ISSRDC

Lessons Learned from Astrobee Operations on the International Space Station

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Technical Session Sponsor

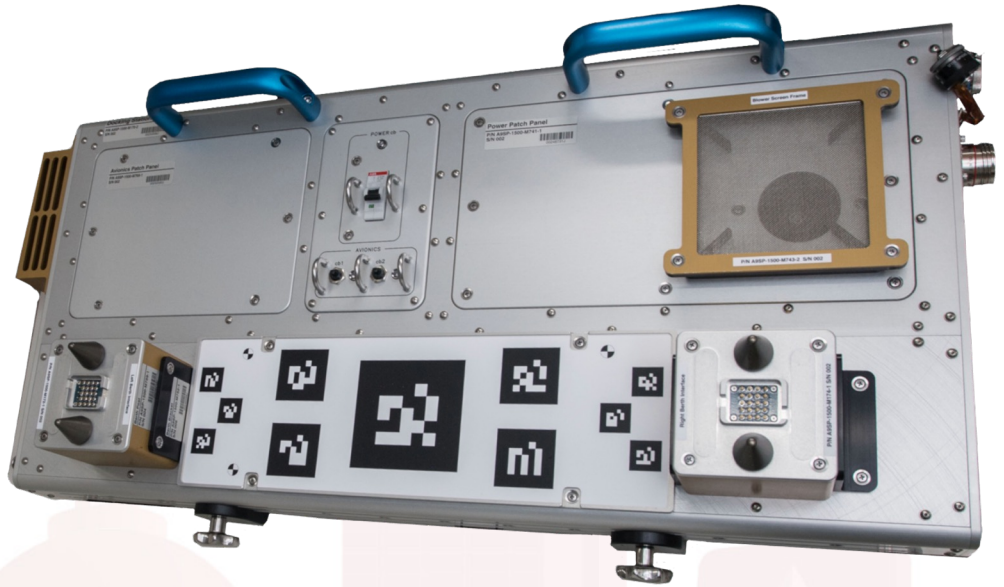
ISS Astrobee Facility Overview

ISS Astrobee Facility Systems: Bumble, Honey, Queen and Dock Station

Astrobee provides the capability to use the ISS environment to test user payloads from commercial, academia, ISS International Partners, NASA Mission Directorates, private industry, executing ISS research, and STEM activities.

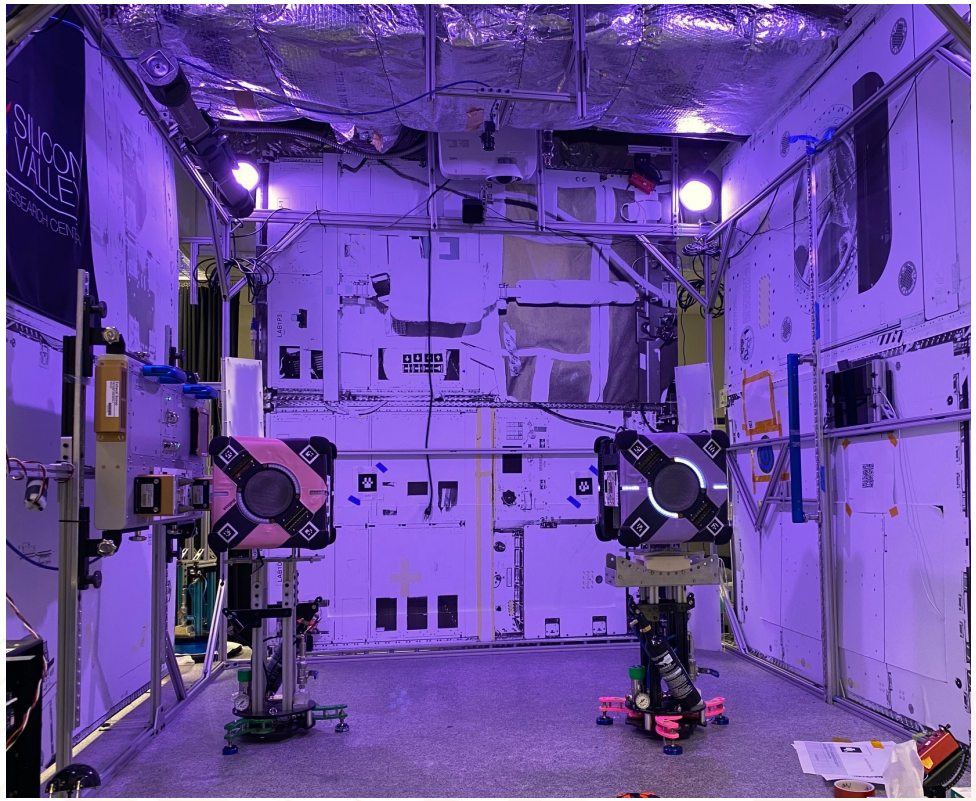
The Astrobee free-flying robotic system consists of cubed-shaped robots, software, a docking station used for recharging, and granite testing facility.

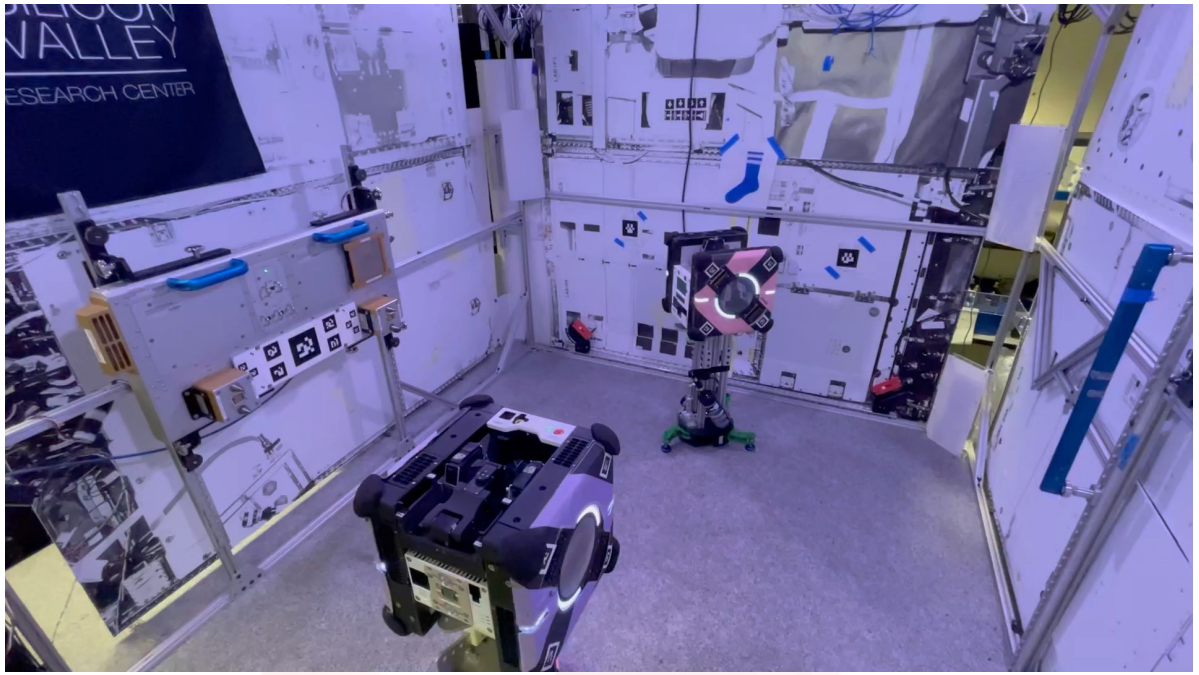
Astronaut Shane Kimbrough poses inside the ISS with all 3 Astrobees



