

National Aeronautics and Space Administration

Space Technology Mission Directorate

Game Changing Development Program

Trey Smith | Maria Bualat | FY23 ISAAC Annual Review Presentation | 09.22.23

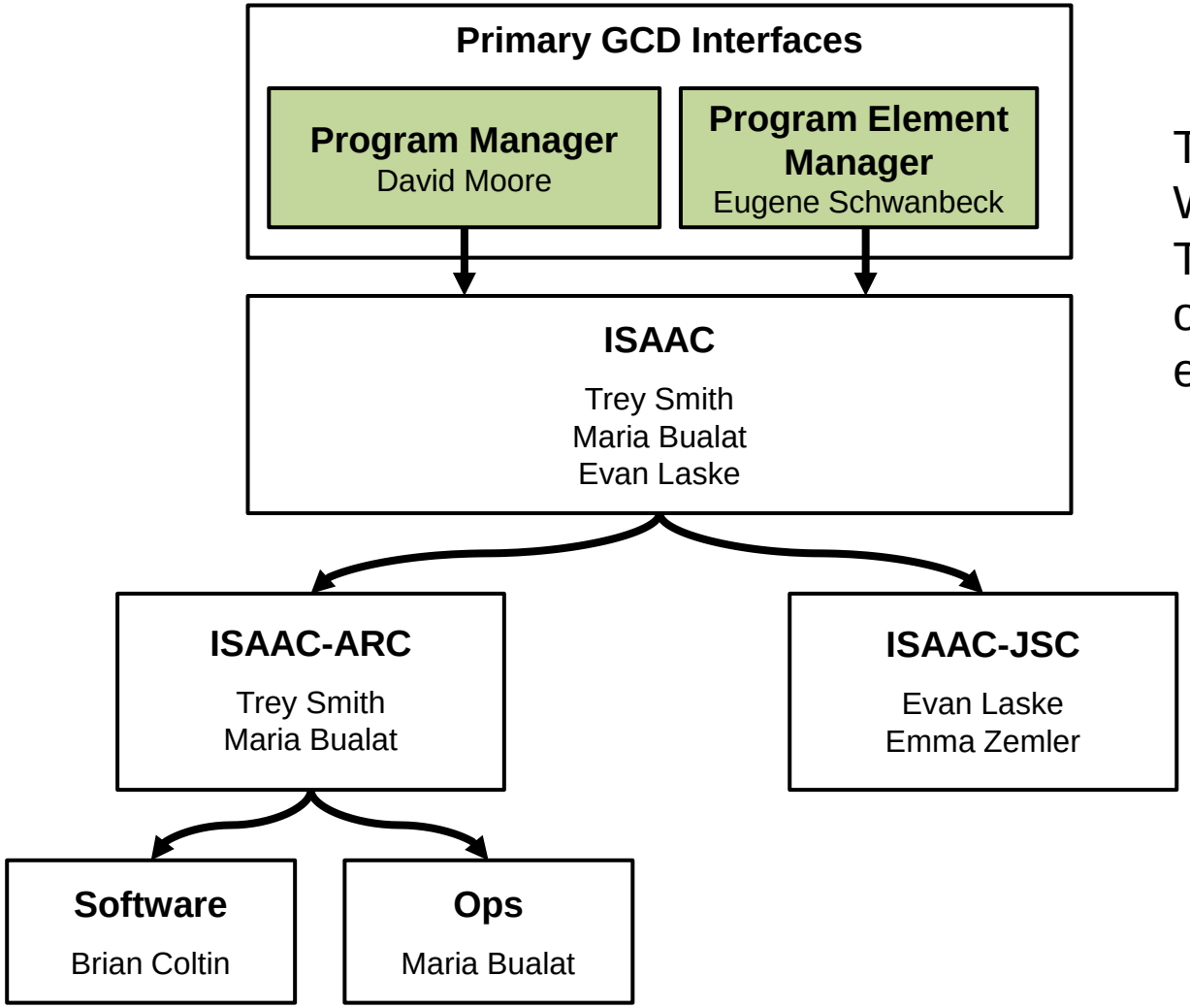
POC: Trey Smith <trey.smith@nasa.gov>

Project Overview

Technology Goals	
Goal #1	Develop/enhance key technologies for the autonomous operation of complex, space-based infrastructure (e.g., Gateway) that provide the capability to support operations where human intervention is limited.
Goal #2	Provide new capabilities for spacecraft that incorporate both autonomy and robotics to enable a new paradigm for in-space operations and adaptive vehicle caretaking.

Project Objectives	
Objective #1 **Integrated data**	Current state of the art in human spaceflight systems is that data from sensors associated with different spacecraft subsystems (Structures, GN&C, and ECLSS, etc.) remain siloed. ISAAC will unify spacecraft data and models with autonomous robotics, linking data streams from spacecraft subsystems, sensor networks, and robots, as well as linking 3D geometry and sensor data map layers, and detecting changes and anomalies. ISAAC will test autonomous state assessment with a mobile inspection robot, ideally on ISS.
Objective #2 **Integrated control interface**	Current state of the art manages spacecraft with largely independent interface tools for different subsystems. Interfaces have different heritage, design assumptions and operator interface styles. Subsystem interactions are hard to analyze due to poor connectivity between separate tools. ISAAC will develop an integrated control interface that combines interface tools for spacecraft subsystems and autonomous robots; improves system-level situation awareness, situation understanding, and operator productivity; enables linking and embedding between tools to improve subsystem interaction analysis; and supports the entire activity life cycle from planning through execution and analysis. ISAAC will test logistics management with mobile inspection and mobile manipulation capabilities, and test operator productivity in a logistics management scenario, both ideally on ISS.
Objective #3 **Coordinated execution**	Current state of the art for executing spacecraft activities that require coordination between subsystems is either manual commanding (operator tracks dependencies between subsystems) or simple sequencing that can be brittle to even minor contingencies during execution. ISAAC will develop coordinated execution technology that models dependencies, uses automated planning to translate a high-level task definition to a plan that can work given the current system state (e.g. include actions to open hatches so that a robot can move where needed), and leverages ISAAC's integrated data technology to watch for execution contingencies and trigger replanning as needed. This technology will reduce the time to effect changes on the system during critical faults and emergencies. ISAAC will test leak detection, isolation, and repair with mobile inspection and mobile manipulation capabilities, ideally on ISS.

