National Aeronautics and Space Administration
Game Changing Development Program

GCD Continuation Review Board Recommendation Memo

Memo Date: 7/21/2016
Review Date & Location: 6/23/2016 at ARC Bld. N258 Auditorium
Project Name: Human Exploration Telerobotics 2 (HET-2)
Project Manager: Terry Fong, Project Manager for HET-2, ARC
Element Name: Astrobee
Element Manager: Chris Provencher, Element Manager for Astrobee, ARC

Continuation Review Board Members:
Kevin S. Kempton, Program Element Manager, GCDPO (Chair)
Jeff Sheehy, Chief Engineer STMD
Mark Micire, Subject Matter Expert, DARPA
Jason Crusan, AES Director, HQ, LaRC

Continuation Review Presenters:
Terry Fong, Project Manager for HET-2, ARC
Chris Provencher, AstroBee Element Manager, ARC (Presenter)
Trey Smith, AstroBee Systems Engineer, ARC (Presenter)
Ernie Smith, AstroBee Safety Lead, ARC (Presenter)
Astrobee Subsystem Leads (Structures, Communications, C&DH, GN&C, Flight SW, Propulsion, Thermal, Avionics, Sensors, Power, Ground Systems, Perching Arm)

Other Stakeholders in Attendance:
LaNetra Tate, GCD Program Executive, HQ
Harry Partridge, ARC Chief Technologist, ARC
Dawn McIntosh, ARC TI, ARC
Drew Demo, Code RE Systems Branch Chief, ARC
Bill Caldwell, Code RE Mechanical Branch Chief, ARC
Andres Martinez, Code R Small Satellite PM, ARC
Steve Jara, Code QS Chief SMA Officer for ISS Payloads, ARC
Ali Luna Guarneros, Code QS Astrobee SMA, ARC
Kenny Vassigh, Office of Ames Chief Engineer, ARC
Shak Ghassemieh, Code D Office of Ames Chief Engineer, ARC
Jose Benavides, SPHERES PM, ARC
Jonathan Barlow, SPHERES Engineering Lead, ARC
Simeon Kanis, SPHERES Ops, ARC
Jessica Marquez, ARC TI, ARC
Dave Korsmeyer, ARC R, ARC
Craig Mhyre, ARC RE Division Chief, ARC

Kuok Ling, ARC RE Avionics Branch Chief, ARC
Jose Bendavides, SPHERES PM, ARC
Jonathan Barlow, SPHERES Engineering, ARC
Maria Bualat, HET 2 DPM, ARC
James L. Broyan, REALM-2/Logistics Reconnaissance (LORE) PM, JSC
Al Holt, ISS Research Integration Office, Technology Development Office, JSC
Andrew W. Chu, REALM-2/Logistics Reconnaissance (LORE) Project Lead, JSC
Pat Fink, REALM-2/Logistics Reconnaissance (LORE) PI, JSC
Henry Orosco, ISS RIO: Payload Integration RIM, JSC
Larry Cotton, ISS RIO: Payload Integration PIM, JSC
Jennifer Goldsmith, ISS Crew Office Crew Rep, ISS
Chris Edelen, FOD Flight Director, JSC
Ivy McLeod, Flight Ops Directorate: ISS flight controller, JSC
Beau Simpson, Payload Operations & Integration Center: Payload Ops Director, JSC
Brian Johnson, Multi Mission Operations Center, JSC
Tameka Stewart, Huntsville Operations Support Center (HOSC)
Margaret Sterling, ISS Payloads: Joint Station LAN facility, JSC
Mai Lee Chang, ISS Requirement Verification/HFIT
Holly Smith, JSC Engineering/Acoustics
Carl Konkel, Payload Software (Boeing)
Chen Deng, ISS Payloads: Verification
Justin Cartledge, ISS Payloads: Displays Standards
Katrina Whitlock, ISS Payloads: Interface Requirements

Purpose of the Review

The GCD Continuation Review is a key decision point for multiyear projects to assess actual performance against expected performance as specified in the approved Project Plan. The output of the Continuation Review is this recommendation report that is sent to the GCD Program Control Board. The Continuation Review provides projects with the opportunity to present technical results and also programmatic performance to Subject Matter Experts and GCD Representatives.

This 2016 Continuation Review was held in conjunction with the Astrobee Periodic Technical Review (PTR) #3 which provided a CDR level review of the Astrobee Certification Unit design.