Astrobee docking station

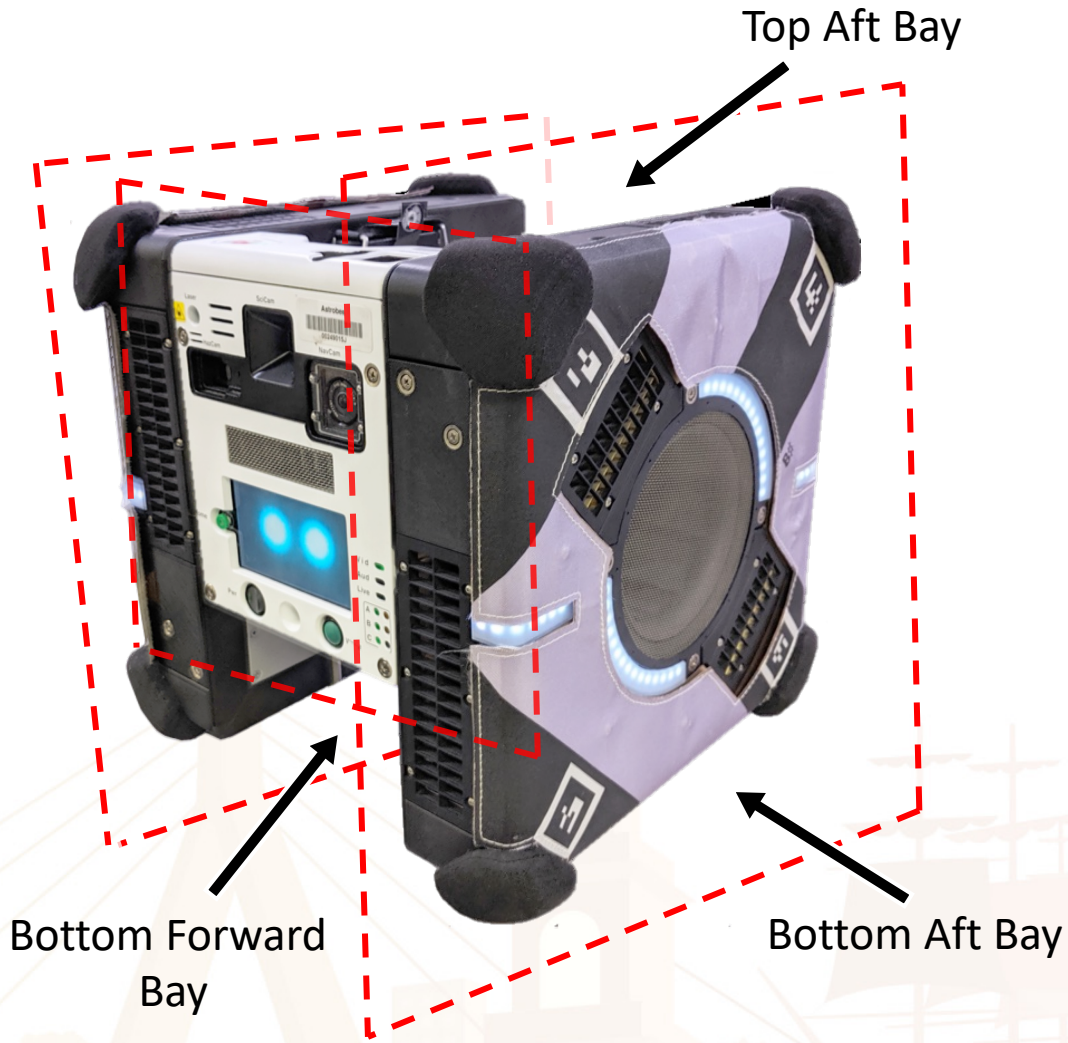
ISS Astrobee Facility Systems: Granite Lab, Bsharp and Wannabee





Ground units Bsharp and Wannabee in the Granite Testing Facility

Astrobee Free Flyer Modularity



Right and left propulsion modules – allow movement in any direction

Core module: containing three main internal processors (High-Level Processor – HLP, Mid-Level Processor – MLP, Low-Level Processor - LLP)

2 Free flying robots inside the ISS: Bumble and Honey (Queen down-massed)

All electric fan-based propulsion

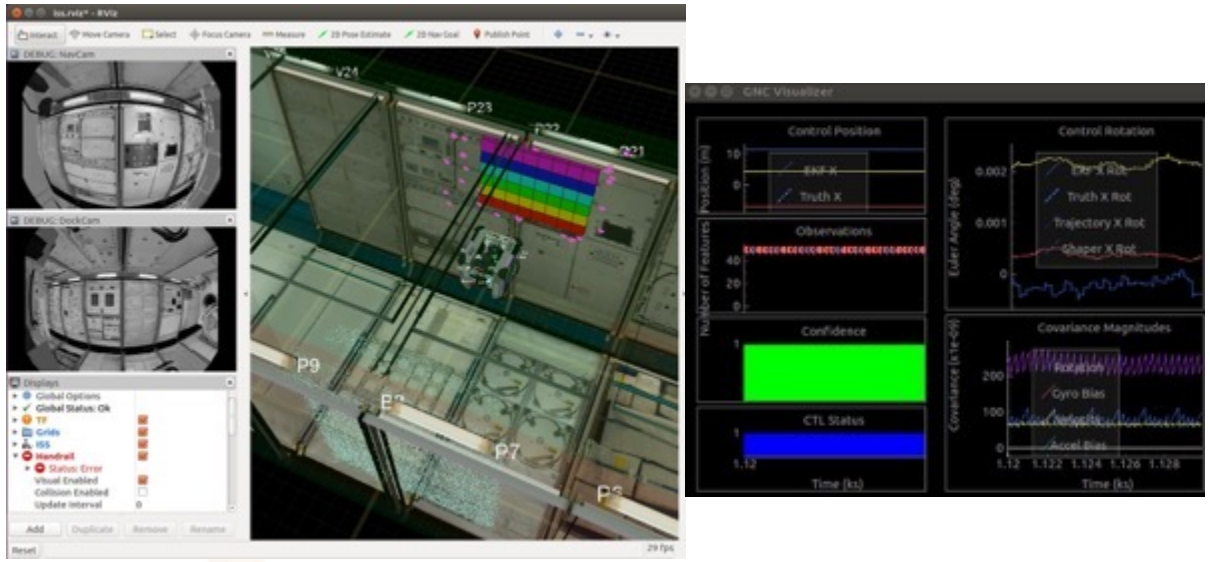
Three payload bays for expansion (top aft, bottom forward, bottom aft)

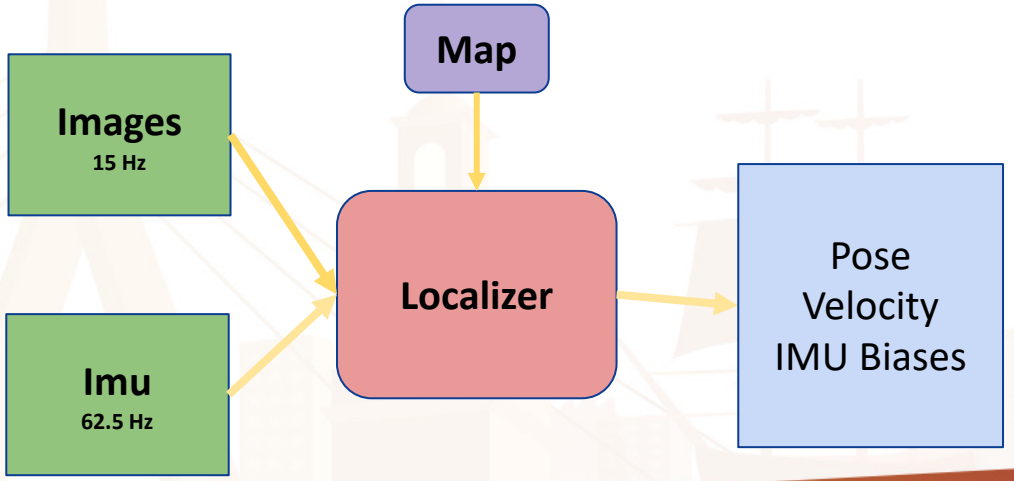
Over 175 on-orbit sessions completed. Logged over 1300hrs of Astrobee operations and made several capability improvements: navigation robustness, general flight software maturity, and ISS interior maps (Kibo, US lab, node 2)

More: www.nasa.gov/astrobee

Overview of anomalies: On-orbit and On-ground

1. On-Orbit Localization Anomaly





How Astrobee localization works:

- Uses pictures from Nav Cam
- Feature-based map matching, integrated with IMU data determine pose

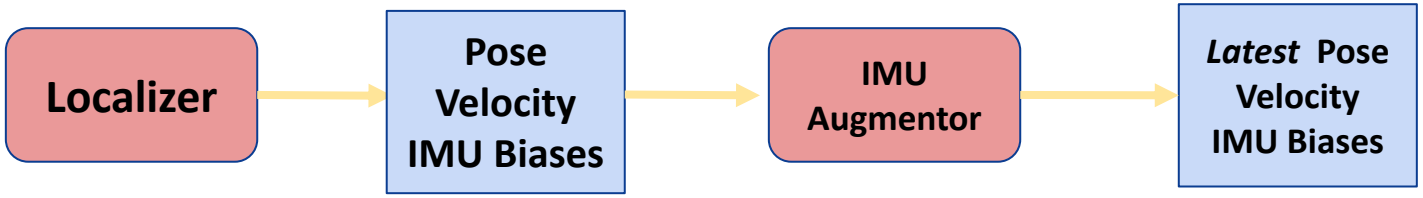
Anomaly:

- Localization performance was more sensitive to environmental factors than expected, causing the Astrobee to get lost frequently
- Lighting, cargo bags movements, new equipment cause errors in map matching, requiring frequent map updates

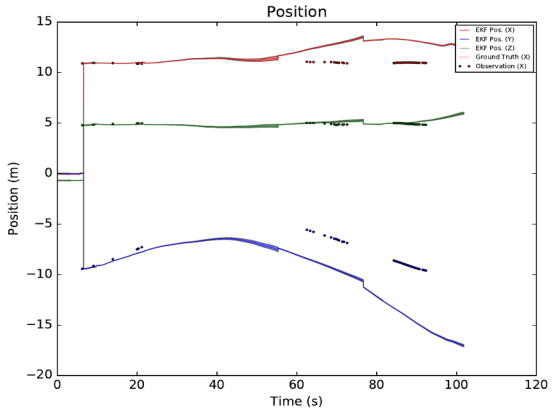
Corrective measures until fix:

- Performed ISS sessions only in areas of the JEM module where localization was known to be best, limiting the operation of Astrobee

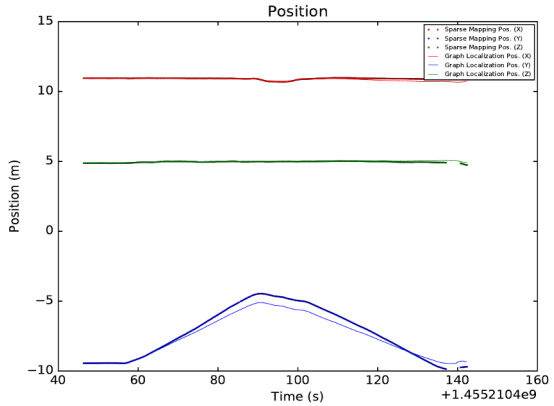
New Localization Architecture



EKF Visual Inertial Odometry (VIO) error

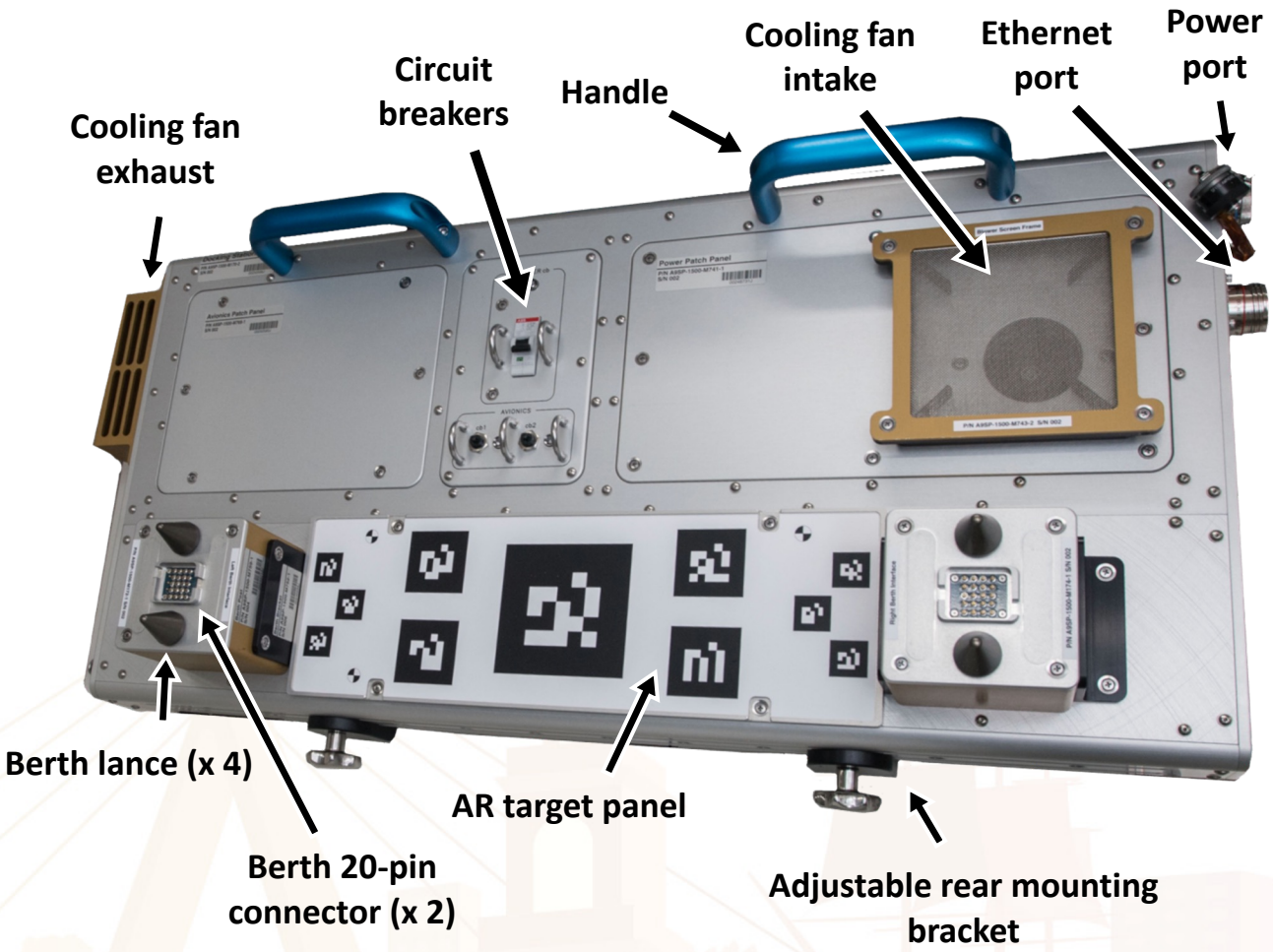


Graph Visual Inertial Odometry (VIO) error



- **Graph-based methods** are more computationally expensive, but optimize a history of poses and other estimates to improve accuracy
- New Localizer greatly improved pose, velocity, and IMU bias estimation accuracy while efficiently running in a limited computation environment, reducing the occurrences of lost localization and leading to more successful and longer duration activities

2. On-Orbit Dock Anomaly



Dock functional summary:

- Supports 2 ISS Free Flyers
- Provides power (24V @ 3A) to recharge Astrobee's portable batteries
- Provides Ethernet data to each docked Astrobee.

