National Aeronautics and Space Administration

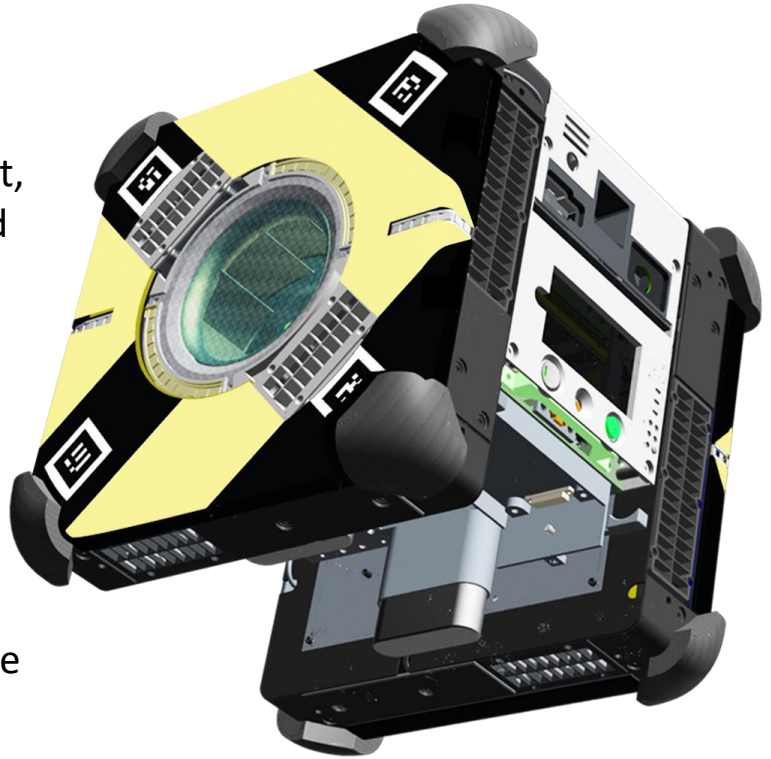
# Space Technology Mission Directorate

## Game Changing Development Program — Astrobee

Maria Bualat | FY19 Annual Review Presentation | 09.25.2019

# Technology Overview

- ***Technology Goal***
  - The purpose of the Human Exploration Telerobotics 2 (HET2) project is to mature telerobotics technology to increase the performance, reduce the cost, and improve the success of human space exploration. To do this, HET2 will develop a new free-flying robot, Astrobee to: (1) off-load routine and repetitive work from astronauts, and (2) extend and enhance crew capabilities.
- ***Technical Capabilities***
  - Vision-based navigation
  - Fan-based propulsion
  - ISS 3D path planning
- ***Exploration & Science Impact***
  - Remotely operated robots can complement astronauts by performing work under remote supervision by humans from a space station, spacecraft, habitat, or even from Earth.
  - A semi-autonomous free flyer, such as Astrobee, offers significant potential to perform a variety of tasks, including routine, repetitive or simple but long-duration work, such as conducting environment surveys, taking sensor readings or performing routine maintenance.
  - In the case of the Gateway, which is uncrewed much of the time, a caretaker free flying robot would allow monitoring, maintenance, and repair of the spacecraft interior when astronauts are not present or are unable to perform such tasks.



# Mission Infusion & Partnerships

Contributing Partner:  HEOMD / AES


SPHERES
ISS Facility

**2006 to 2018**

- ISS Operations
- Consumables
- Maintenance
- Payload Support

**Astrobee Development & Build**

**FY16 to FY18**

- Infrastructure & Lab Upgrades
- Integration & Test Support
- Flight Build Support
- Operations Planning Products

**Astrobee Commissioning**

**FY19**

- Guest Science SW & Processes
- Simulator Development
- On Orbit Install Checkout & Demo

**Astrobee ISS Facility**

**2019 to 2024+**

- ISS Operations
- Maintenance
- Payload Support

# Astrobee
# Technology Goals & Project Objectives

| Technology Goals | |
|---|---|
| **Goal #1** | Develop a free-flying robot that is capable of performing Intravehicular (IVA) work on the ISS. |
| **Goal #2** | Develop robotic technologies required for autonomous operations, remote ground control, and human-robotic interaction. |

| Project Objectives | |
|---|---|
| **Objective #1** | Design, build, and test 3 Astrobee free flyer robots (2 flight, 1 ground)*, 2 Docking Stations (1 flight, 1 ground), and all associated hardware, software, and ground systems needed to operate Astrobee on ISS. |
| **Objective #2** | Develop supporting technologies include propulsion, robot user interface (proximal and remote), supervisory control, payload interface, and navigation. |
| **Objective #3** | Check out, tune, and characterize performance on board the ISS during commissioning. |

*3 additional units (1 flight, 2 ground) will be delivered to ISS Program Astrobee Facility

# Astrobee Performance

| Key Performance Parameters | | | | |
|---|---|---|---|---|
| **Performance Parameter** | **State of the Art** | **Threshold Value** | **Project Goal** | **Estimated Current Value** |
| Max velocity (cm/s) | 4 | 10 | 40 | **40** |
| Flight time (hr) | 0.5 | 2.0 | 5.0 | **3.1** |
| Dock & resupply | Crew tended | Crew tended | Autonomous | **Autonomous** |
| Hosted Payloads | 1 | 2 | 4 | **3** |
| Consumables per ISS test | 6 | 0 | 0 | **0** |

**Notes:** Current value justification: inspection, analysis and testing. The “State of the Art” for ISS free-flying robots is SPHERES.

