National Aeronautics and Space Administration
Game Changing Development Program

GCD Continuation Review Board Recommendation Memo

Memo Date: 11/17/2015
Review Date & Location: 10/01/2015 at ARC Bld. N262 Room 100
Project Name: AstroBee
Project Manager: Terry Fong, Project Manager for Human Exploration Telerobotics II (HET2), ARC

Continuation Review Board Members:
Kevin S. Kempton, Program Element Manager, GCDPO (Chair)
Rob Ambrose, Principal Technologist STMD
Mark Micire, Subject Matter Expert, DARPA
Jason Crusan, AES Director, HQ, LaRC

Continuation Review Presenters:
Chris Provencher, AstroBee Element Manager, ARC (Presenter)
Maria Bualat, HET2 Deputy Project Manager, ARC
Trey Smith, AstroBee Systems Engineer, ARC (Presenter)
Jonathan Barlow, AstroBee, 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:
Mary Beth Wusk, GCD PIM, LaRC
Bill Van Dalsem, ARC TI Division Chief, ARC
Dawn McIntosh, ARC TI, 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
Kenny Vassigh, Office of Chief Engineer, ARC
Jose Bendavides, SPHERES PM, ARC
Jonathan Barlow, SPHERES Engineeting, ARC
Aric Katterhagen, SPHERES Operations, ARC
James L. Broyan, AES Logistics Reduction Sponsor PM, JSC
Andrew W. Chu, AES Logistics Reduction Technical Lead, JSC
Pat Fink, AES Logistics Reduction Principle Investigator, JSC
Phong Ngo, AES Logistics Reduction Chief Engineer, JSC
Al Holt, ISS Research Integration Office, Technology Development Office, JSC
Leonard Yowell, ISS Research Integration Office, Technology Development Office, JSC

Henry Orosco, ISS RIO: Payload Integration RIM, JSC
Larry Cotton, ISS RIO: Payload Integration PIM, JSC
Don Pettit, ISS Crew Office Astronaut, JSC
Jennifer Goldsmith, ISS Crew Office Crew Rep, ISS
Chris Edelen, FOD Flight Director, JSC
Andrea Kramer, Joint Station LAN (JSL) Lab (SDIL)
Tameka Stewart, Huntsville Operations Support Center (HOSC)
Mai Lee Chang, ISS Requirement Verification/HFIT
Holly Smith, JSC Engineering/Acoustics
Carl Konkel, Payload Software (Boeing)

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 letter 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.

The 2015 AstroBee Continuation Review was held in conjunction with an AstroBee Periodic Technical Review (PTR #2).

State of the Project

The AstroBee Project Element falls under the Human Exploration Telerobotics 2 (HET2) Project. The HET2 Project Plan was approved on November 17, 2014. A GCD Change Request (CR-248) was approved on June 28, 2015 that added $60K for parts and $149K for WYE labor. In addition the CR approved $350K in FY16 & FY17 to cover FTE backpack fees which were not accounted for in the original cost estimate provided at the DPMC.

The AstroBee project is beginning its second year of a four year development effort and maintains strong support from its stakeholders as demonstrated by their participation at this technical review. The team is focused on delivering an extremely versatile system that will be operationally ready to take over from the highly successful SHPERES system as one of the most used research tools on the ISS. In addition to the research capabilities, the team is performing a significant amount of design work to ensure AstroBee will be an effective operational tool for performing routine tasks on the ISS.

The AstroBee project is taking a spiral development approach by developing higher and higher fidelity prototypes and learning from each one to improve the next prototype. This year the AstroBee team has completed Prototype 2 and prototype 3 on schedule.

Prototype 2 provided a basic development platform with interim avionics and propulsion, and provides 3-DOF mobility (x, y, yaw). It tested closed loop control of 4 fans with variable pitch propellers using computer vision based tracking to perform docking. The Avionics subsystem implemented low and midlevel processors and the Flight Software subsystem utilized the Robot Operating System (ROS). The use of ROS will greatly promote collaboration with academia in the development of future capabilities.