Team Members / Project Org Slide



Thanks also to Doug Willard and Elizabeth Taylor for providing outstanding PEM support earlier this year!

Collaboration & Partnerships

NASA Centers
- ARC (lead)
- JSC
- LaRC (program mgmt)

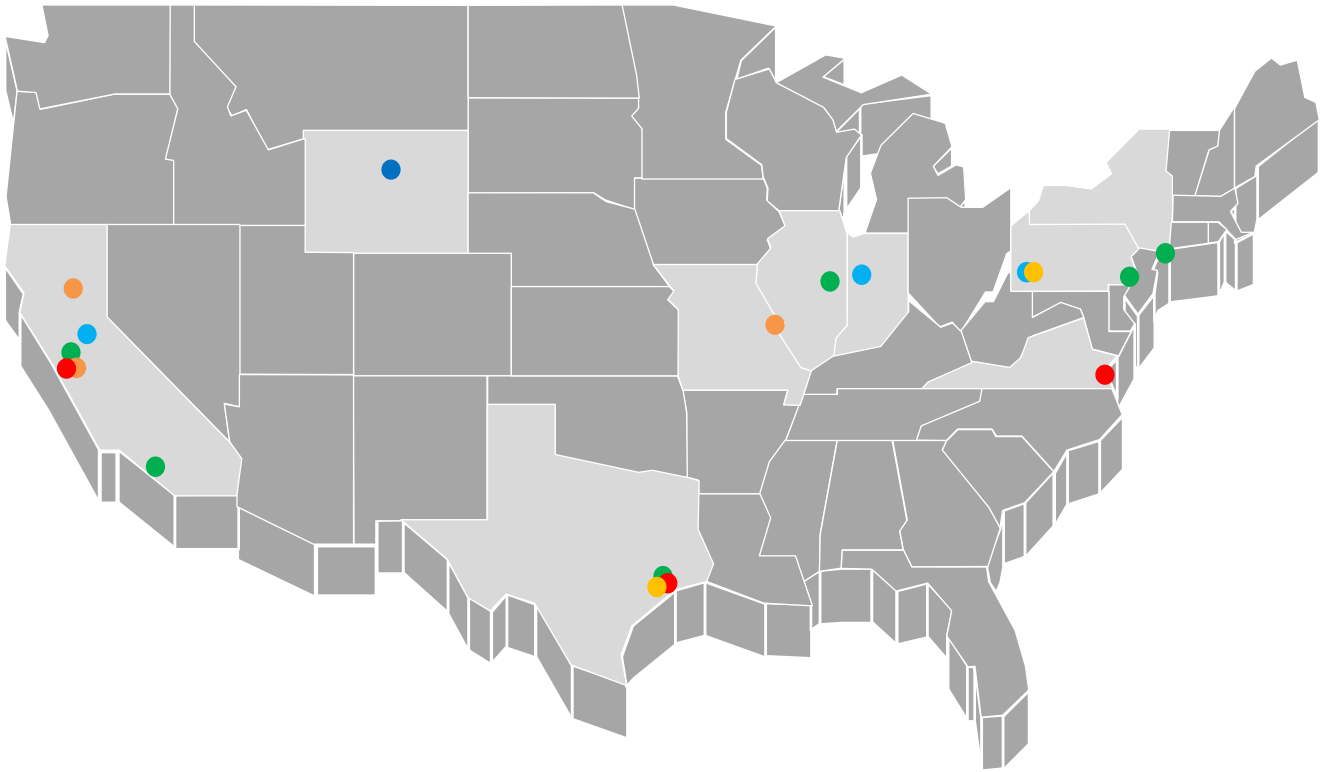
NSTRF/NSTGRO
- UC Berkeley
- USC
- UIUC
- Rice University
- Penn
- Columbia

STRI
- UC Davis, HOME
- Purdue, RETHi
- CMU, HOME

SBIR/STTR
- Makel Engineering, Air quality Astrobee payload
- SPEC Sensors, Air quality Astrobee payload
- UMSL, Air quality machine learning
- TRACLabs, multi-robot coordination