# Astrobee Technical Approach

- The project will conduct **incremental design and development** of a free flyer that meets project, stakeholder, and ISS interface and safety requirements. Stakeholders include the ISS SPHERES Facility, the SPHERES Working Group, HEOMD AES program, ISS program, Flight Operations Directorate (FOD), Payload Operations & Integration Center (POIC) and others. The project and stakeholders have provided general and scenario specific functional requirements.
- Astrobee will be developed incrementally over a **series of prototypes**. Earlier prototypes will address trade studies and areas of risk. The later prototypes will implement system requirements and **incrementally mature the system design**. Each prototype will have stated objectives, both as overall system, and for subsystem development. Astrobee testing will validate system requirements and capabilities, and buy down risk.
- The **prototypes are not treated as flight** hardware. Prototyping allows the team to make design changes at a rapid pace, without the overhead of flight hardware processes. The Astrobee Project is willing to accept the risk of damage to prototype hardware in order to take advantage of the limited processes.
- The **Certification Units** will be developed off the final prototype design, with any modifications as a result of prototype testing. These units will not only be used for **performance testing**, but also for **ISS interface requirement verification and certification**.
- Finally, two Flight Units will be developed. These units will be developed and assembled following ARC procedures and processes for flight hardware. They will then be shipped to JSC for launch processing.

# Project Accomplishments – Docking Station

***Successfully Launched, Installed and Checked Out Astrobee Dock***

- The Astrobee Docking Station launched on board Northrup Grumman 10 (NG-10) on 11/17/2018.
- The Cygnus cargo ship was captured and berthed at the Unity module of the ISS on 11/19/2018.
- Canadian astronaut David Saint-Jacques installed and checked out the Astrobee Docking Station (Dock) in the Japanese Experiment Module (JEM) on 2/15/2019.

CSA Astronaut David Saint-Jacques tests the operation of the Astrobee magnetic berths.

# Project Accomplishments – Integration

***Successfully Built and Shipped Free-Flyer Flight Units***

- Completed building all flight free flyers on 1/4/2019.
- The first two flight free flyers (Honey and Bumble) were shipped to JSC on 1/8/2019. The second two (Queen and spare) were shipped to JSC on 1/22/2019.
- Implemented a fix for an issue found with the perching arm gripper. Four flight grippers were shipped to JSC on 3/28/2019 and underwent acoustic testing on 4/2/2019.


Family photo: Queen (green), Honey (yellow), Bumble (blue), 2 perching arms, 2 batteries

# Project Accomplishments – Testing

***Completed Free-Flyer Pre-Launch Testing***

- Completed EMI testing on 1/15/2019. Received an exception for radiated emissions.
- Passed magnetic tests for launch and ops in the USOS.
- Completed Joint Station LAN (JSL) testing on 1/15/2019, including remote ops from ARC via MSFC HOSC.
- Completed acoustic testing on 1/30/2019 in the Acoustic Test Facility at JSC. Received an exception to allow extended free flyer ops.

Astrobee in the JSC acoustic test facility. Pictured Astrobee team members from left to right: Vinh To, Honey Bee, Ernie Smith, Roberto Carlino.

# Project Accomplishments – Launch #2

***Successfully Launched 2 Free Flyers to ISS***

- The first two Astrobee free-flyers, Honey and Bumble, along with the Docking Station spares kit, launched on the Northrup Grumman 11 (NG-11) rocket from Wallops Flight Facility on 4/17/2019. The Cygnus spacecraft was captured and berthed at the ISS on 4/19/2019.

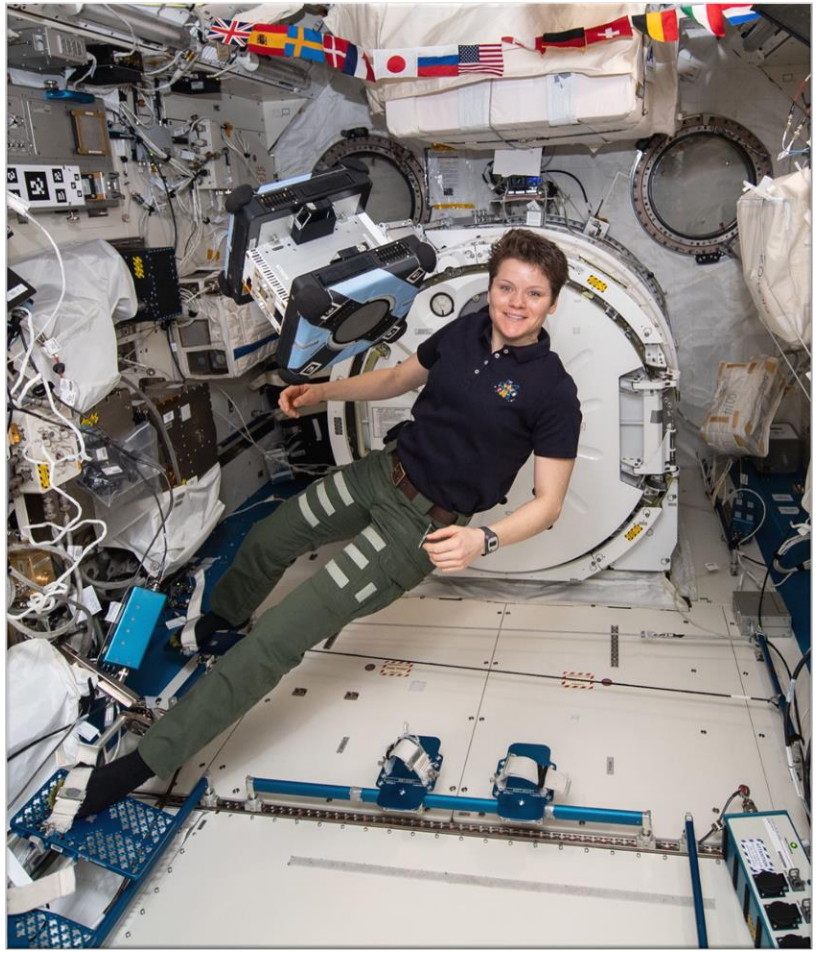
NG-11 launch
(Photos: NASA/Bill Ingalls)