With a near flight like C&DH system, prototype 3 is currently being used as a test bed to continue advancing key technologies such as vision based navigation and automatic docking technologies. In addition to the prototype units, the team has designed the AstroBee docking station and communication system for the ISS. They have also designed the AstroBee Ground data system and have upgraded the primary navigation test facility at ARC. The navigation test facility (granite lab) provides a two dimensional navigation simulator that can test a wide variety of AstroBee functions. The team provided a tour to the review attendees with a live demonstration of the waypoint navigation and docking using a visual target.

Prototype 3 uses variable pitched propellers for propulsion which have been deemed too risky for the final design. The AstroBee Project has now converged on an innovative propulsion design which has reduced volume and lowered the likelihood of some key technical and safety risks. The new design has a modular architecture which will help reduce operational maintenance issues and also makes it easier to distribute the development work. This new design architecture is being incorporated into the Prototype 4 which is expected to be ready for testing in February 2016. The prototype 4 design incorporates electrical and mechanical interfaces that will simplify the integration of experiments and operational tools to the AstroBee system. This includes the development of open source Application Program Interfaces (APIs) to simplify the software integration and testing with AstroBee experiments.

The AstroBee team has developed a large set of project management and systems engineering documents (PM Plan, SEMP, SMA Plan, CM Plan, RMP, I&T Plan, ConOps, IMP, etc.) which were made available to the review team. All of the key systems engineering process areas are actively being addressed and are documented in the Project's SEMP. The team has also performed several formal trade studies to select the specific components used in the prototypes. These include trade studies on the Propulsion approach, the perching approach, the operating system, the data bus, the processors, the visual mapping approach, the visual pose estimation approach, the software framework, the external sensors and the thermal approach.

The team is activity communicating with stakeholders to elicit feedback on how AstroBee will operate on the ISS. They have developed a stakeholder assessment spreadsheet to identify stakeholders and expectations. Much of this communication was facilitated by providing excellent story board ConOps descriptions. The team is also actively working safety issues with ISS safety personnel to ensure the design will meet ISS safety requirements. A payload safety review panel was conducted to review the AstroBee safety data package. Finally, a wide variety of software tools and simulators have been developed to support testing and operations.

Project cost, and schedule performance against the plan

Cost Performance: The team has maintained development to the planed cost. Workforce levels have tracked very closely to the plan. A Change Request for additional AstroBee resources was submitted due to a misunderstanding of whether the FTE backpack costs were included with the FTE allocations was approved. Since the backpack costs were not included in the original estimate, they had to come out of AstroBee procurement which was inadequate to cover the large backpack cost.

Schedule Performance: The GCD Controlled Milestones for “Prototype 2 testing complete” and Prototype 3 testing complete” were accomplished close to the planned dates. The design and build cycle for prototype 4 is underway and many parts have been ordered or are being fabricated. With a better understanding of the work needed to deliver Astrobee Flight Units the refined schedule indicates there will be a 3 to 4 month slip in delivery of the flight units which will push them into FY18.

Controlled Milestone	Description	Completion Date
FY15 #1	**Prototype 2 testing complete**	**2/15/2015 (Actual)**
FY15 #2	**Prototype 3 testing complete**	**7/28/2015 (Actual)**
FY16 #1	Prototype 4 testing complete	3/15/2016 (estimated)
FY17 #1	Cert Units testing complete	8/31/2016 (In approved plan)

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

The AstroBee Project has KPPs which remain valid and are shown below:

Parameter	State of the Art (SPHERES)	Threshold Value (Minimum success)	Project Goal (Full success)
Max velocity	4 cm/sec	4 cm/sec	50 cm/sec
Max acceleration	10 cm/sec^2	10 cm/sec^2	17 cm/sec^2
Localize & position	+/- 3 cm	+/- 5 cm	+/- 2 cm
Measure angle & point	+/- 2 deg	+/- 5 deg	+/- 2 deg
Flight time	0.5 hr	1 hr	2 hr
Standby time	6 hr	8 hr	12 hr
Dock & resupply	Crew tended	Crew tended	Autonomous
# Expansion ports	1	2	4
Use cases supported with expansion ports	1	1	3
Consumables used per test session	6	0	0
ISS operational space	2m x 2m x 2m	JEM, US Lab, and Node 2	All USOS

1. Max Velocity: It is believed this KPP is important in performing useful tasks within a reasonable amount of time. The current propulsion architecture being used prototype 4 will should easily meet the threshold value. The challenge is ensuring reliability at high speeds.