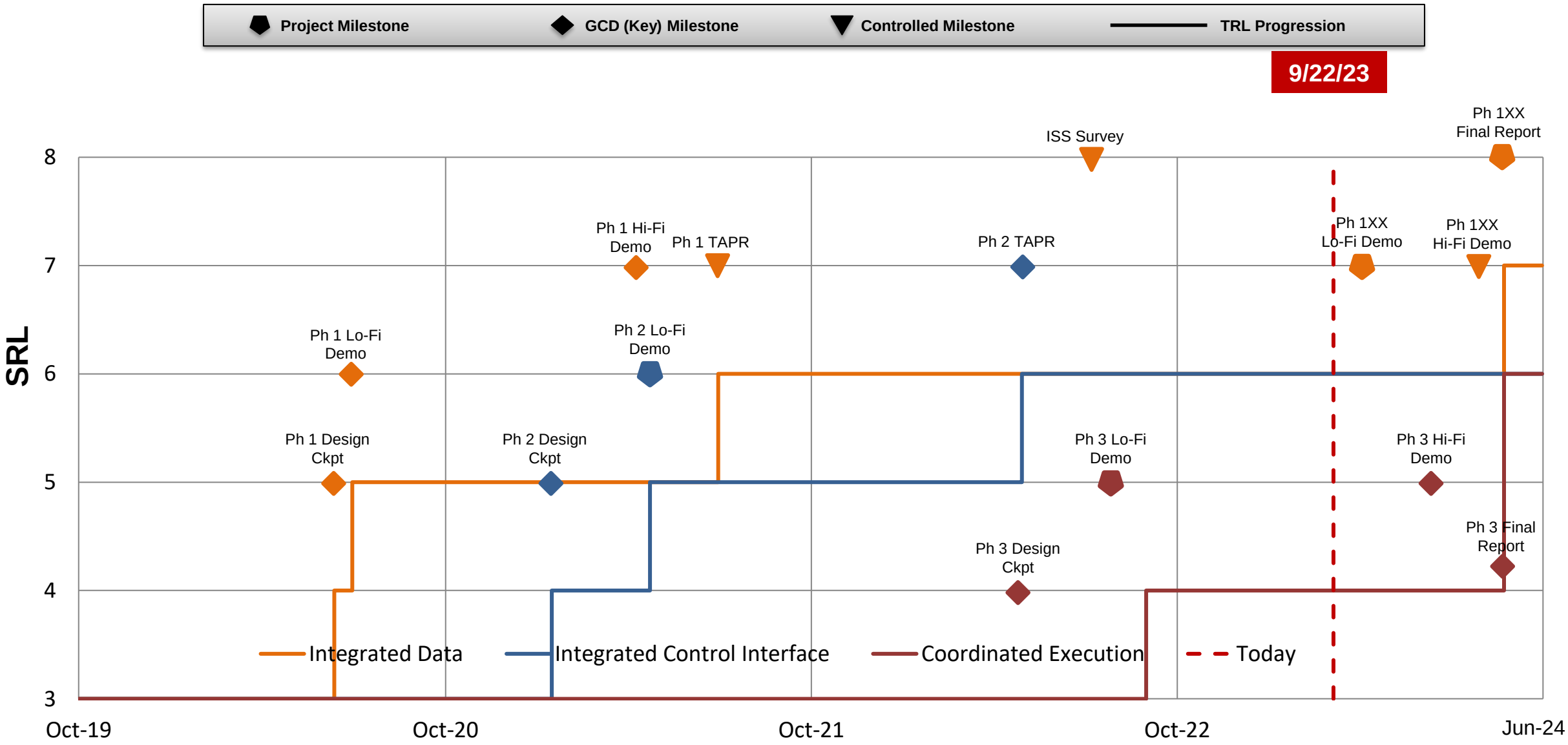
ECF
- Colorado School of Mines

Private/Public Collaboration
- Bosch USA, SoundSee Astrobee payload



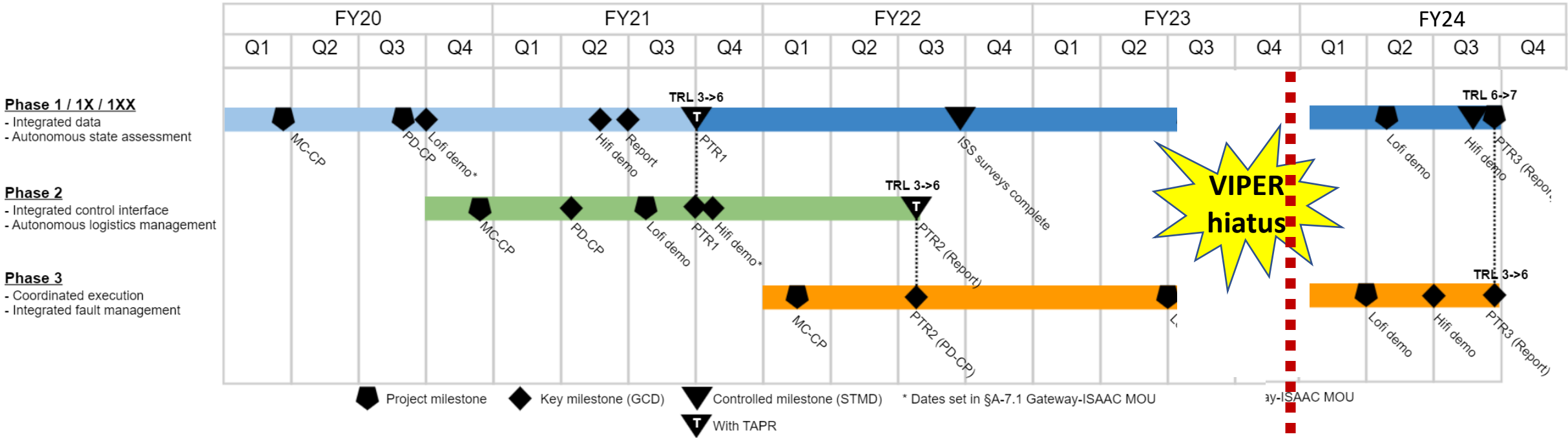
➢ Infusion/transition plan
- Gateway-ISAAC MoU
- ISS Utilization with Astrobee

ISAAC Lifecycle Milestone/Maturity Schedule



Project Schedule Context: VIPER Hiatus

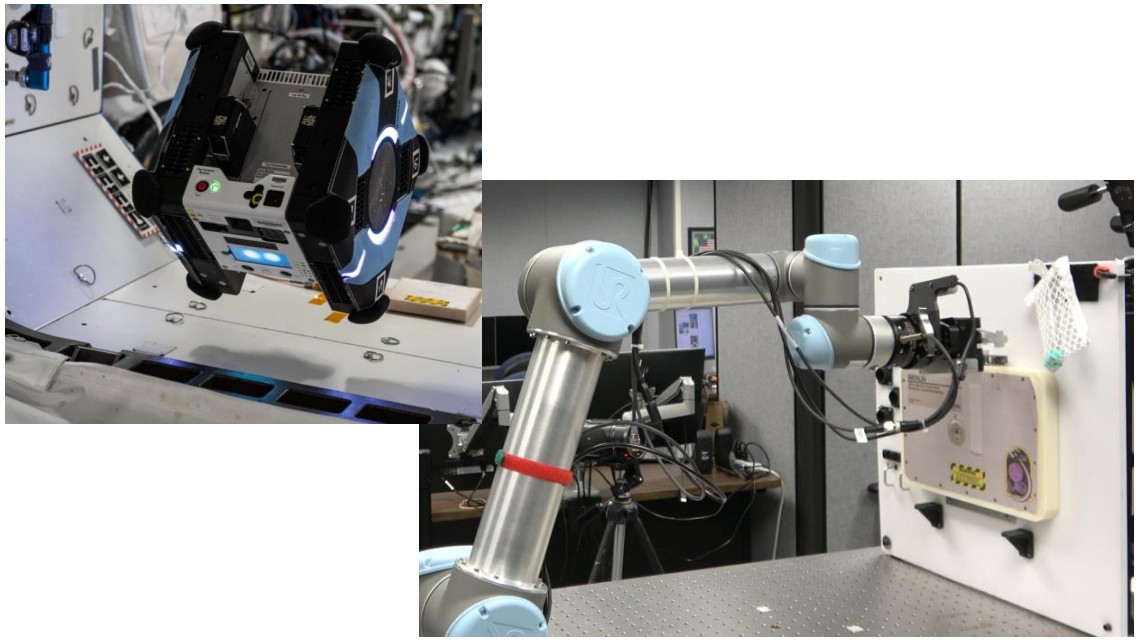
- Almost the entire ISAAC team is currently on a 6-month hiatus, working to help the VIPER mission software development get back on schedule.
- Upcoming slides describe what was previously considered FY23 scope as FY23/FY24 scope, with the key ISS demos still to come.