Anomaly:

- Anomaly 1 occurred in September 2019
- Anomaly 2 occurred in November 2021
- During ISS ops, attempt to communicate with the dock was unsuccessful
- Crew power cycled the dock with no change

Corrective measures until fix:

- Dock controller not affected, so Astrobee's batteries could recharge
- Used wifi connection to the Astrobees to see commands or receive telemetry/data

On-Orbit Dock Repair: SD Card Replacement

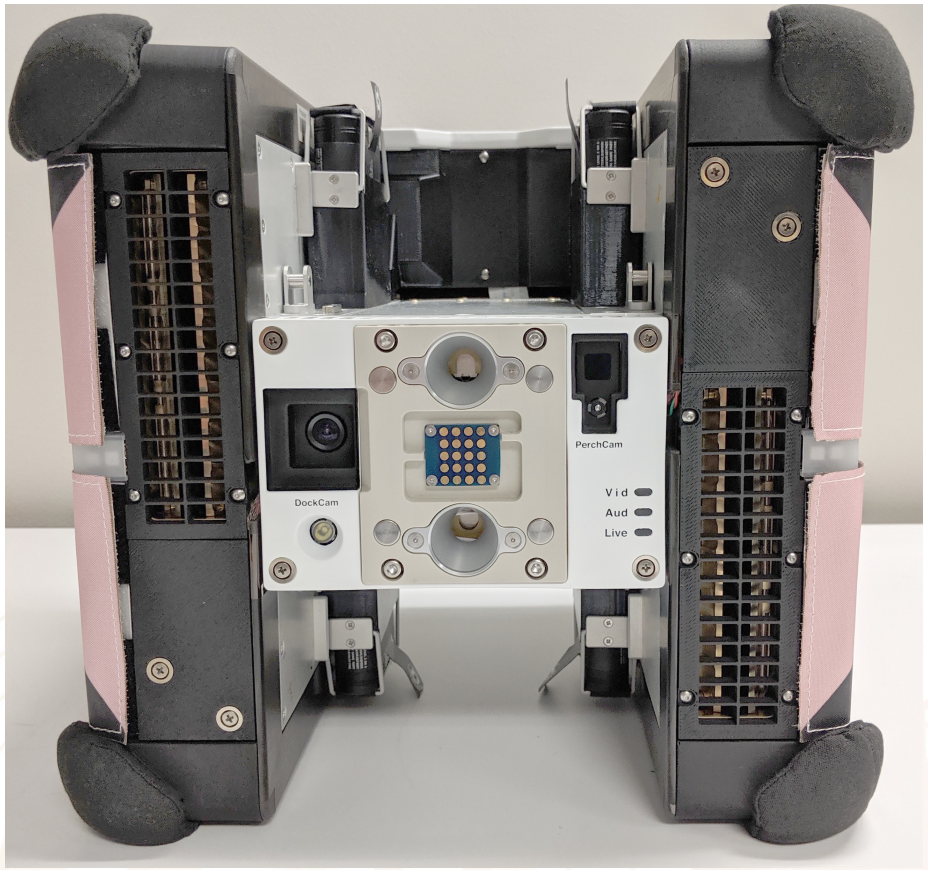
Astronaut Shannon Walker performs Dock repair in February 2021

Dock's avionics patch panel removed

Resolution:

On the second instance of on-orbit SD card repair (September 2023), new more robust industrial grade SD cards (Western Digital Industrial XI) were used.

3. On-orbit Astrobee Batteries Anomaly



Anomaly:

- After a few weeks of non-operations, Astrobee's batteries were found drained despite being connected to a powered docking station.
- Crew power cycled the dock with no change
- First observed in August 2019, but continued to occur multiple times since then

Corrective measures until fix:

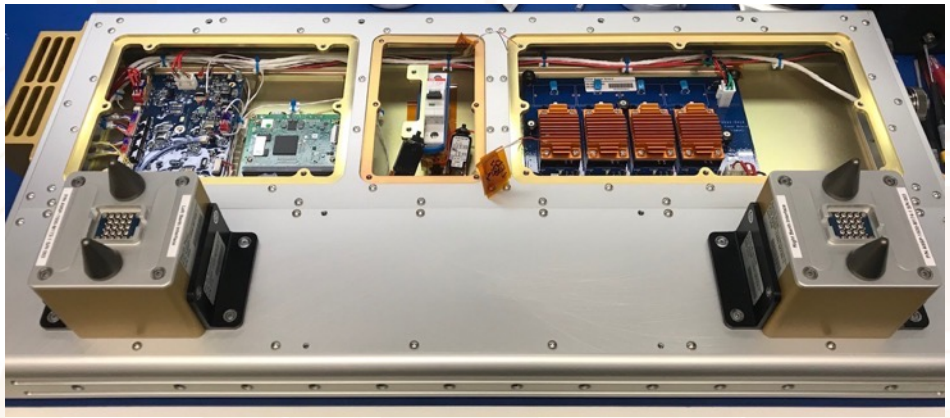
- Resolution involved swapping out Astrobee’s drained batteries with fresh, fully-charged ones
- Until cause of the issue was found, mitigation was to ask crew to turn off the Astrobee after each session and turn it on before the start of each session (using more crew time)

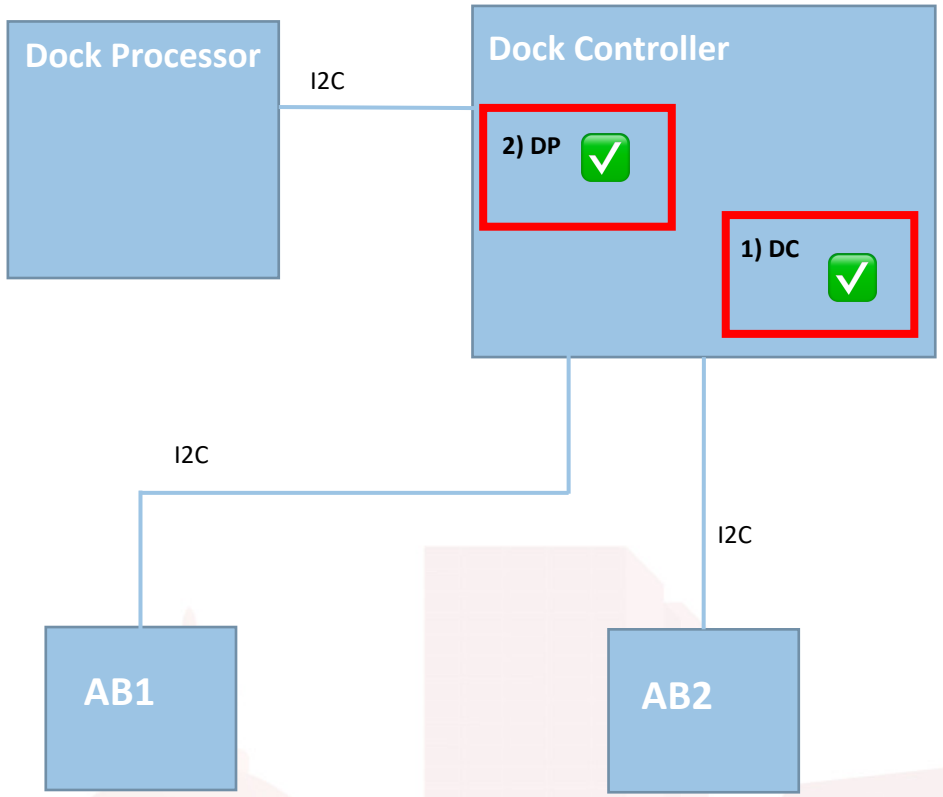
Resolving Batteries Drained Anomaly: Watchdogs

- Exact cause of the anomaly still unknown
- Most leading cause is possible misalignment of the Astrobee on the dock berth, causing the dock to stop charging Astobee's batteries