# Project Accomplishments – Bumble Checkout

***Successfully checked out Bumble on ISS***

- On 4/30/2019, Astronaut Anne McClain unpacked, powered on, and checked out the first Astrobee robot (Bumble). All Bumble Bee subsystems are operating nominally.

Bumble on the Docking Station



NASA Astronaut Anne McClain unpacks Bumble.

# Project Accomplishments – Calibration

***Collected Bumble Calibration and JEM Mapping Data***

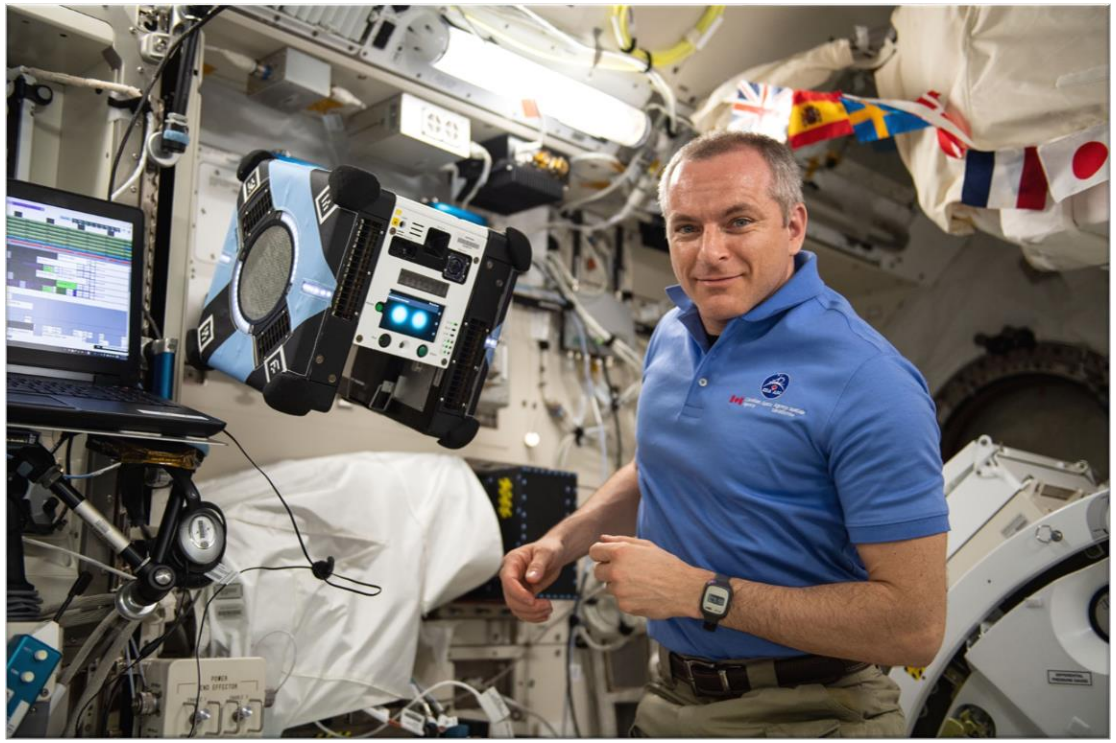
- On 5/13/2019, Astronaut Anne McClain manually "flew" Bumble Bee throughout the Japanese Kibo laboratory module to collect NavCam imagery. We used this data to build a feature map for localization. McClain then collected calibration data for Bumble's NavCam, DockCam, and Inertial Measurement Unit (IMU). Comparison of data collected on orbit to pre-flight shows that Bumble suffered no loss of calibration during launch.

NASA Astronaut Anne McClain spins Bumble to collect IMU calibration data.

# Project Accomplishments – Mapping

## *Second Mapping Activity on ISS*

- On 5/23/2019, Astronaut David Saint Jacques performed an Astrobee mapping activity, collecting navigational camera (NavCam) imagery of the Japanese Kibo Laboratory.



CSA Astronaut David Saint Jacques and Bumble Bee

CSA Astronaut David Saint Jacques moves Bumble to collect mapping imagery data.

# Project Accomplishments – First Flight

***Astrobee Localization and Mobility Activity***

- On 6/14/2019, the first Astrobee robot, Bumble Bee, flew under its own power on the ISS for the first time. During the first Localization and Mobility session, the Astrobee team verified the robot's ability to hold position (station keeping against a variety of external forces), to perform specific motions (translations and rotations), to navigate using its computer vision system, and autonomously undock.

CSA Astronaut David Saint-Jacques observes as Astrobee undocks itself for the first time.