* Timeline edits rough, don't try to read exact dates

We are here

ISAAC FY23/24 Focus Areas





Phase 1XX
Technical thrust: Integrated Data
Capability area: Autonomous State Assessment
Hifi demo scenarios:

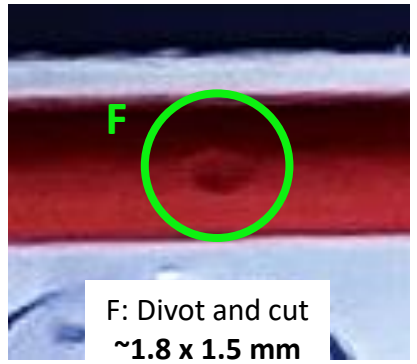
- ARC: ISS demo: Astrobee close-up targeted inspection of hatch seals
- JSC: Ground lab demo: Mobile manipulator inspection of freezer seals

Phase 3
Technical thrust: Coordinated Execution
Capability area: Integrated Fault Management
Hifi demo scenarios:

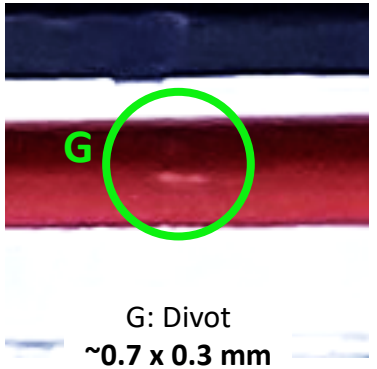
- ARC: ISS demo: Coordinated ISS interior survey with multiple Astrobees

Phase 1XX ARC: Close-Up Targeted Inspection Scenario

- Close-up targeted inspection capability
  - Designate a specific target site (e.g., in imagery from a previous survey)
  - Astrobee autonomously maneuvers its SciCam as close as possible with the target centered
  - Astrobee fine-tunes the standoff distance (~20-25 cm) to properly focus and maximize effective image resolution on the target
- Broad applicability
  - This capability is relevant for any task where maximum image resolution is important
  - An obvious example would be inspection related to ISAAC's original motivating scenario of a micrometeoroid-induced cabin air leak. (The leak site would likely be quite small.)
- Specific application for production ISS operations:
  - The ISS OSO console team reached out to the Astrobee Facility to ask whether Astrobee could perform hatch seal inspections to save crew time.
  - The hatch seals are exposed to the crew cabin and could be damaged whenever the hatches are open (as they usually are)
  - Since hatch closure would be used as an emergency hazard mitigation for some catastrophic hazards, hatch seal damage significant enough to cause a leak would be taken very seriously
  - Hatch seals are presently inspected by crew about twice a year
- Activity to date
  - As a late-breaking change to ISAAC Phase 1X, secondary hatch seal inspection tasks were added to mapping activities ISAAC9, 10, and 11. ISAAC/Astrobee worked with OSO to iterate, improving targeting and image quality.
  - OSO's most recent evaluation is that the Astrobee hatch seal inspection demonstrated to date is not yet ready to be deployed for production use, but they are interested in further evaluation if the inspection process can be improved (potential improvements to image quality and analyst user interface for image review)



F: Divot and cut
~1.8 x 1.5 mm

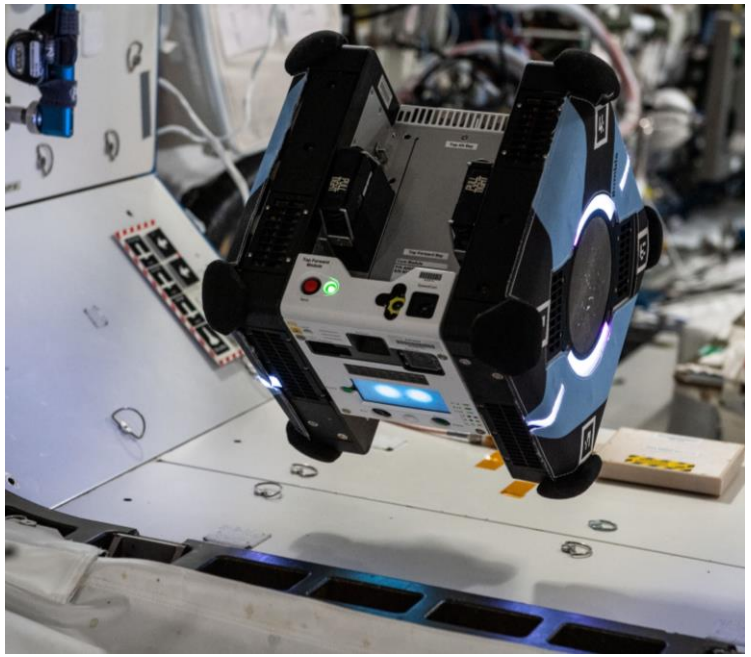


G: Divot
~0.7 x 0.3 mm

These Astrobee photos confirmed previously known hatch seal damage sites (ISAAC11, 2022/06/16). A new "focus stack" ops approach was used to get improved focus on the targets, yielding Astrobee's highest-resolution ISS images to date (~0.1-0.2 mm).