State of the Project

The AstroBee Project Element falls under the Human Exploration Telerobotics 2 (HET2) Project. The latest version of the HET2 Project Plan was approved on January 27, 2016. A GCD Change

Request (CR-362) was approved on 3/30/2016 that added L1 requirements for Astrobee. An earlier change request added funds for FTE backpack costs that were not included in the original budget.

The AstroBee project is well into its second year of a four year development effort. Astrobee continues to have strong support from its end users and AES customer as demonstrated by their participation at this technical review.

The Astrobee project has recently completed testing on its 4th generation design (Prototype 4) and is completing final designs for the Astrobee "Certification Unit". Lessons learned during development of Prototype 4 have greatly influenced the design of the Certification Unit.

At this review the Astrobee team presented CDR level designs of the Certification Unit, which will be used to qualify the Flight Units and uncover any design issues. A delta PTR#3 is scheduled for November. This review will be more focused on the software. The Astrobee project plans on releasing the official science payload interface document at this time. After this review, changes to the flight unit design will be limited to fixes needed based on issues found during the testing of the certification unit.

Currently, the project is funded to deliver two Astrobee flight units. Per the approved HET-2 Project Plan the Flight Unit Testing is scheduled to complete on 8/15/2017. The customer for Astrobee, Advanced Exploration Systems (AES), has requested that the project deliver additional operational support hardware (including a third flight unit, additional ground hardware, and spares) for which AES will provide the funding for and for the Astrobee project to perform system qualification testing on the ISS prior to handover in FY18 which would require additional funding from STMD to complete. This effort is being referred to as the Astrobee Commissioning Phase. Funding for the STMD portion of the Commissioning Phase will be discussed by STMD management in the 4th quarter of FY16 after FY18 funding projections are better understood when the current PPBE cycle completes. AES has provided a budget commitment for the transition of operations, on going operations, and the additional operational support hardware as part of the PPBE18 process.

Technical Notes

The Astrobee Prototype 4 (P4) design represented a significant change from earlier prototypes and now that it has been fabricated and tested, it appears to be able to meet the many requirements for the system. During a lab tour in the granite lab at ARC, Astrobee P4 demonstrated the new plenum/vent based propulsion system. This demonstration incorporated the updated vision based navigation software that allowed P4 to autonomously exit the docking station, follow a 2D path and return to its docking station.

The Current Best estimate for mass (7 kg) exceeds the current design budget (6 kg). Mass affects acceleration, impact hazards, and overall performance as a research facility once in operational use. The team may need to elevate mass reductions to a higher priority. Astrobee mass was compared to that of a bowling ball.

The maximum dimension of the current design is 12.5” on a side, which exceeds customer requirements of 12” on a side. This increase is due to additional padding needed to reduce impact energy in the event of a collision (which partially results from exceeding the mass limit). The primary AES customer agreed to provide relief on this requirement if required. The team discussed adding impact tell tails to indicate if a serious impact had occurred.

The acoustic noise is close to the allowable limit for the ISS. The team identified simple mitigation options that should provide more margin such as replacing the aluminum back plate in the plenum with composite material (a CNT sheet may be an option if EMC and thermal conductivity is an issue).

Astrobee is not yet on the ISS launch manifest although the current launch date is listed as December 2017. ISS payload personnel said the project should get on the launch manifest at least one year out so this needs to be completed by December.

The Astrobee system design will now support communication between Astrobee Free Flyers. This was an option at the PTR #2 review.

The current design is very modular. This provides the ability to reconfigure and repair system components on the ISS by swapping them out with spare parts. A payload attachment model was passed around and it was easy to operate.

The P4 Avionics subsystem has low, mid-level, and high-level processors to manage the various SW tasks which utilize the Robot Operating System (ROS). The use of the ROS promotes collaboration with academia in the development of future capabilities. This includes the development of open source Application Program Interfaces (APIs) to simplify the software integration and testing with AstroBee experiments.

Locations on the ISS for the Astrobee docking station are very limited. The AstroBee docking station design for the ISS currently allows two Astrobee free flyers to dock side by side. The footprint for the docking station may have to change based on where it will be located. This is being carried as a risk and the team is actively working with ISS personnel to close it. Although the review panel also suggested that the Astrobee team may want to mitigate this risk using an approach to the design of the docking station that is less location depended. It was noted that the location is likely to change over the operational life of the Astrobee facility.