# Project Accomplishments – Launch #3

Image Credit: NASA/Tony Gray & Kenny Allen


Image Credit: NASA

## *Queen Bee and Perching Arms Arrive on ISS*

- The 3rd Astrobee free-flying robot, Queen Bee, launched aboard the SpaceX CRS-18 Falcon 9 on 7/25/2019. Also onboard were 3 perching arms (one for each of the flight robots) and 8 Li-Ion batteries. Astronaut Nick Hague captured the Dragon capsule using Canadarm2 on 7/27/2019.

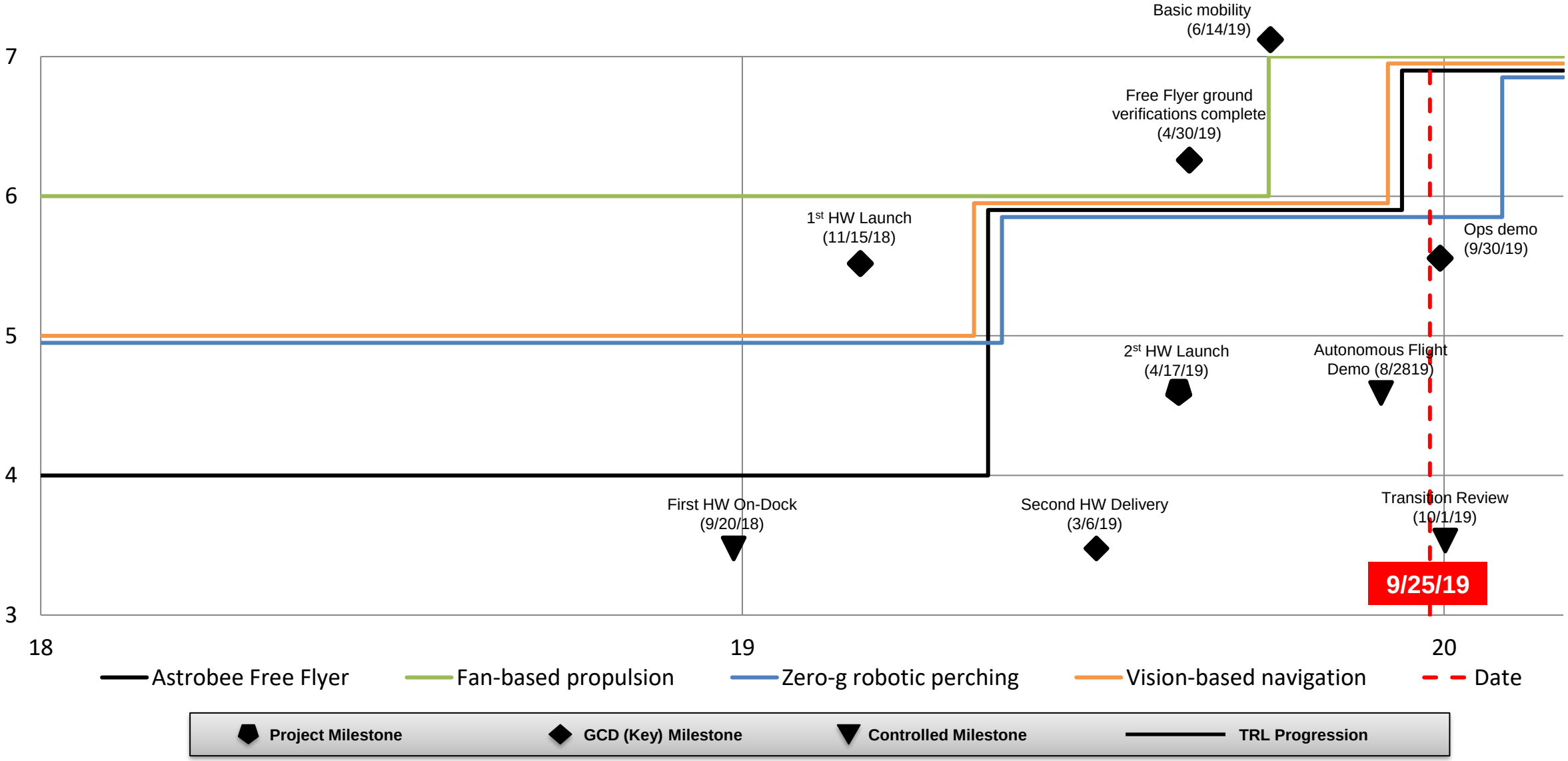
# Project Accomplishments – Autonomous Flight