Phase 1XX ARC: Technical Development

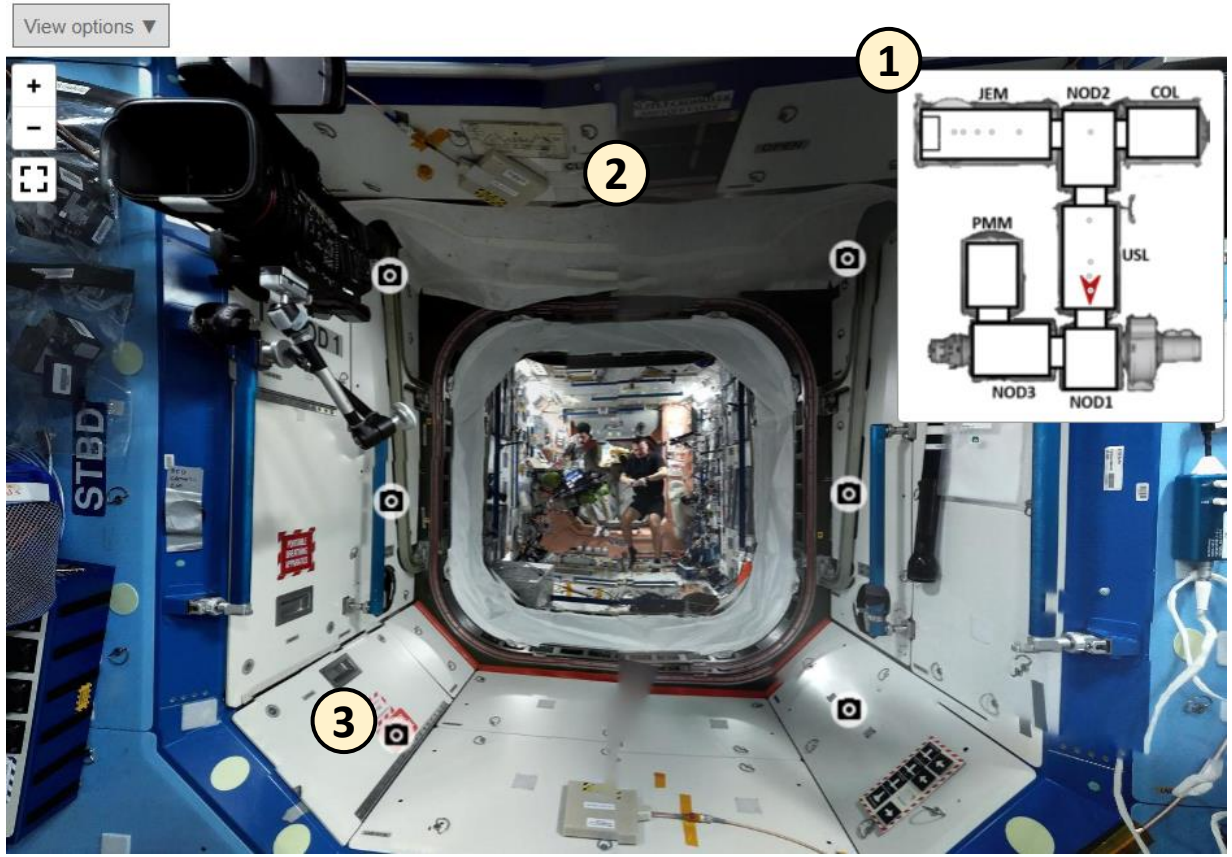
Task	Status
Close-up targeted inspection	
Target selection: Develop an interface for ISS ops staff to select targets for close-up inspection using panoramic imagery from a previous ISAAC-style Astrobee survey	In work, see next slide
Precision targeting: Improve Astrobee's capability to image a precise target location, potentially making use of prior imagery of the target to center it in the camera field of view.	Initial software version developed. Currently planning to rely on Astrobee general-purpose localization. Inspection algorithm optimizes viewing direction considering obstacle constraints.
Precision focus: Improve Astrobee's capability to precisely focus on a specific target, potentially adjusting standoff distance using its HazCam depth sensor.	Initial software version developed. Refining conops for focus in high-relief situations. Needs further testing in Astrobee Granite Lab prior to ISS.
Context imagery: Develop an interface for ISS ops staff to view the resulting high-resolution image "postage stamps" located in context relative to prior survey imagery to aid interpretation.	Not started yet. Interface will likely derive from target selection interface.
Change & anomaly detection	
Develop a flexible framework that enables an analyst to define and detect events of interest in Astrobee survey data	Framework core interface set up. Work on Phase 1XX ISS demo scenarios not started yet.

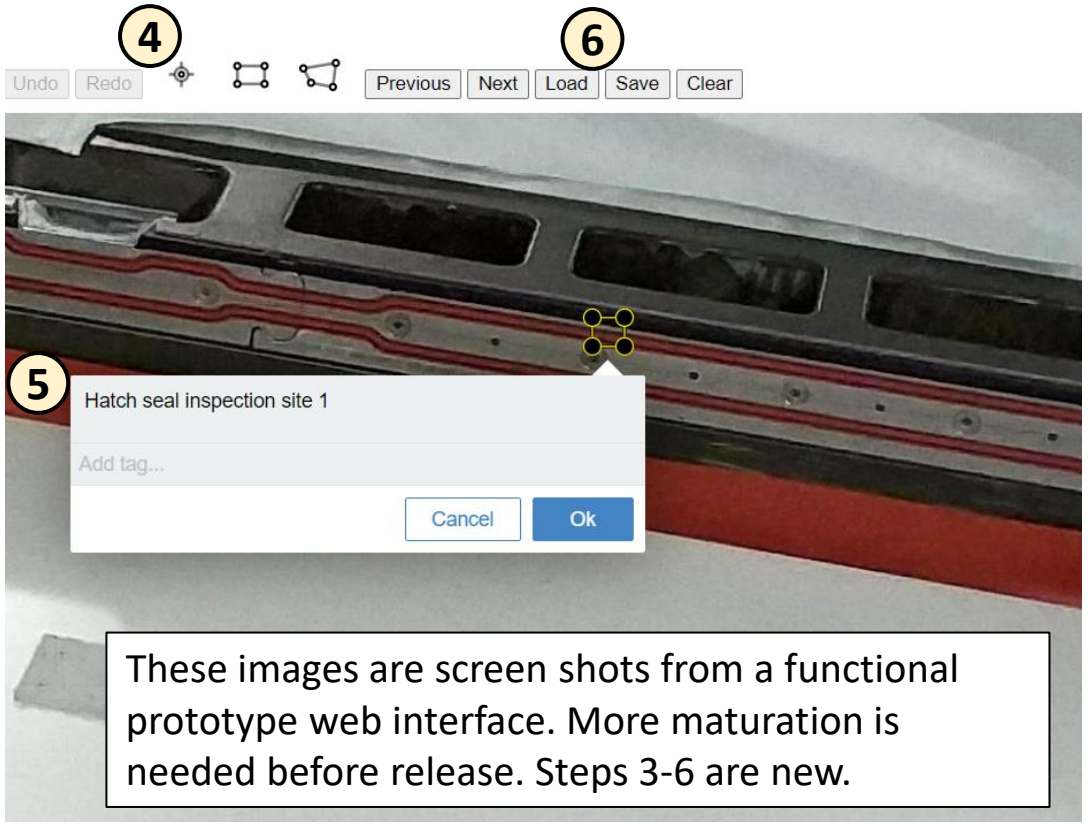


Bumble performing a close-up inspection of a hatch seal in USL during ISAAC-11 (2022/07/11)