2. Max Acceleration: The rational for this KPP was to support research efforts such as SLOSH. The current architecture being used prototype 4 will should meet the threshold value.

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 must

rely on vision based navigation based on elevation maps and imagery of the interior of the ISS.

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.

5. Flight Time: The KPP allows the Astrobee to go anywhere it is allowed on the station, perform a task, and return with plenty of margin. The current best estimate for flight time is 4.8 hours which is well above the threshold.

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 is currently testing autonomous docking. It is likely this KPP will meet the goal of autonomous docking.

8. # of Expansion Ports. The current design for prototype 4 will exceed the goal.

9. Use Cases Supported with Expansion Port. The current design for prototype 4 will meet the goal.

10. Consumables Used per Test Session. The current design for prototype 4 will meet the goal.

11. 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

Individual Technologies identified as being advanced by the AstroBee team include:

Vision Based Navigation – It is expected that this will be at a TRL of 4 after prototype 4 testing is complete.

Fan Based Propulsion – 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 3. This will be at TRL 4 upon completion of prototype 4 testing in the spring of 2016.

Zero-g robotic perching – The perching arm design is being finalized and this will be tested in a 2D environment on prototype 4 which should take it to 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 in the spring of 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 articles at the end of FY17. If schedule relief for the delivery date is not obtained then the technical risk will be significantly increased. This is because the build of the flight certification unit will have to start before the testing of prototype 4 is complete. This overlap will not allow prototype 4 test results to inform the design and build of the certification unit. The design of the certification unit is due to start in February 2016.

- **Proposed Astrobee FY18 Extension**
  - **Description**: Extend Astrobee by one year to: (1) mitigate schedule risk, (2) conduct ISS check-out, and (3) perform HEOMD/STMD payload demo
  - **Amount**: 6 FTE (ARC) + $1.6M procurement
  - **Why?** Overlapping development, certification, and flight unit build poses extreme schedule risk. Delivering flight units without on-orbit testing is a significant infusion risk.
  - **When?** Need to decide by Jan 2016 in order to mitigate development (Prototype 4) and certification unit schedule overlap.

The team has a significant amount of software development, integration, and test work ahead of them. Although some of the most difficult software pieces are making 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. An experienced SW lead has been brought on to coordinate the development of the AstroBee SW which has been functionally broken out to distribute the work. Since AstroBee will be a high visibility project, it is critical that the software is mature when delivered to the ISS for operational use. It was recommended that the team explore ROS compatible simulation products for GN&C and possibly other functions.

The current system decomposition which is based around technical disciplines instead of hardware based subsystems will make integration and verification more challenging since it will be difficult to define clear requirements and interfaces between subsystems. At this point in the project lifecycle it is probably too late to adjust the system decomposition since much of the documentation has already been developed.

The Current Best Estimate for AstroBee mass is above a self-imposed requirement to stay under 6 Kg. The excess mass will affect acceleration and safety requirements so the team is working hard to shave mass on all subsystems. The customer has specified a hard limit for maximum volume/dimensions (< 30 cm on any side) and the team is using that constraint in the Prototype 3 design. Other technical resources such as power, CPU usage, memory, etc. are being actively tracked by the team with no significant issues.

An ongoing design challenges is the tradeoff between simplifying operations at the expense of increased system complexity which impacts an already tight schedule. Improving the user interfaces is notorious for consuming time and schedule and a key challenge will be determining what is good enough to deliver to the customer.