The GN&C team has incorporated and tested optical flow velocity measurement in the Granite Lab on P4. Astrobee may be one of the first systems to actively use optical flow in a zero G environment.

The team expects to use the ISS communication simulator at JSC to verify communication links. They have also designed the AstroBee Ground data system and have upgraded the primary navigation test facility at ARC.

Astrobee path planning tools have greatly matured and appear user friendly.

The team continues to activity communicate with stakeholders to elicit feedback on how Astrobee will operate on the ISS. Communication has been facilitated by the story board descriptions in the ConOps. The team continues to actively work safety issues with ISS safety personnel and have recently completed a key System Safety Review at JSC.

Project cost, and schedule performance against the plan

Cost Performance: The Astrobee project budget allows for approximately 12 FTE and $3M in FY16 and also in FY17. The procurement provides for ~ 10.5 WYEs and $400K non-labor costs.

The team has maintained development to the planed cost. Workforce levels have tracked very closely to the plan.

The estimated cost for In-House fabrication of parts exceeds what was planned. The team is looking at external providers and renegotiation with the In-House Fabrication group.

Schedule Performance: The GCD Controlled Milestones for “Prototype 4 testing complete” was accomplished near the planned date. The design and build cycle for the Certification Unit is underway and many parts have been ordered or are being fabricated now that PTR #3 has been successfully completed. The schedule indicates delivery of the flight units which will slip into FY18.

Controlled Milestone	Description	Completion Date
FY16 #1	Prototype 4 testing complete	3/15/2016
FY17 #1	Cert Units testing complete	8/31/2016
FY17 #2	Certification Unit ready for integration, validation and test	10/13/2016
FY17 #3	Flight Unit ready for integration, validation and test	1/2/2017

Technical performance relative to Key Performance Parameter (KPP) thresholds and goals

The AstroBee Project KPPs have had changes from the last Continuation Review and are noted in the descriptions.

Table 9. Key Performance Parameters (Astrobee)

Parameter	State of the Art (SPHERES)	Threshold Value (Minimum success)	Project Goal (Full success)
Maximum velocity	4 cm/sec	10 cm/sec	40 cm/sec
Flight time	0.5 hr	2 hr	5 hr
Dock & resupply	Crew tended	Crew tended	Autonomous
# of expansion ports	1	2	4
Consumables used per test session	6	0	0
ISS operational space	2m x 2m x 2m	JEM, US Lab, and Node 2	All USOS

KPPs in latest approved HET2 Project Plan

Parameter	SPHERES	Threshold Value (Minimum success)	Project Goal (Full success)	Corresponding Technical Performance Measure
Max velocity	4 cm/sec	10 cm/sec	50 cm/sec	N/A – Design will achieve goal; challenge is ensuring reliability at high speeds.
Max acceleration	10 cm/sec^2	5 cm/sec^2	10 cm/sec^2	N/A – Design will achieve **threshold**. Propulsion thrust is on target; acceleration performance now depends on mass.
Localize & position	+/- 3 cm	+/- 20 cm	+/- 2 cm	**TPMs 4, 6**
Measure angle & point	+/- 2 deg	+/- 20 deg	+/- 8 deg	**TPMs 5, 7**
Flight time	0.5 hr	2 hr	5 hr	**TPM 1**
Dock & resupply	Crew tended	Crew tended	Autonomous	N/A – Design will achieve goal
# peripheral ports	1	2	3	N/A – Design will achieve threshold
Sorties supported with peripheral ports	1	1	3	N/A – Design will achieve goal
Consumables used per test session	6	0	0	N/A – Design will achieve goal
ISS operational space	2m x 2m x 2m	JEM, US Lab, and Node 2	All USOS	N/A – Design will achieve goal (modulo safety keepout zones that might include Cupola, Airlock)