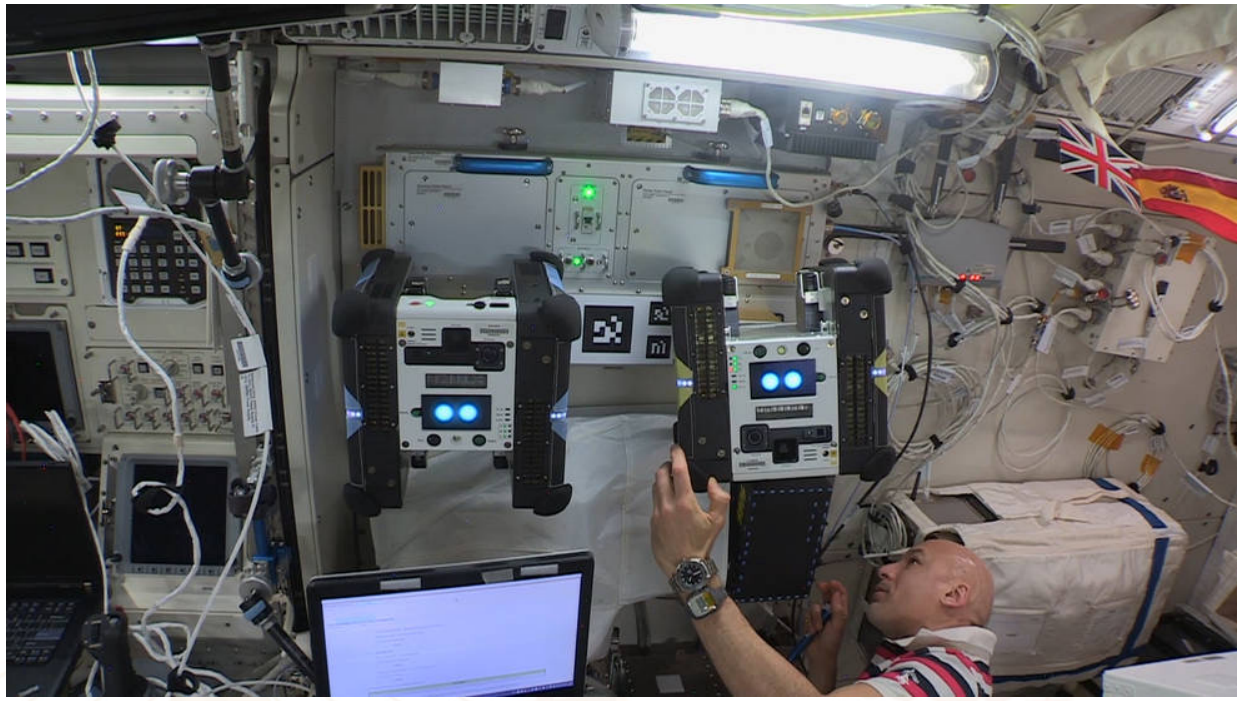
Resolution:

- Two watchdogs implemented on the dock processor and dock controller that will reset them if batteries stop charging
- Enhanced logging capability to monitor faults





4. On-Orbit Honey Anomaly



ESA Astronaut Paolo Nespoli performs Honey checkout in September 2019

Anomaly:

- Following power ON, Honey had an unexpected LED configuration
- That was an indication that one of Honey's processors had failed to properly boot up.
- Crew performed a power cycle of Honey and saw the same LED configuration.
- Occurred in August 2021

Corrective measures until fix:

- Ops proceeded using the 2nd Astrobee
- Following test sessions requiring 2 Astrobees had to be postponed
- Queen (3rd Astrobee) was checked out soon after, allowing the use of 2 Astrobees at the same time

On-Orbit Honey Anomaly: Down-Massed For Repair

September 20th, 2021, Megan McArthur
Unpacking Queen and packing Honey for down-mass

Resolution:

- Honey arrived at NASA Ames for repair and testing in early 2022
- SD Card failure confirmed on the ground
- New more robust industrial grade SD cards were used
  - Western Digital Industrial XI
  - S/N: SDSDQED-064G-XI
  - https://www.mouser.com/ProductDetail/SanDisk/SDSDQED-064G-XI?qs=gZXFycFWdAPuTpJ2z5SQUA%3D%3D
- Cleanliness evaluated
  - Some maintenance for on-orbit units recommended (e.g., using vacuum cleaner for dust accumulation)
- Honey was returned to the ISS and checked out in August 2023

5. On-Orbit Queen Anomaly

Anomaly:

- During one of the ISS OPS, we lost telemetry with Queen despite being ON and docked.
- After crew powered cycle Queen, it was working nominally, but its was not able to recharge its batteries through the dock.
- Occurred in June 2023

Resolution:

- Queen was down-massed in early 2024
- A short circuit with one of the connectors on the LLP board seemed to be the issue for the dock not charging the batteries
- Faulty LLP board has been replaced
- New SD cards also replaced

6. Anomaly On Ground Unit Wannabee

Wannabee ground unit is identical in HW/SW to the flight units on the ISS

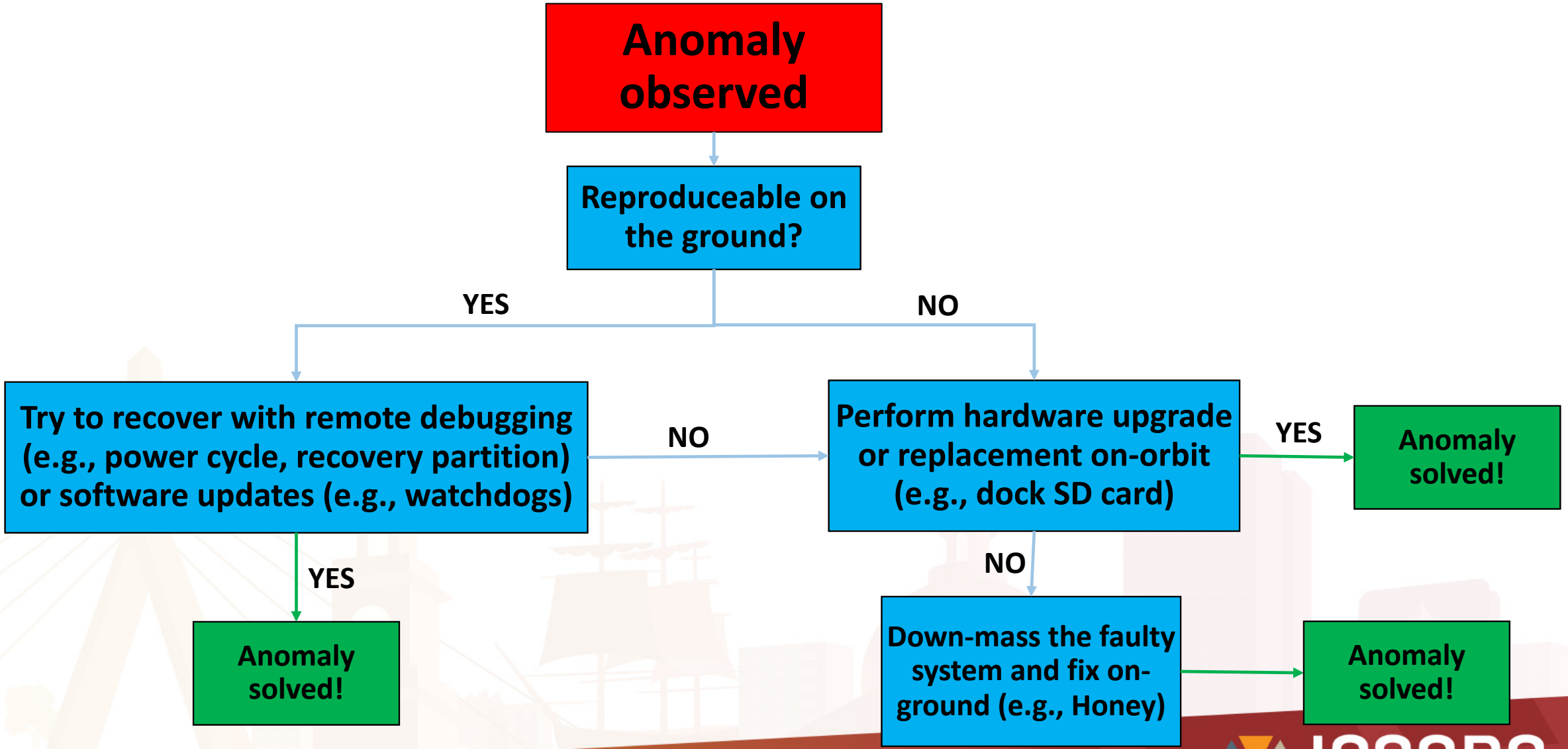
Anomaly:

- SSH connection refused on the MLP
- SD Card failure on MLP

Resolution:

- Using the Payload Serial-USB Debug cable allowed us to log into the MLP and use the system utility fsck to repair the corrupted sectors.

