments provide important information about ISS surfaces and structural integrity as the ISS ages. The imagery is also used to assess and verify the physical configuration of ISS structure, appendages, and components.

During the Space Shuttle Program, a general survey of the ISS with shuttle imagery assets could be performed during approach, while docked, and during the departure Shuttle fly-around. Shuttle images of the ISS comprised most of the imagery used to observe the condition of the ISS exterior. With the retirement of the Space Shuttle, many external surfaces of ISS became blind spots that cannot be easily viewed with ISS imaging assets alone. ISS assets include external video cameras