KPP Progress listing From the PTR #3 charts

#	TPM	Thresh	Desired Margin	Threshold with margin	Current best estimate	PTR2 Status	PTR3 Status
TPM 1	Flight time (h)	≥ 2	15%	≥ 2.3	3.1	Good	Good
TPM 2	Mass (kg)	≤ 6	15%	≤ 5.2	7.0	Insufficient margin	Off target
TPM 3	Noise (dBA)	≤ 65	3 dB	≤ 62	64.5	Good	Insufficient margin
TPM 4	Estimation Error (cm)	≤ 20	15%	≤ 17	8.6	Good	Good
TPM 5	Estimation Error (deg)	≤ 20	15%	≤ 17	3.7	Good	Good
TPM 6	Control Error (cm)	≤ 20	15%	≤ 17	9.3	Good	Good
TPM 7	Control Error (deg)	≤ 20	15%	≤ 17	8.5	Good	Good
TPM 8	Navigation MTBF (h)	≥ 10	15%	≥ 11.5	> 1000	Good	Good
TPM 9	CPU (%)	≤ 100%	50%	≤ 50%	49%	None	Good
TPM 10	Memory (%)	≤ 100%	50%	≤ 50%	47%	None	Good

Progress on Other Technical Performance Measures From the PTR #3 charts

1. Max Velocity: It is believed this KPP is important in performing useful tasks within a reasonable amount of time. The Max Velocity value listed in the presentation does not match what is in the current project plan (was 40 cm/sec and now 50 cm/sec). The current propulsion architecture being used prototype 4 is expected meet the goal.

2. Max Acceleration: The rational for this KPP was to support specific research efforts such as SLOSH. The current architecture being used on prototype 4 should meet the threshold value. (Note that the original KPP was 10 and 17 however this KPP is not listed in the updated plan.) According to the Astrobee team the acceleration tests were done with the perching arm and two of the four batteries removed to reduce mass. May need to reassess how important this KPP is.

3. Localize and Position: This requirement is for AstroBee to be equivalent to SPHEREs however it is much more difficult since AstroBee will not have the beacon system that provides relative position for SPHERES and instead it must rely on vision based navigation which are based on 3D elevation maps and imagery of the interior of the ISS. (Note that the original KPP was 5 and 2 however this KPP is not listed in the updated plan.)

4. Measure Angle & Point: Pointing accuracy will be important for some experiments as well as for routine tasks such as when AstroBee is used as a video platform to help integrate mission operations with crew activities. The current estimate for pointing knowledge should allow AstroBee to meet the pointing accuracy threshold and will be tested on prototype 4.

    a. Note that the original KPP was +/- 5 deg and +/- 2 deg. This KPP is not currently listed in the updated plan but in the PTR #3 presentation it has been greatly reduced to +/- 20 deg and +/_ 8 deg.). Since the Astrobee is planned to be used as a video camera platform this reduction in pointing accuracy by a factor of 4 should be approved by the end users. The LI requirement "The Free Flyer System shall support live streaming and recording high-quality video of crew activities." Implies pointing stability as well as accuracy.
    b. Free Flyer Jitter was discussed. The Astrobee GN&C lead believes the update control rate will allow jitter to be controlled. Vibration testing on the qualification unit will help understand if there are any resonant frequencies that can be induced by the propulsion system.

5. Flight Time: The KPP allows the Astrobee to go anywhere it is allowed on the station, perform a task, and return with margin. The current best estimate for flight time is 3.1 hours which is above the threshold. (Note that the estimate at PTR #2 was 4.8 hours indicating this KPP needs to be closely watched)

6. Standby Time. This KPP allows AstroBee to perch without retuning to the docking port. Given that the team is planning to use an ARM based processor and the CBE for flight time is well above the threshold this should be achievable.

7. Dock and Resupply: This KPP requires that the AstroBee can autonomously dock at its power port. The team has demonstrated autonomous docking in a 2D test environment. It is likely this KPP will meet the goal of autonomous docking.

8. # of Expansion Ports (now peripheral ports). The current design for the certification unit meets the threshold (2). (Note that the goal above (3) does not match what is in the approved project plan (4)).

9. Consumables Used per Test Session. The current design for prototype 4 will meet the goal of none.

10. ISS Operational Space: This is based on a SPHERES limitation to operate with a small area where location beacons have been set up. This KPP is related to the localization KPP which will allow AstroBee to operate throughout the US portion of the station. The current design for prototype 4 will meet the goal.

TRL Advancement

The Astrobee project does not define specific technologies for TRL advancement other than Astrobee itself. Individual Technologies that are being advanced by the AstroBee team in order to meet the Astrobee Requirements include:

Vision Based Navigation for Intra-Vehicular Activities (IVAs) – It is expected that this will be at a TRL of 4 after the latest testing is complete. (This includes Optical Flow for velocity sensing and control)

Fan Based Propulsion for IVAs – This was demonstrated on the low friction granite table and can be considered TRL 4 at this time.