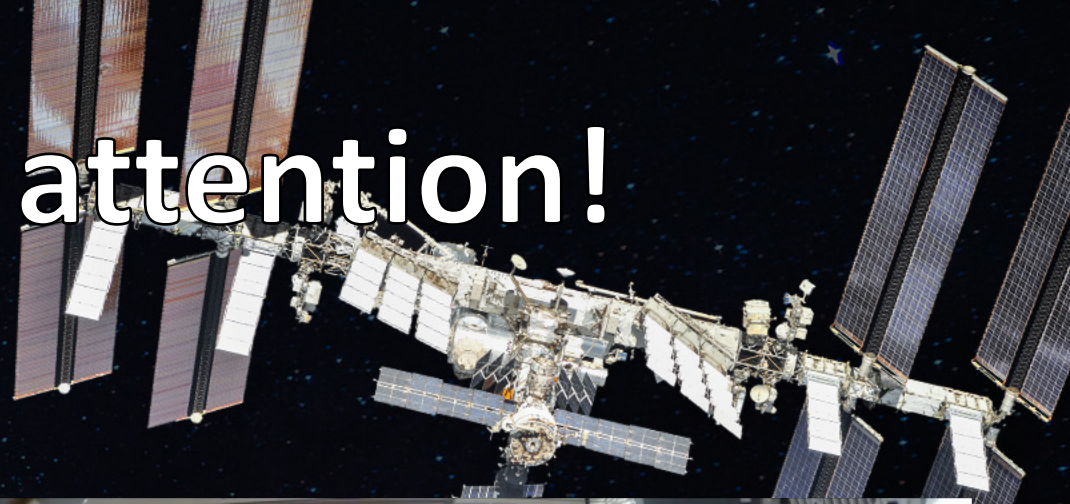
Steps To Resolve Anomalies



Conclusions

- Overview of the different faults and anomalies occurred on the Astrobee systems on-orbit and on-ground.
- Processes and procedures worked to resolve such anomalies.
- SD cards very common point of failure.
- New industrial-grade SD cards (Western Digital Industrial XI) were used to replace the old, more sensitive ones
- Implementation of software updates and hardware upgrades can reduce the risk on returning anomalies.
- Lessons learned in increasing Astrobee's robustness and resilience to future anomalies.

Thank you for the attention!



Fun with Robots

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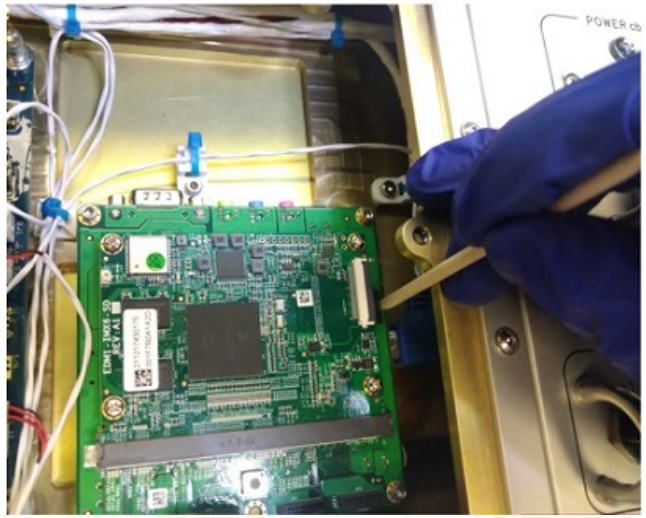
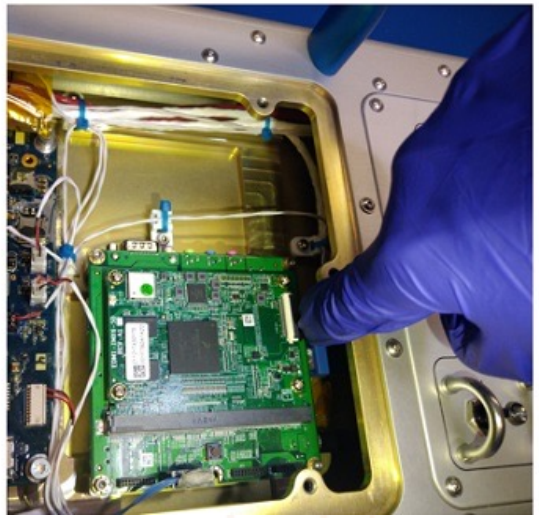
Back-up slides

Procedure performed for Dock repair





- Two different ways for unlocking the Dock Memory Card: With a tool (left) and without a tool (right).
- Included three alternative ways for accessing and replacing the Dock Memory Card located on the Dock Processor Board, due to uncertainty of actual location of the SD card

Lessons learned

- SD card technology [1]:
  - SLC (Single Level Cell) - highest grade, highly reliable but expensive
  - aMLC – rare, between SLC and MLC
  - MLC (Multi-Level Cell) - most common grade, cheaper, but lower speed, reliability and durability
  - TLC (Triple Level Cell) - lowest grade, should not be used in any applications running operating systems or storing critical data.
- Paper sent by Andrew Chu [4] compares SLC vs MLC. SLC is the clear winner
- SD card designations:
  - Industrial: Wider temperature range, SLC
  - Extreme: Faster speeds, seems [3] like a mix between SLC and MLC

Options Considered

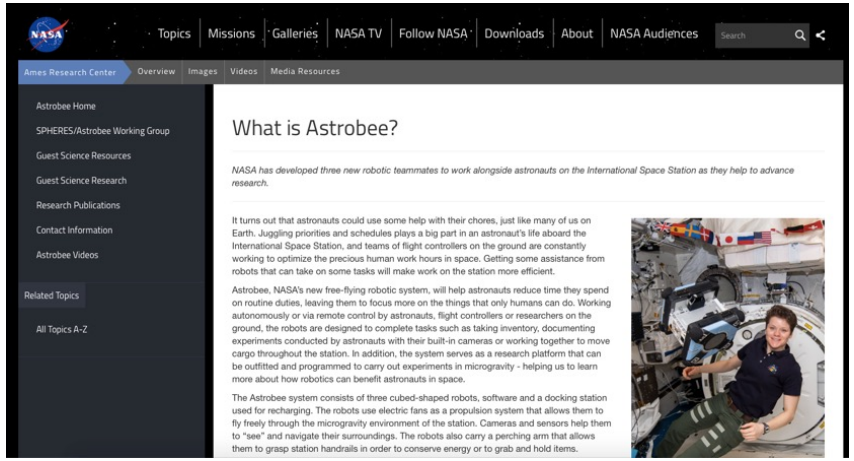
#	Source	Manuf acturer	Format	Capacity	Designation	Url
1	Craig Pires	Apacer	microSD	4GB	Industrial	https://www.mouser.com/ProductDetail/Apacer/AP-MSD04GIHI-T?qs=2W5sgKM%2F370uC%252BBoRQgmZQ%3D%3D
~~2*~~	~~Craig Pires~~	~~Xiphos~~	-	-	~~None~~	~~https://xiphos.com/products/~~
3	Andrew Chu	Delkin	SD	8GB	None, Class 6	https://www.newark.com/delkin-devices/se08tfphl-c6000-d/memory-card-sdhc-class-6-slc-8gb/dp/37AC8557
4	Andrew Chu	Transcend	SD	8GB	Industrial, Class 10	https://harddiskdirect.com/ts8gsdhc100i-transcend-flash-memory.html
5	Astrobee	SanDisk	microSD	64GB	Extreme Plus	https://www.amazon.com/SanDisk-SDSQXSG-064G-GN6MA-Extreme-microSDXC-Adapter/dp/B089WK3C6R
6	Search	SanDisk	microSD	32GB	Industrial	https://www.mouser.com/ProductDetail/SanDisk/SDSDQAF3-032G-XI?qs=F5EMLAvA7IDuINqXQWsrSg%3D%3D&mgh=1&gclid=CjwKCAiAl-6PBhBCEiwAc2GOVCdEPW8EBZKDvoYHVJR6yX3y4Zgyq0GtUv3Laba3-w2EH6sVi1AuWRoCVGcQAvD_BwE
7	Search	SanDisk	microSD	64GB	Industrial XI	https://www.mouser.com/ProductDetail/SanDisk/SDSDQED-064G-XI?qs=gZXFycFWdAPuTpJ2z5SQUA%3D%3D