Phase 1XX ARC: Target Selection Interface Prototype

1. Select a panorama near the target of interest using the ISS overview map.
2. Use intuitive mouse/touch controls to pan and zoom within the selected panorama.
3. Camera icons indicate the centers of the individual Astrobee SciCam image frames that were stitched to form the panorama. Select the image closest to your target.
4. Use one of the provided drawing tools (point, rectangle, polygon) to annotate a region of the image to target for inspection. The pixel coordinates will be converted to 3D positions for Astrobee to target.
5. Add details about the target (e.g., motivation, priority, what you want the analyst to look for in the resulting imagery).
6. Save your annotations and submit to the Astrobee Facility to convert to an Astrobee ISS targeted inspection plan.





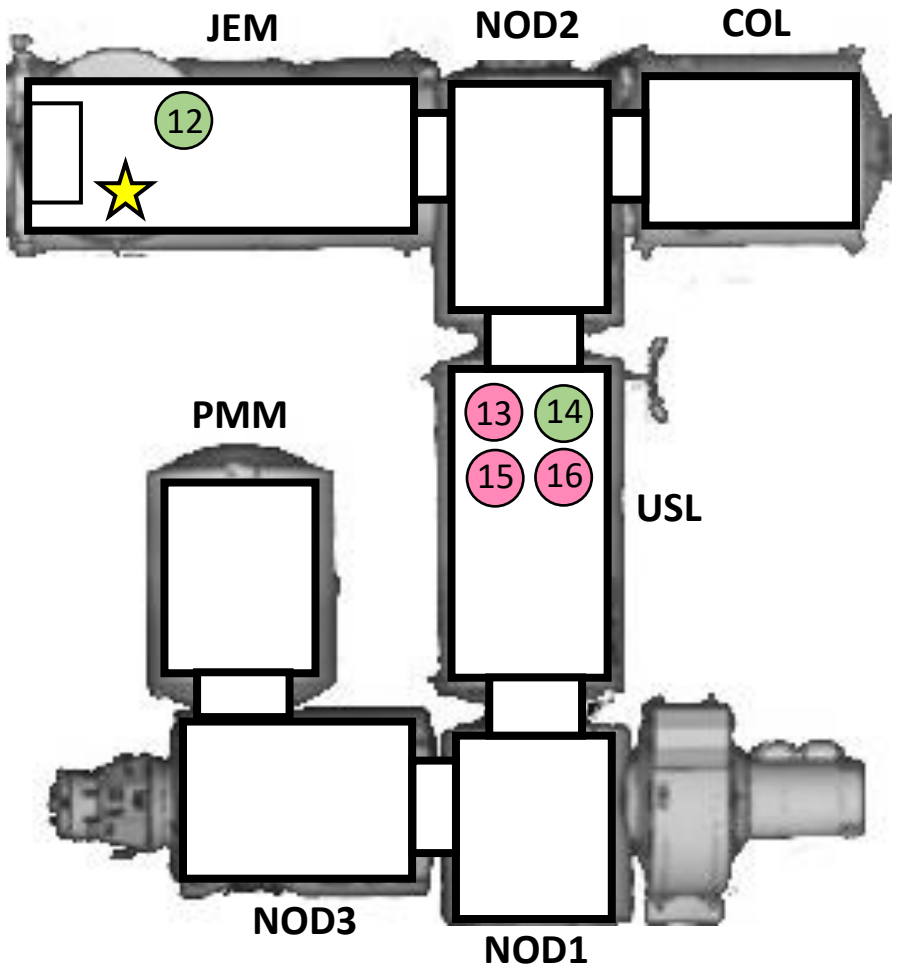
These images are screen shots from a functional prototype web interface. More maturation is needed before release. Steps 3-6 are new.

Phase 1XX ARC: Astrobee ISS Campaign

3 of 5 requested activities allocated to Phase 1XX

Act #	Ph.	Objective	Module	Date *
12	3	Multi-sensor mapping coordinated execution	JEM	2023/12/06
13	1XX	Targeted inspection	USL	2024/01/03
14	3	Multi-sensor mapping coordinated execution	USL	2024/01/31
15	1XX	Targeted inspection	USL	2024/02/21
16	1XX	Targeted inspection	USL	2024/03/13

* Dates approximate, requested in Inc70 1-pager



Phase 3 ARC: Coordinated Multi-Robot Mapping Scenario

- Aim for near-term infusion of ISAAC multi-sensor mapping to **operational use with Astrobee on ISS** in addition to medium-term use on a future Gateway IVR platform
- Autonomous robotic multi-sensor mapping can provide several operational benefits to ISS:
  - **Save crew time.** Autonomous robotic data collection could partially replace the need for crew safety videos (although Astrobee can't cover all parts of the ISS)
  - **Provide more accurate and timely information**. The ISS interior is a very dynamic environment, and the robot could collect map updates more frequently than the current tempo of crew safety videos (once every few months).
  - **Enhance usability.** Enable users to navigate directly to the area of interest in a 3D model of the ISS, rather than downloading a massive video file and scrubbing through it to find the area of interest
  - **Provide new "superpower" senses**. In the near term, we propose to enhance ISAAC maps with sound source information from the SoundSee microphone array payload for Astrobee. Going forward, the ISAAC mapping framework can easily accommodate new sensor payloads added to Astrobee.
  - **Enable automated change and anomaly detection.** Automated detection of many types of anomaly (e.g., hardware intruding into a keepout zone) requires understanding the scene geometry and naturally builds on ISAAC's 3D map building. Without automation, labor-intensive manual review of safety videos is presently slow enough that by the time the review is done, its recommendations are often obsolete.
- Initial candidate ISS use cases for map data:
  - **Safety:** Check keepout zone violations, hatch seals, Emergency Egress Guidance System visibility, translation paths, and other items.
  - **Logistics:** Spot check the locations of cargo. Review available capacity of stowage locations. Correlate data from RFID Recon payload and update Inventory Management System database.
- The ISS program is currently considering a proposal from the Astrobee Facility team to perform Astrobee surveys of the USOS every six months, starting in January 2023
  - Further ISAAC development is needed to streamline operations and post-processing so the Astrobee Facility can support this service going forward