ISS 3-D path planning – This requires ground software and flight software, both of which have been used in the testing of prototype 4. The IVA planning tool was presented at this review. This technology will be at TRL 5 upon completion of Certification Unit testing in late 2016.

Zero-g robotic perching – The perching arm design is being finalized. A prototype version of the perching arm and GN&C software to position it was successfully tested in a 2D environment in the Granite Lab on P4. It is estimated that this technology is at TRL 4.

ISS free flying robotic system – This TRL represents the Integrated AstroBee system. TRL has been increasing with the increased fidelity of the AstroBee prototypes. The certification system being built 2016 will be environmentally qualified bringing the TRL to 5 and flight operations after delivery will continue to advance the TRL to 7 and above.

Technical Challenges

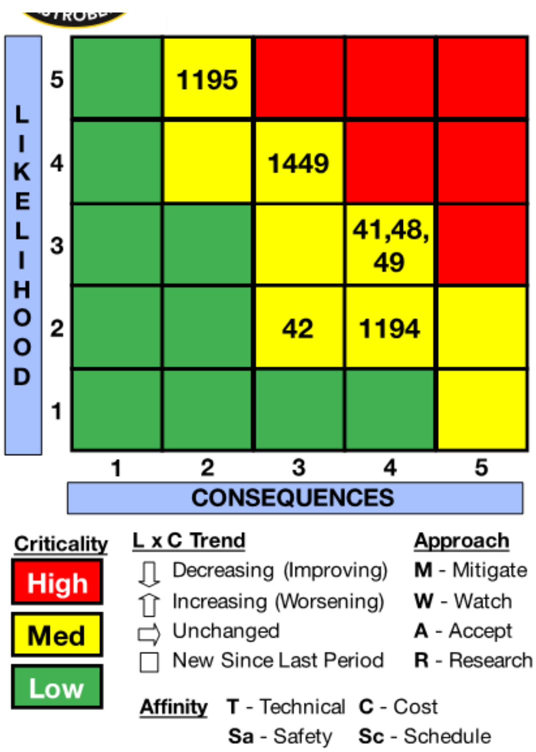
The team’s major challenge is meeting the development schedule which is very aggressive given the amount of work that needs to be accomplished to deliver operationally ready Flight Units at the end of FY17. This schedule requires that the build of the Flight Units start before the testing of the Certification Unit is completed. This limits the use of Certification Unit test results from impacting the design and build of the Flight Units.

Although the team has made a significant amount of progress on the software, there is still a lot of work ahead of them. Although some of the most difficult software pieces have made progress (i.e. vision based navigation, docking), the effort needed to integrate, test, and certify Astrobee for operational use is a large effort. The current architecture includes three processors (low level, mid level, and a high level) and also has several external interfaces which must be tested and verified including multiple sensors and a touch screen user interface. Given the difficulty in obtaining ISS crew time for testing and helping debug issues, AstroBee software must be mature when delivered to the ISS for operational use.

System Reliability was discussed and is a concern. For example, each Free Flyer has 12 nozzle servos and they all must work in order to operate. Reliability targets must be documented and a reliability analysis needs to be performed now that all the components have been identified to help determine part quality requirements. The team was asked to review their parts management rigor to ensure it is adequate and to determine what spares need to be maintained on orbit. This should be covered in the delta PTR#3.

Risks

The AstroBee team has identified several risks with the highest ones all related to the aggressive development schedule. Much of this is described in the technical challenges section. These risks are all actively being worked by the AstroBee team.



Risk ID Trend*	Approach *Affinity*	Risk Name
41	M *Sc*	Cert Unit schedule
48	M *Sc*	Flight Unit schedule
49	W *Sa*	PSRP approval for operations without crew tending
1449	*M* *Sc*	Dock placement not determined
1195	M *T*	Negative mass margin
1194	M *C, Sc*	Technology transition is incomplete
42	M *T*	Pose accuracy with vision based navigation
1479	R *C, Sc*	Unexpected QA & QC requirements
1478	R *C, Sc*	Flight hardware costs & phasing

** Risk numbers not sequential*

Other:

The AstroBee presentations can be found on NX:
https://nx.larc.nasa.gov/dsweb/View/Collection-87131

The AstroBee Project Plan can be found on NX at:
https://nx.larc.nasa.gov/dsweb/View/Collection-65920

Continuation Review Board Recommendation:

Astrobee will provide a key research capability on the ISS and will allow many more experiments to be performed than the current SPHERES System which has been a highly successful in supporting a wide range of ISS science experiments.