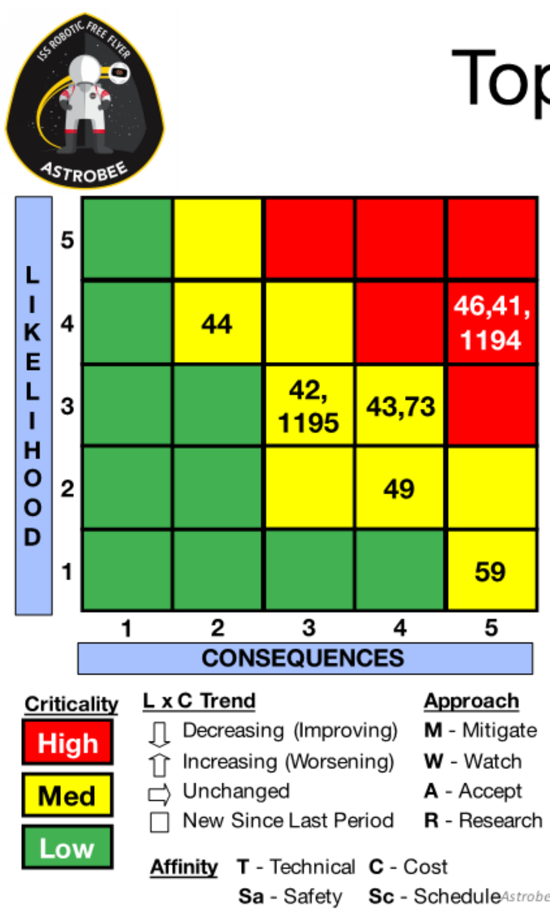
The perching system is probably one of the least mature systems as far as design and technology readiness. In order to perch the system must identify and grasp ISS handrails which is a significant challenge. Hand rail grasping has been extensively worked by the Robonaut team. It is recommended that the AstroBee team collaborate with the Robonaut team to help reduce technical risks in this area.

AES, the primary customer for AstroBee, would like to receive 3 flight units however only two flight units are planned. A cost estimate for a third AstroBee flight unit is being refined. It may be possible to convert the certification unit into a flight spare if it survives the qualification testing.

Risks

The AstroBee team has identified several risks with the highest ones all related to the aggressive development schedule along with the need to transfer the corporate knowledge on how to operate and maintain the AstroBee system. Much of this is described in the technical challenges section. These risks are all actively being worked by the AstroBee team.

Top Risks



Risk ID Trend*	Approach *Affinity*	Risk Name
46	W *Sc*	Schedule is best case
41	W *Sc*	Cert Unit schedule
43	W *Sc*	Prototype 4 schedule
1194	M *C, Sc*	Technology transition is incomplete
73	R *C*	Destructive testing with Cert Unit
42	M *T*	Pose accuracy with vision based navigation for high accuracy research activities
1195	M *T*	Negative mass margin
44	R *T*	# fans vs. battery size vs. overall dimensions
49	W *Sa*	PSRP approval for autonomous operations
59	W *Sc*	Flight Unit delivery is after on-dock date

** Risk numbers not sequential*

Astrobee Continuation Review / PTR 2
10/1/15

Continuation Review Board Recommendation:

The AstroBee Project is unlikely to deliver 2 fully operational units by the end of FY17. The current best estimate for delivery is February 2018. It is recommended that a decisional meeting be held to consider an extension to the AstroBee development schedule into FY18.

Since the AstroBee project is currently meeting all of its commitments in the approved project plan, is on track to meet its KPPs, has very strong customer support, and has no significant risks other than the schedule risk described above the Board unanimously recommends continuation of the AstroBee project.

//Signature on File	11/17/2015
Kevin S. Kempton	Date
Chair, Continuation Review Board	

Additional Review Notes:

The AstroBee presentations can be found on NX:
https://nx.larc.nasa.gov/dsweb/View/Collection-79655/Document-450718
The AstroBee Project Plan can be found on NX at:
https://nx.larc.nasa.gov/dsweb/View/Collection-65920