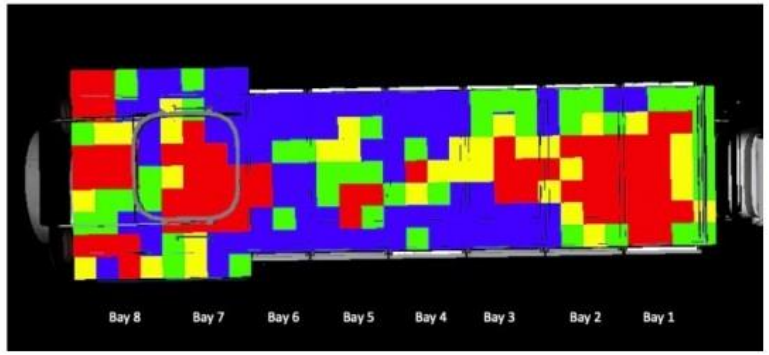
Bumble and Queen operate side-by-side to map USL during ISAAC-11 (2022/07/11)

Phase 3 ARC: Technical Development

Task	Status
Multi-robot coordination	
Demonstrate coordinated multi-robot automated task planning and execution with two Astrobees on ISS	Software development in work.
Automated multi-robot planning will be available for future Astrobee platform users as part of ISAAC open-source release	Happens automatically with ISAAC rolling open-source release
Astrobee Robot Software improvements	
Begin migration to ROS 2 framework with better quality assurance, potentially enabling future software infusion into robot platforms with more mission-critical capabilities	Well under way. Core modules and software sim migrated.
Robust map-building: For post-activity automated map registration, improve reliability and require less manual oversight, requiring less processing time between survey activities	Some automation improvements already available for Astrobee Facility's standard navigation map updates. Others in work.
Robust navigation: Improve overall Astrobee navigation, especially including sparse map localization reliability	Software development in work.
Gather recommendations for future IVR software architecture based on ISAAC experience	Not started yet.



Astronaut Chris Cassidy poses with Bumble and Honey Astrobees on ISS



Astrobee localization is complicated by areas of the prior map that have fewer features (red)

Why Move to ROS2?

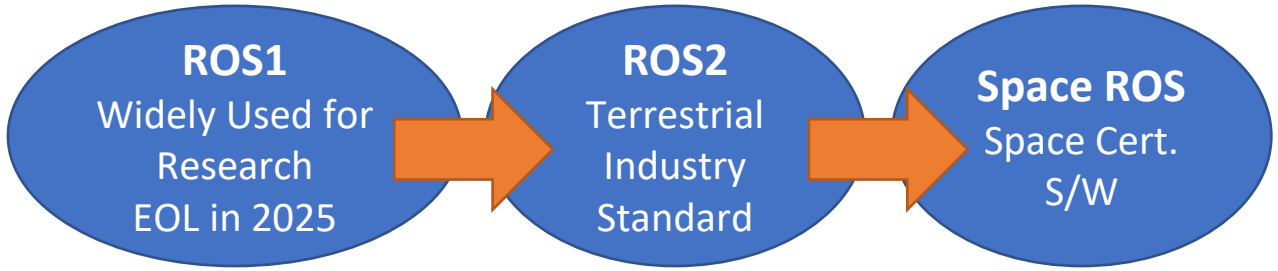


Table 1. Summary of ROS 2 features compared with ROS 1.

Category	ROS 1	ROS 2
Network transport	Bespoke protocol built on TCP/UDP	Existing standard (DDS), with abstraction supporting addition of others
Network architecture	Central name server (roscore)	Peer-to-peer discovery
Platform support	Linux	Linux, Windows, and macOS
Client libraries	Written independently in each language	Sharing a common underlying C library (rcl)
Node versus process	Single node per process	Multiple nodes per process
Threading model	Callback queues and handlers	Swappable executor

S. Macenski, T. Foote, B. Gerkey, C. Lalancette, W. Woodall, "Robot Operating System 2: Design, architecture, and uses in the wild," Science Robotics vol. 7, May 2022.

- ROS = Robot Operating System
- ROS1 will be deprecated in 2025
- New tech developments from industry players moving to ROS2
- Space ROS (kicked off via Blue Origin ACO) is an open-source extension of ROS2 designed to support robot flight software