***Astrobee Autonomous Flight Demonstration***

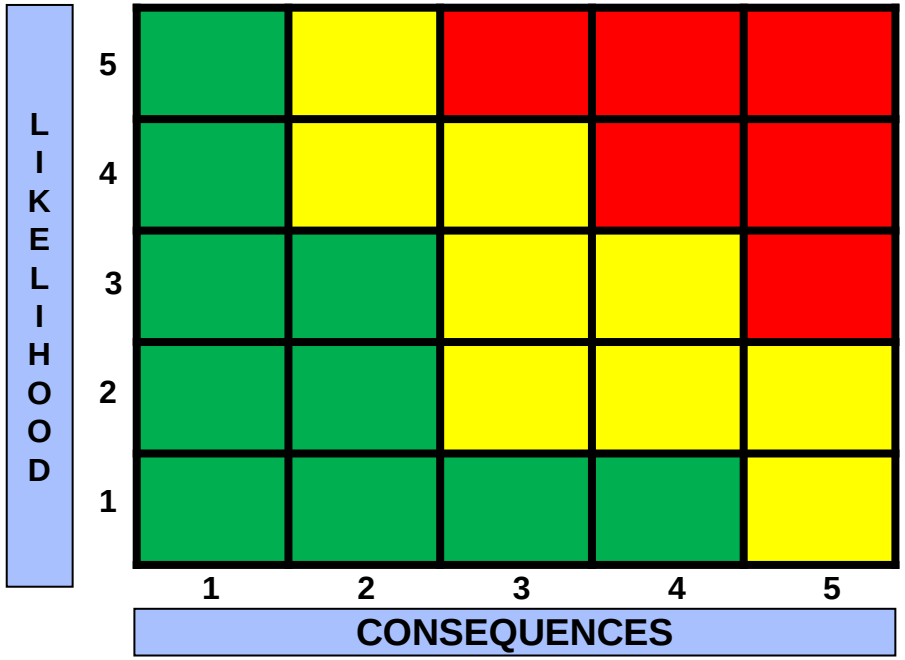
- On 8/28/2019, we completed our fourth Localization and Mobility on-orbit activity with Astronaut Christina Koch. We saw improvement in Astrobee localization using a new map of the Japanese Experiment Module (JEM) that keeps more features than previous maps. During the activity, we completed several successful autonomous flights, including a simple camera survey of panel JPM1F3.

NASA Astronaut Christina Koch observes as performs its first autonomous camera survey.

# Astrobee
# Lifecycle Milestone/Maturity Schedule



# Risk Summary




| Risk ID | Approach *Affinity* | Description/Status | Trend |
|---|---|---|---|
| | | | |
| | | | |

No red or upward trending yellow risks.

**Criticality**

- High
- Med
- Low

**L x C Trend**

- Decreasing (Improving)
- Increasing (Worsening)
- Unchanged
- New Since Last Period

**Approach**

- M - Mitigate
- W - Watch
- A - Accept
- R - Research

**Affinity:** **T**-Technical **C**-Cost **Sc**-Schedule **Sa**-Safety

# EPO Summary Chart

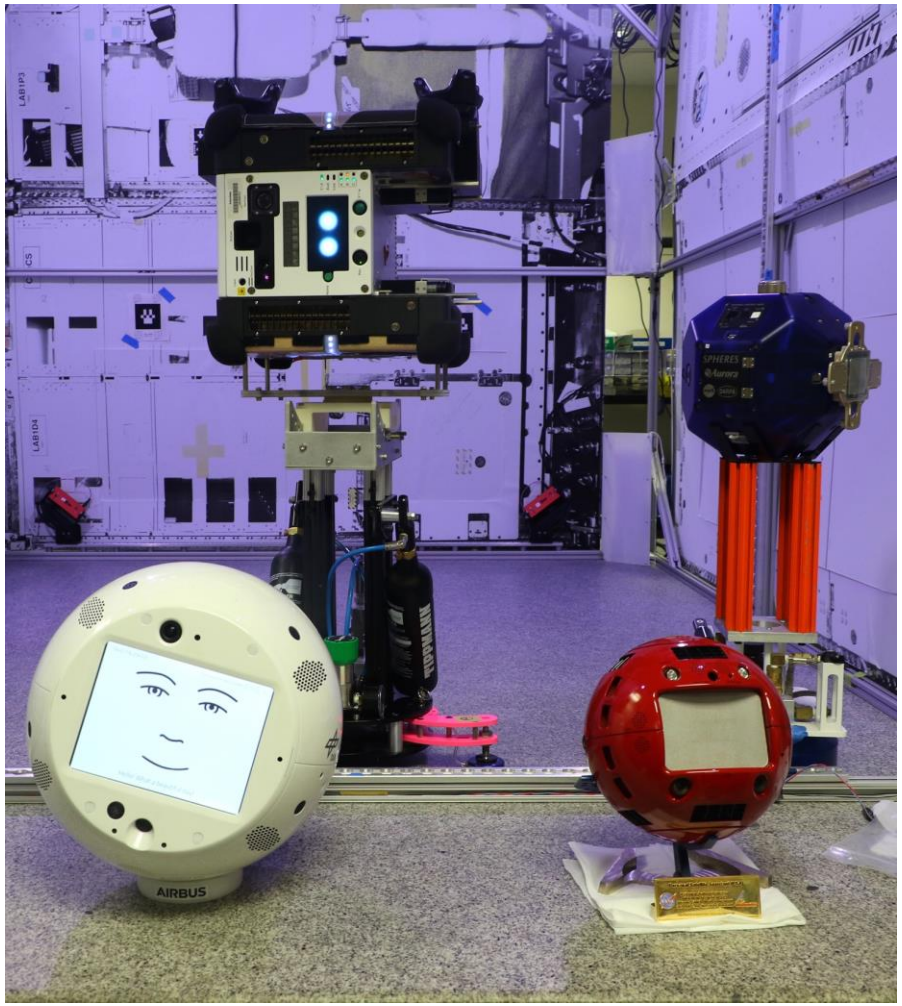
- Summary of Education and Public Outreach
  - On 03/14/19, His Excellency Carlos Alvarado Quesada, President of the Republic of Costa Rica, and his delegation, toured the Granite Lab and Micro-Gravity Test Facility.
  - Astrobee was featured on the “What’s On Board” briefing for Northrup Grumman 11 on 4/16/19.
  - We participated in SPHERES/Astrobee Working Group quarterly meetings on 10/03/18, 12/12/18, 3/20/19, and 7/22/19.
  - Maria Bualat and the Astrobee Stunt Double (full-scale model) staffed the Apollo 50th Anniversary festival on the National Mall from 7/18 - 7/20.
  - Astrobee is featured in an Innovation Now podcast from 9/3/19: http://podcasts.whro.org/innovationnow/2019-09-03-04-52-40-090319_Robotic_Caretakers.mp3
- Significant Media Coverage
  - Astrobee was on the cover of Make Magazine.
  - Astrobee is featured in a Popular Science Article: https://www.popsci.com/astrobee-robot-space-station
  - Astrobee appears in an IEEE Spectrum article: https://spectrum.ieee.org/automaton/robotics/space-robots/nasa-launching-astrobee-robots-to-iss-tomorrow
  - Astrobee is featured in a Space.com article: https://www.space.com/astrobee-bumble-first-space-station-flight.html