*Not an actual SD card, they make processor boards, mention SanDisk card in paper

Evaluation Criteria (1-low, 4-high)

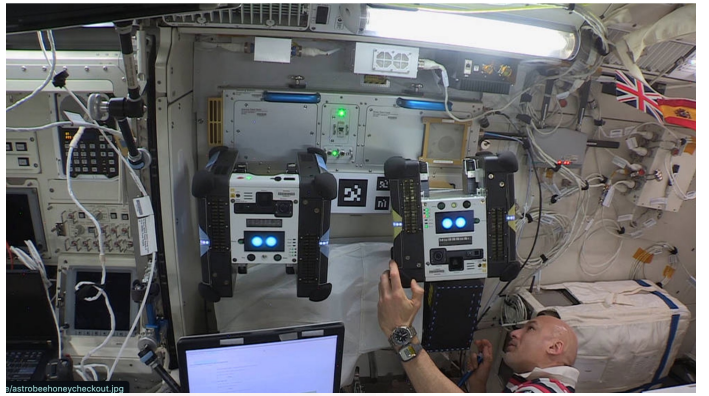
#	Capacity	Reliability
1	1	4
3	2	4
4	2	4
5	4	3
6	3	4
7	4	4

Web Features



www.nasa.gov/Astrobee

Hi Honey! NASA's Second Astrobee Wakes Up in Space



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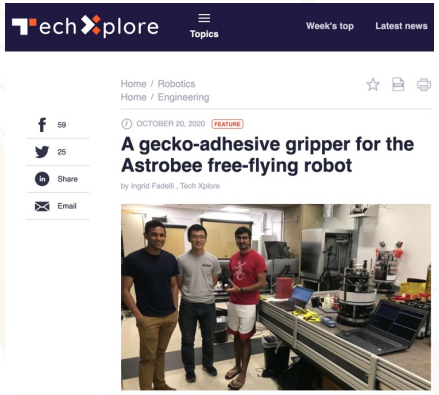
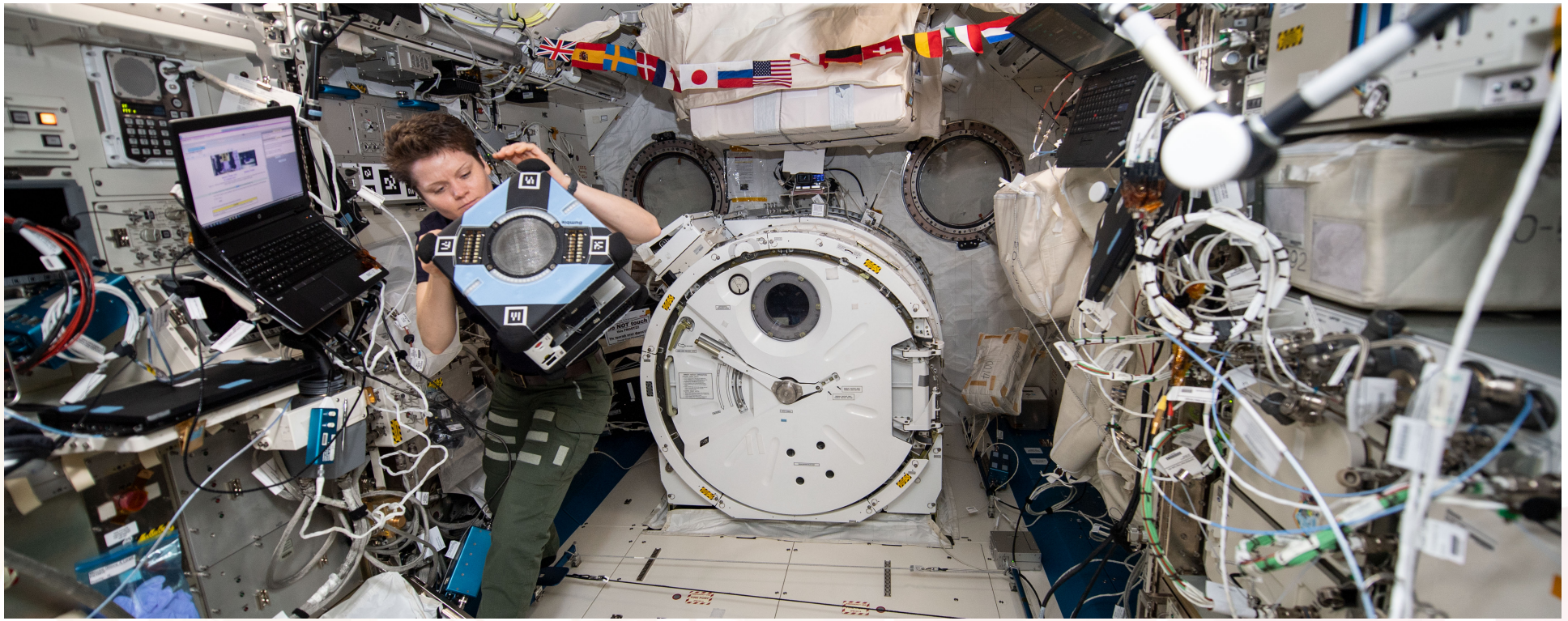
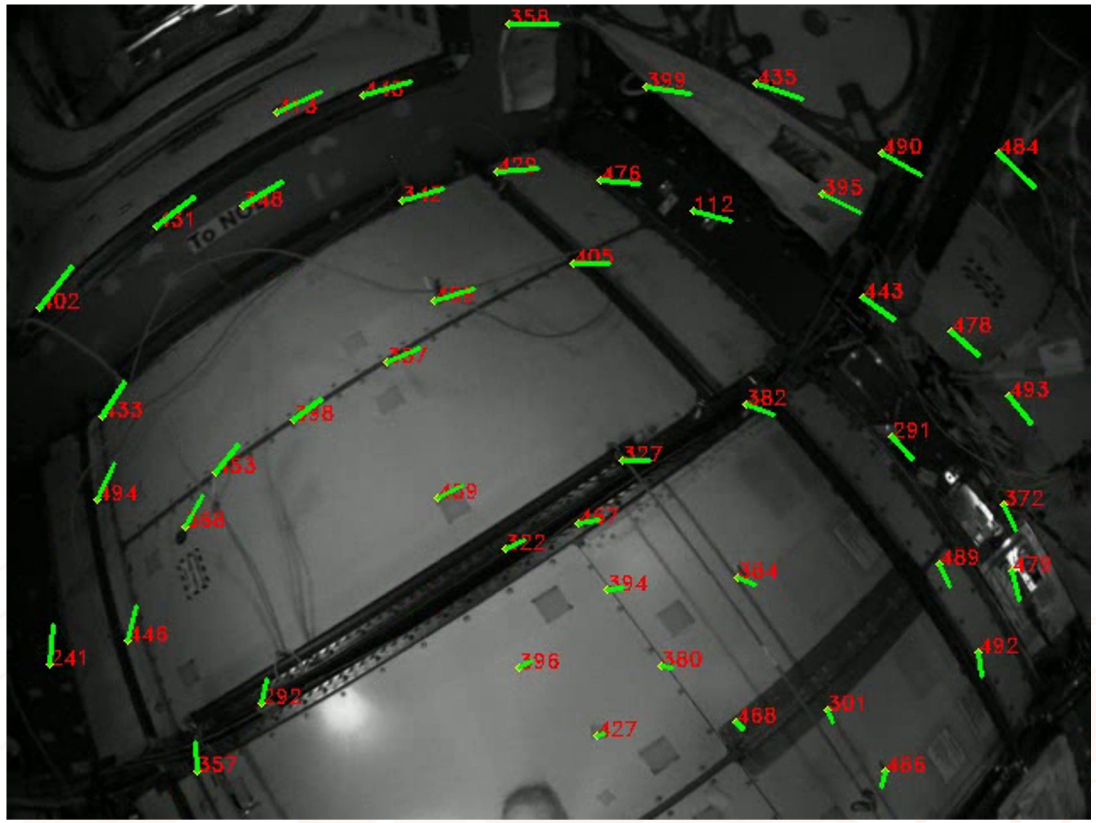