Since the AstroBee project is currently meeting its commitments in the approved project plan, is on track to meet its KPPs, has very strong customer support (i.e. “They are absolutely building the right thing.”), and is actively mitigating project risks the Board unanimously recommends continuation of the Astrobee project.

//Signature on File | *07/21/2016*
Kevin S. Kempton | Date
Chair, Continuation Review Board

Review Notes and Recommendations from the Board:

From Kevin Kempton:

The PTR #3 presentations had a much higher design maturity and fidelity than PTR #2. Progress has been made on many of the challenges identified in the last review (i.e. Perching System, the propulsion system, software, GN&C)

Given the amount of work that needs to be done, the team will be challenged to complete the testing of their flight units by the end of FY17 to meet the approved schedule. The team should invest effort into automating test activities. This effort should reduce the overall workload since there will be multiple free flyer units to test and qualify. It may also help streamline debugging activities on the ISS.

After PTR#3 (CDR for the certification unit), the team must ensure design changes go through a formal change approval process. Adding design changes late in development could prevent the project from meeting its cost and schedule commitments. The CMP describes the change approval process in section 6. It was not evident that the project is actively using the documented change approval process. Those CCRs found in the repository did not provide clear identification of the changes. Also, there are no dates or version numbers on any of the documents which makes it hard to ensure the latest documents are being reviewed. At this point the team needs to be very careful when adding new “features” such as User Interface enhancements. The team must also hold the line on their technical resource budgets (i.e. size and mass).

All of the Astrobee subsystem presentations included a “Design Maturity” Chart that identified the key components and functions of the subsystem and identified the technical readiness and risk of each. This was a great help to reviewers and showed that the subsystem leads were actively identifying and managing their technical risks. Where appropriate, these charts should match the “official” Astrobee Level 4 system decomposition. The design maturity charts should be maintained and presented at the next review.

If the Commissioning Phase is approved, the handover should be based on the formal verification of requirements. A verification sheet for each requirement that identifies the verification artifacts and who shall do what for verification should be agreed to by the project stakeholders. A clear plan and clear success criteria will ensure a clean handover.

The I&T documentation in the document repository was really hard to follow and appears to be at a low level of maturity. The Astrobee I&T Plan provided general information but did not provide a cohesive I&T story. It does not appear that several items in the I&T Plan are being implemented. The Astrobee I&T plan referenced “Test Suite Descriptions” which may be what is needed for a better understanding of the I&T plans. The Astrobee project should provide a

Certification Unit Test Plan for review at the delta PTR#3 in November. Verification is a team effort and must be distributed. These plans should specify what verification artifacts will be produced to close each requirement and specify who will produce it.

At a CDR level review, a description of how the requirements will be verified should be clearly documented. There are several test procedures, and test data items but the relationship to the requirement closure is difficult to determine. There should be clear success criteria. The test procedures do not align with the requirement flow down in the Requirements Management Plan. The project team uses the JIRA project tracking tool for requirements management and verification tracking. Spreadsheets exported from JIRA could be improved. Since I&T will require significant resources I would like to see more documentation on test set ups and who is responsible for what on I&T, especially if it requires external support. As stated at the last CR the system decomposition which is based around technical disciplines instead of hardware based subsystems will make integration and verification more challenging since it will be more difficult to define clear requirements and interfaces between subsystems.

Test results from P4 testing seem to be limited. Would expect an overall test report or some type of artifact that can be associated with the completion of the milestone.

Astrobee reset rates, due to the space radiation environment were discussed. Astrobee will use several COTS boards and electronics that do not have space heritage. The team expects a low reset rate based on the historical reset rate of laptops on the ISS and with experience using SPHERES. Is this a valid assumption? Is there a requirement for maximum allowable occurrence of system resets based on discussions with the end user?

From Jason Crusan:

Verbal concurrence to continue the Astrobee Project Element at the Review.

From Jeff Sheehy:

Verbal concurrence to continue the Astrobee Project Element at the Review.

From Mark Micire:

Per Email Mark has no additional comments and concurs with findings in report.