See lots more in the backup slides


Astrobee on the cover of Make Magazine

# Annual Summary

- Launched, installed, and checked out Astrobee Docking Station
- Completed free flyer and perching arm flight hardware build
- Delivered all flight hardware for launch (3 free flyers, 3 perching arms, on-orbit spare parts)
- Completed ISS verifications
- Launched all flight hardware (except Astrobee spares kit – scheduled on NG-12 10/21/19)
- Checked out and calibrated first free flyer, Bumble
- Mapped the Japanese Experiment Module (JEM)
- Completed first flight
- Completed first autonomous flight
- Ready for Honey hardware checkout




4 Free Flyers (clockwise from top): Astrobee, SPHERES, PSA, CIMON (DLR/Airbus)


BACKUP

# Project Assessment Summary

| Project | Performance | | | | Comments |
|---|---|---|---|---|---|
| | C | S | T | P | |
| Mid Year | | | | | Cost – CR submitted on 3/15/2019 requesting additional labor and procurement funds to address: (1) a latent design defect in the Astrobee "perching arm" that was not discovered until functional testing of the flight hardware and that poses a potential failure risk over the expected robot life cycle, (2) underestimation of the amount of software team support required for development of ops products (e.g., crew procedures). |
| Annual | | | | | Though crew time is extremely scarce at this time and several commissioning activities will have to slip into October and November, the project is working with the Astrobee Facility team and other projects to support completion of commissioning. |

# EPO Summary Chart

## *Education and Public Outreach*

**News about Bumble Bee's first flight has appeared on several websites:**

- **NASA**
  - NASA Image Feature: https://www.nasa.gov/image-feature/ames/look-no-hands-nasa-s-first-astrobee-robot-bumble-starts-flying-in-space
  - This Week at NASA: https://youtu.be/NeHQcS1kRVQ
  - Space to Ground: Tending the Hive: 06/21/2019: https://youtu.be/13HJ62g4tPQ
- **External**
  - SlashGear: https://www.slashgear.com/nasas-first-astrobee-robot-is-now-flying-around-the-iss-21581378/
  - Engadget: https://www.engadget.com/2019/06/23/nasa-astrobee-robot-flies-in-space/
  - HotHardware: https://hothardware.com/news/astrobee-firs-iss-flight
  - TechExplorist: https://www.techexplorist.com/bumble-became-first-astrobee-robot-fly-own-power-space/24287/
  - TechCrunch: https://techcrunch.com/2019/06/20/one-of-nasas-robotic-astronaut-helper-just-flew-on-its-own-in-space-for-the-first-time/
  - TechTheLead: https://techthelead.com/nasas-astrobee-robot-flies-in-space-for-the-first-time/
  - Space Daily: http://www.spacedaily.com/reports/NASAs_first_Astrobee_robot_Bumble_starts_flying_in_space_999.html
- **Astrobee also appears in:**
  - Space Station Research: Intersecting the Magical and the Technical: https://youtu.be/-L6AMwZDmhs
  - Singularity Hub: https://singularityhub.com/2019/06/04/a-closer-look-at-the-robots-helping-us-explore-space/

# EPO Summary Chart

## *Education and Public Outreach*

- On 10/18/18, we gave an Astrobee tour of the Granite Lab and Micro-Gravity Test Facility to the NATO Parliamentary Delegation. The group included representatives from Czech Republic, Denmark, Estonia, France, Germany, Greece, Iceland, Latvia, Lithuania, Luxembourg, Netherlands, Poland, Portugal, Spain, Turkey, UK, and US.
- On 10/29/18, we gave an Astrobee tour of the Granite Lab to a group of 6th to 8th grade girls from the Menlo School in Atherton, CA, including several members of their FIRST robotics team.
- On 02/20/19, Astrobee made the JSC Roundup front page with a write up entitled “Four Things to Know About Astrobee” with images from acoustic testing.
  - https://roundupreads.jsc.nasa.gov/pages.ashx/1078/Four%20Things%20to%20Know%20About%20Astrobee
- Astrobee appeared on NASA Twitter and Facebook
  - https://twitter.com/NASA/status/1113260606973460481?ref_src=twsrc%5Egoogle%7Ctwcamp%5Eserp%7Ctwgr%5Etweet
- On 5/10/2019, Lorenzo Fluckiger and Brian Coltin gave a guest lecture, “Astrobee Robot Software and Astrobee Localization,” to the Robotic Multibody Systems class at the Naval Postgraduate School.