A gecko-adhesive gripper for the Astrobee free-flying robot

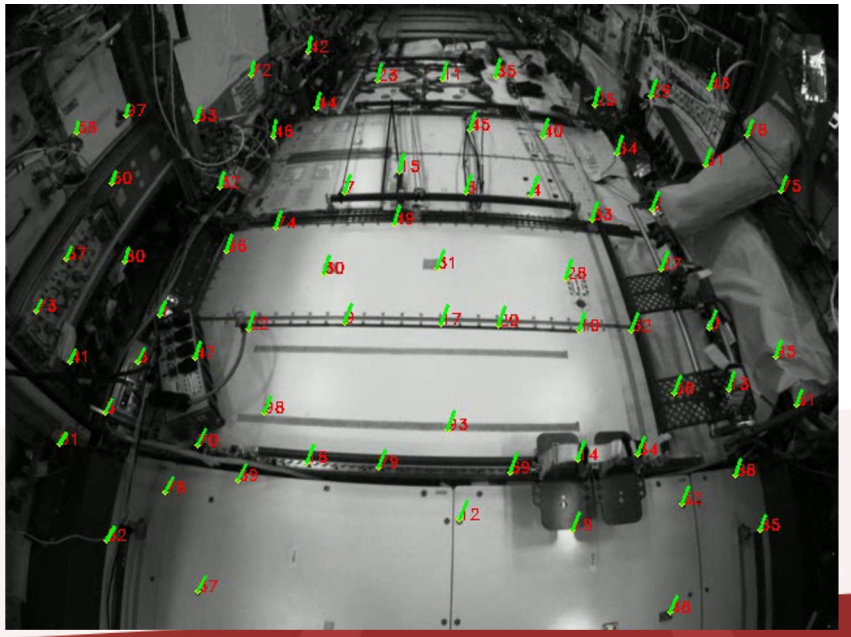
www.nasa.gov/astrobee



Optical Flow Features

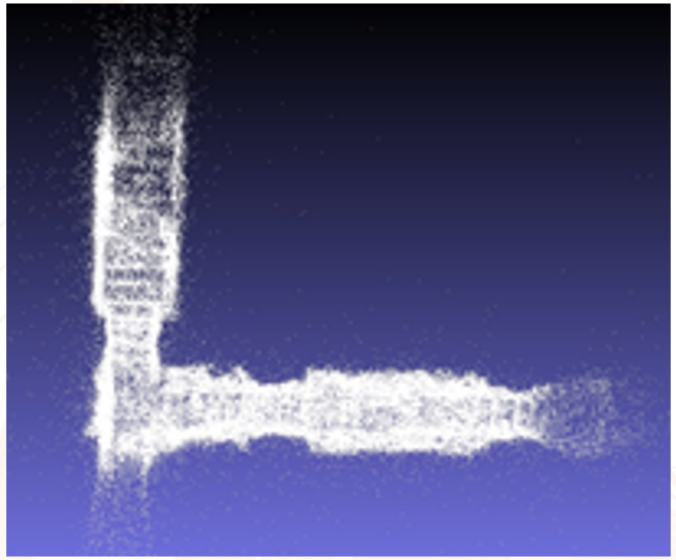


- Independent of map
- Ids and tracks local features
- Used for visual odometry

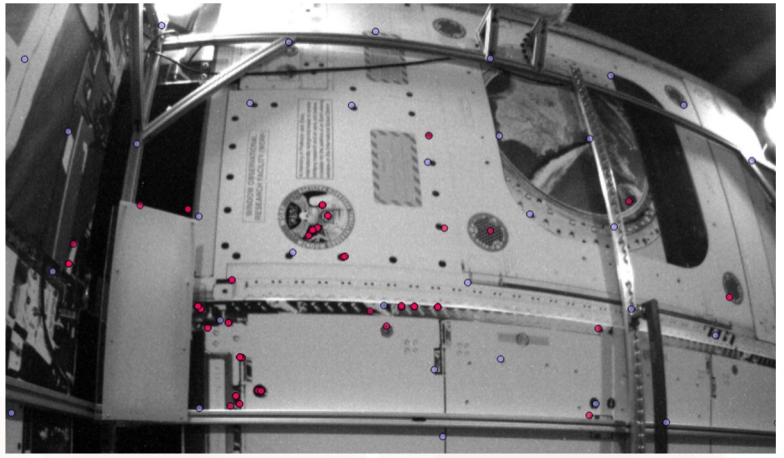


Brisk Map Features

- Build map before localizing with labeled features
  - Use feature descriptors that are uniquely identifiable based on attributes, unlike optical flow features which are locally matched
- Match incoming images during localization with labeled images from mapping to get global pose estimates of robot



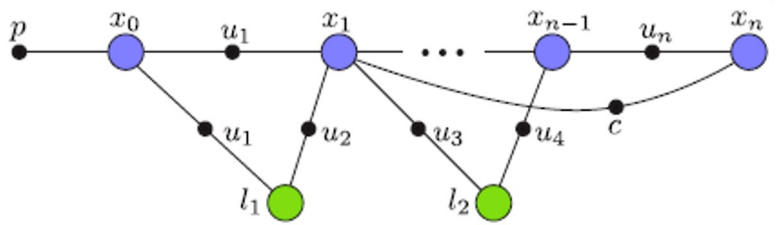
Map Coverage

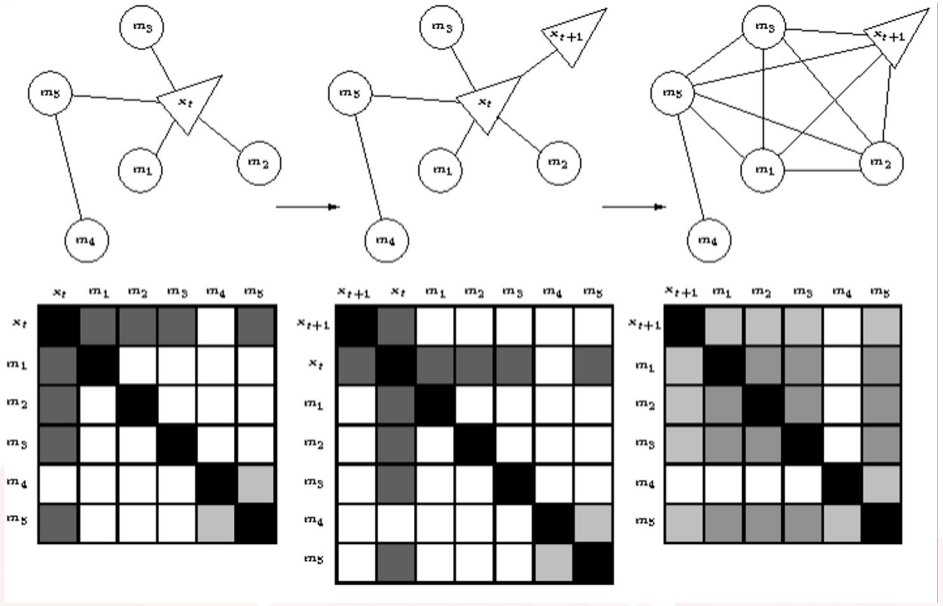


Map features detected in image

Solution: More Accurate Localization Estimate Using Graph-based Methods

- Graph-based methods have become quite popular over the last couple of years and graph-based solvers have become efficient enough to run as live localizers
  - Use open-sourced gtsam library
- Graphs are **more computationally expensive,** but do multiple iterations of optimization to **more accurately** calculate localization estimate
  - EKF can be thought of as doing a single iteration which is faster and more efficient but more error prone
  - Graph optimizes a history of poses and other estimates to improve accuracy





Walter, Matthew R. et al. “A Provably Consistent Method for Imposing Sparsity in Feature-Based SLAM Information Filters.”