# EPO Summary Chart

## *Education and Public Outreach*

- On 5/17/2019, we gave an Astrobee demo to Associate Administrator James Reuter.
- On 07/22/2019, the quarterly SPHERES/Astrobee Working Group meeting took place at Kennedy Space Center. The SPHERES and Astrobee teams presented project status and we heard from many of the upcoming Astrobee Guest Scientists.
- Astrobee (B♯) and the Granite Lab provided the background for filming of Ames Center Director Eugene Tu's segment of the "We Go as the Artemis Generation" video. (Don't blink, it's only a couple of seconds.)
  - https://www.youtube.com/watch?v=dOKKkV-30dE
- ISS Twitter post about Bumble:
  - https://twitter.com/ISS_Research/status/1150862218302349312
- Bumble is in a Space Station image feature dated July 19, 2019:
  - https://www.nasa.gov/image-feature/flight-engineer-christina-koch-monitors-astrobee
- Lead Mechanical Engineer Earl Daley did an interview with The American Society of Mechanical Engineers (ASME) magazine on 8/14/2019.

# EPO Summary Chart

- Conferences attended

| Conference Name | Papers/Posters/Panel Discussions |
|---|---|
| ROSCon (Robot Operating System Conference) 2018 | “Astrobee: ROS-based Flight Software for a Free-flying Robot in Microgravity,” Oral presentation, Andrew Symington. |
| 2018 IEEE/RSJ International Conference on Intelligent Robots and Systems | “HTC Vive: Analysis and Accuracy Improvement,” Miguel Borges, Andrew Symington, Brian Coltin, Trey Smith, Rodrigo Ventura. |
| 69th International Astronautical Congress (IAC), 2018 | “Astrobee: Current Status and Future Use as an International Research Platform,” Andres Mora Vargas. |
| IEEE/SICE International Symposium on System Integration 2019 | "Thermal design of Astrobee perching arm,” In Won Park, Trey Smith, and John Love. |
| ISS R&D Conference 2019 | “Astrobee: A Stepping Stone to Caretaking Intra-Vehicular Robots ,” Trey Smith, Jonathan Barlow, Jose Benavides, Maria Bualat, Aric Katterhagen, Ernest Smith, and the Astrobee Team. |
| ISS R&D Conference 2019 | “Astrobee, the Future of Free Flyer Science on the ISS,” Aric Katterhagen, Jose Benavides, Jonathan Barlow, Andres Mora Vargas. |

# EPO Summary Chart

- Academic involvement – Students

| # of Students | Education Level | School Name |
|---|---|---|
| 1 | Graduate | Oregon State University |
| 1 | Graduate | MIT |
| 2 | Graduate | Stanford University |
| 1 | Graduate | École Polytechnique Fédérale de Lausanne, Switzerland |
| 1 | Graduate | Instituto Superior Técnico, Portugal |

# EPO Summary Chart

➢Academic involvement:  Other

- **ECF 2016 – Effective Human-Robot Interaction for Space Exploration**
  - Sonia Chernova, GA Tech – adjustable autonomy and learning
  - Dan Szafir, UC Boulder – human-free-flying robot collaboration methods

- **ESI 2015 – Payload Technologies for Assistive Free-Flyers**
  - Matei Ciocarlie, Columbia – compact, lightweight versatile manipulator
  - Mark Cutkosky, Stanford – gecko inspired adhesive appendages
  - Matt Spenko, IIT – electrostatic microstructured adhesive

Note: STRG provided a 1 year extension to Stanford in order to test a “Gecko Gripper” with Astrobee on ISS in 2020.

# Astrobee
# Vision-based navigation (FFREQ-42)

**Risk ID #**
1

**Trend**

**Criticality**
Closed

**Current L/C**
1x3

**Affinity Group**
Technical

**Planned Closure**
8/24/2019

**Open Date**
10/1/2014

**Risk Statement :**

**Approach**: Mitigate

Given that a solution for vision-based navigation (VBN) in a free-flying robot has limited resources (size, power, computation), there is a possibility that pose estimation will not meet the required accuracy, resulting in poor performance for some 0g robotics research tasks.

**Context**

VBN is likely to provide sufficient resolution for general navigation. AR targets will be used for docking. Additional targets may be needed in a small area to provide accurate pose estimations for 0g robotics research.

**Status**

9/2019. On-orbit testing has shown that, with a map of sufficient quality, VBN works correctly.

CLOSED

| Mitigation Steps | Dollars to implement | Trigger/ Start date | Schedule UID | Completion Date | Resulting L/C |
|---|---|---|---|---|---|
| P2 testing with AR tracking. | | 2/5/15 | | 2/15/15 | 3x5 |
| P3 testing | | 7/1/15 | | 9/1/15 | 3x3 |
| P4 requirements development | | 9/15/15 | | 12/15/15 | 3x3 |
| P4 testing | | 2/12/16 | | 8/5/17 | 2x3 |
| Cert Unit testing | | 12/1/16 | | 4/30/2019 | 1x2 |

# Astrobee
# Avionics and fan noise (FFREQ-47)

**Risk ID #**
2

**Trend**

**Criticality**
Closed

**Current L/C**
2x2

**Affinity Group**
Technical

**Planned Closure**
4/30/2019

**Open Date**
10/1/2014

**Risk Statement :**

**Approach**: Mitigate

Given that avionics and fans make noise, there is a possibility that the desired Astrobee design will not meet ISS safety standards, resulting in either it not being certified for operations on ISS, or a fan design with low noise but inferior performance will be used.

**Context**

The ISS has limitations on the amount of noise caused by a payload, both continuously and intermittently. The Astrobee team will need to find/design high performance fans that fall within the noise limits.

**Status**

9/2019. Acoustic exception Astrobee-Exception-0003 is approved. Astrobee is allowed to operated 8 hours per day.

CLOSED

| Mitigation Steps | Dollars to implement | Trigger/ Start date | Schedule UID | Completion Date | Resulting L/C |
|---|---|---|---|---|---|
| Requirements review with ISS Acoustics group | | 1/21/15 | | 2/4/15 | 3x4 |
| Propulsion subsystem testing. | | 3/1/15 | | 7/30/15 | 3x3 |
| Test fans in flight-like configuration | | 2/15/16 | | 6/1/17 | 2x2 |
| Requirement exceptions approved | | 2/25/17 | | 4/30/19 | 1x1 |

# Astrobee
# Cert/Flight Unit schedule (FFREQ-46)

**Risk ID #**
5

**Trend**

**Criticality**
**Closed**

**Current L/C**
3x3

**Affinity Group**
Schedule

**Planned Closure**
4/30/2019

**Open Date**
10/1/2014

**Risk Statement :**

**Approach**: Watch

Given the serial Prototyping and Flight development efforts, there is a possibility that the flight unit delivery will be delayed. Any delay in delivery will reduce the time available to perform on-orbit commissioning work in FY19.

**Context**

The Astrobee development approach uses iterative prototyping to refine requirements, mature design, and reduce risk, thus the efforts are in series.

**Status**

9/2019. The perching arms and 3rd free flyer launched on SpX-18. All exceptions have been approved.

CLOSED

| Mitigation Steps | Dollars to implement | Trigger/ Start date | Schedule UID | Completion Date | Resulting L/C |
|---|---|---|---|---|---|
| Baseline schedule with optimized distribution of reserve and slack for PTR 1. | | 2/20/15 | | 2/25/15 | 4x5 |
| Release reserve in P4. | | | | 3/1/16 | 4x5 |
| Approve new baseline CR. | | | | 4/15/18 | 3x4 |
| Release reserve in Cert Unit. | | 3/1/18 | | 5/15/18 | 3x4 |
| Release reserve in Flight Units. | | 12/15/18 | | 1/31/19 | 2x4 |
| Exceptions for on-orbit operations approved. | | | | 4/30/19 | 1x1 |

# Astrobee
# Design changes (FFREQ-1522)

**Risk ID #**
15

**Trend**

**Criticality**
Closed

**Current L/C**
2x3

**Affinity Group**
Technical

**Planned Closure**
4/30/2019

**Open Date**
8/1/2016

**Risk Statement :**

**Approach**: Mitigate

Given the sum of all the new design and design changes that resulted from P4C tests, PSRP 2 and PTR 3, there is a possibility that the design will not close if we go straight to the Cert Unit.

**Context**

No single design change is very high risk. However, the sum of the changes is high enough risk that we are not ready to commit to the Flight design until it has been tested.

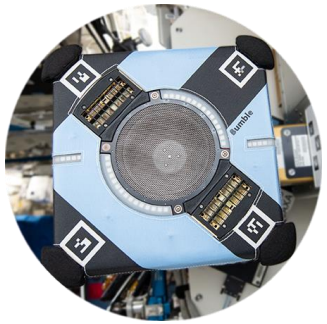
**Status**

9/2019. All exceptions are approved, Astrobee approved for operations on-orbit.

CLOSED

| Mitigation Steps | Dollars to implement | Trigger/ Start date | Schedule UID | Completion Date | Resulting L/C |
|---|---|---|---|---|---|
| Develop prototyping plan; determine which design components need mitigation | | 8/1/16 | | 9/15/16 | 4x4 |
| Finalize design changes | | 8/1/16 | | 11/7/16 | 3x4 |
| Complete prototype testing | | 11/7/16 | | 5/15/17 | 2x4 |
| Exceptions for on-orbit operations approved. | | | | 4/30/19 | 1x1 |

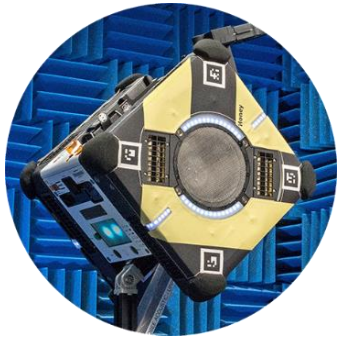
# Astrobee



Caption: Astrobee free flyer, Bumble, placed on the docking station on ISS for the first time on April 30, 2019.

Caption: Astrobee Flight Software Lead, Lorenzo Fluckiger, operates Astrobee on ISS from the Multi-Mission Operations Center at Ames Research Center.

Caption: "Family photo" of 3 flight Astrobees in the SPHERES/Astrobee Integration Lab at Ames Research Center prior to launch delivery.



Caption: Astrobee free flyer, Bumble, underwent testing in the Acoustics Lab at Johnson Space Center on January 29, 2019.

Caption: Astrobee free flyer, Bumble, placed on the docking station on ISS for the first time on April 30, 2019.

Caption: NASA Astronaut, Anne McClain, unpacks Astrobee free flyer, Bumble, onboard the ISS on April 30, 2019