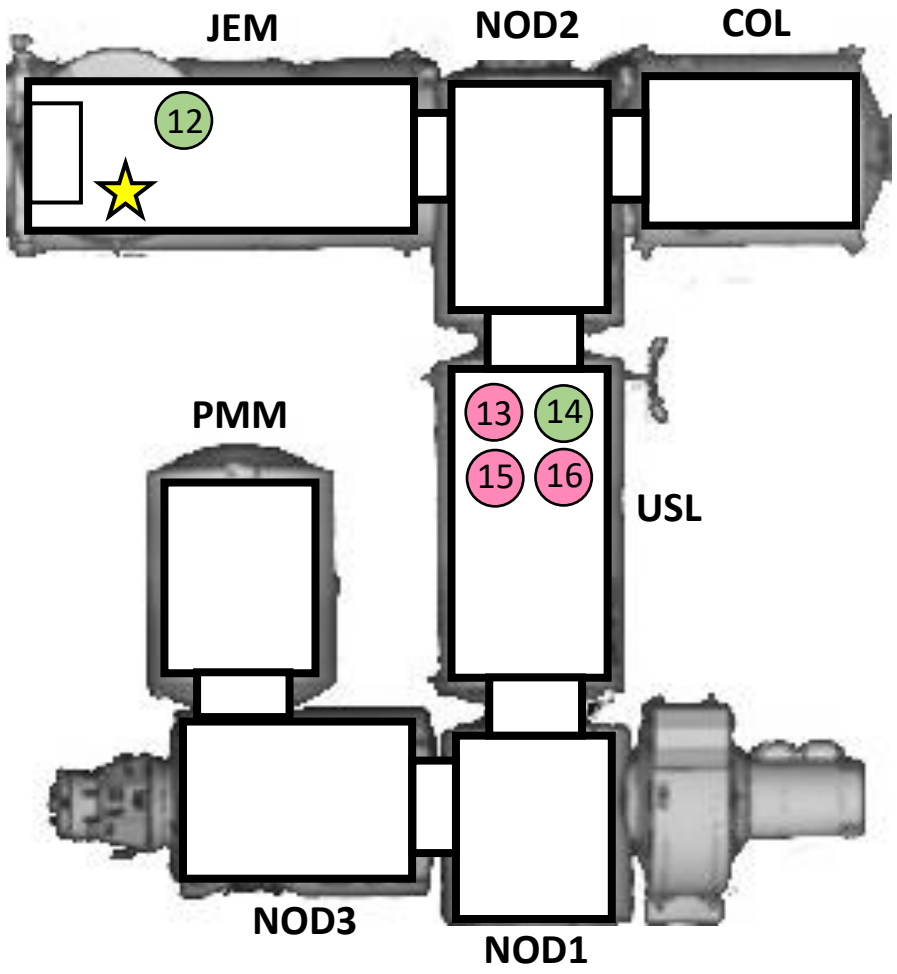
Features	ROS1	ROS2	Space ROS
Swappable middleware		✓	✓
Multi-platform		✓	✓
Built-in network security, authentication, quality of service		✓	✓
Additional aerospace-focused V&V			✓
Artifacts for NPR 7150.2 certification / analysis			✓

Phase 3 ARC: Astrobee ISS Campaign

2 of 5 requested activities allocated to Phase 3

Act #	Ph.	Objective	Module	Date *
12	3	Multi-sensor mapping coordinated execution	JEM	2023/12/06
13	1XX	Targeted inspection	USL	2024/01/03
14	3	Multi-sensor mapping coordinated execution	USL	2024/01/31
15	1XX	Targeted inspection	USL	2024/02/21
16	1XX	Targeted inspection	USL	2024/03/13

* Dates approximate, requested in Inc70 1-pager

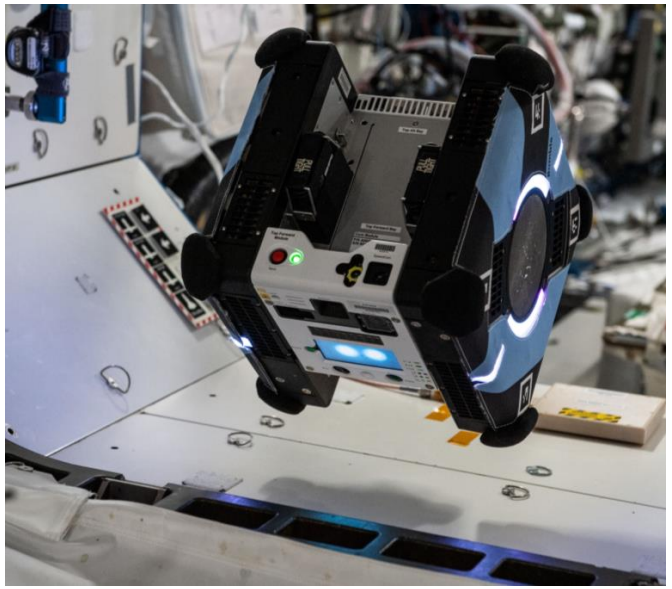


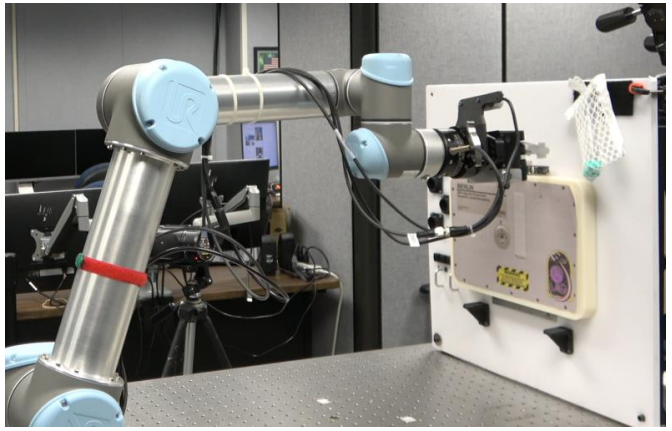
Project Assessment Summary

Project Name	Performance				Comments
	C	S	T	P	
Mid Year					Programmatic – Risk that ISS OZ would not approve reactivating ISAAC Integrated Payload List support (since resolved)
Annual					Currently on hiatus. Preparing to ramp effort back up. ISS activities tentatively scheduled for December 6 – March 13.

Plans Forward and Transition / Infusion Plan

- Plans forward:
  - Phase 1XX
    - ARC: ISS demo: Astrobee close-up targeted inspection of hatch seals
    - JSC: Ground lab demo: Mobile manipulator inspection of freezer seals
  - Phase 3
    - ARC: ISS demo: Coordinated ISS interior survey with multiple Astrobees
- Infusion plan:
  - ISAAC technology was originally targeted to facilitate near-term development of Gateway IVR. Given Gateway IVR subsystem schedule delays, this infusion path will now be realized only after the ISAAC project ends.
  - Therefore, ISAAC has opened up a second near-term potential infusion path of delivering an Astrobee interior survey capability for sustainable use in production ISS operations.
    - Several orgs within ISS have expressed interest in timely survey data. However, more coordination is needed to piece together sufficient resources (funding, crew time, etc.) to sustain these operations.





Education/Public Outreach

EPO Involvement

- June 2023: Presented ISAAC progress to Astrobee guest scientists and stakeholders at the Astrobee Working Group

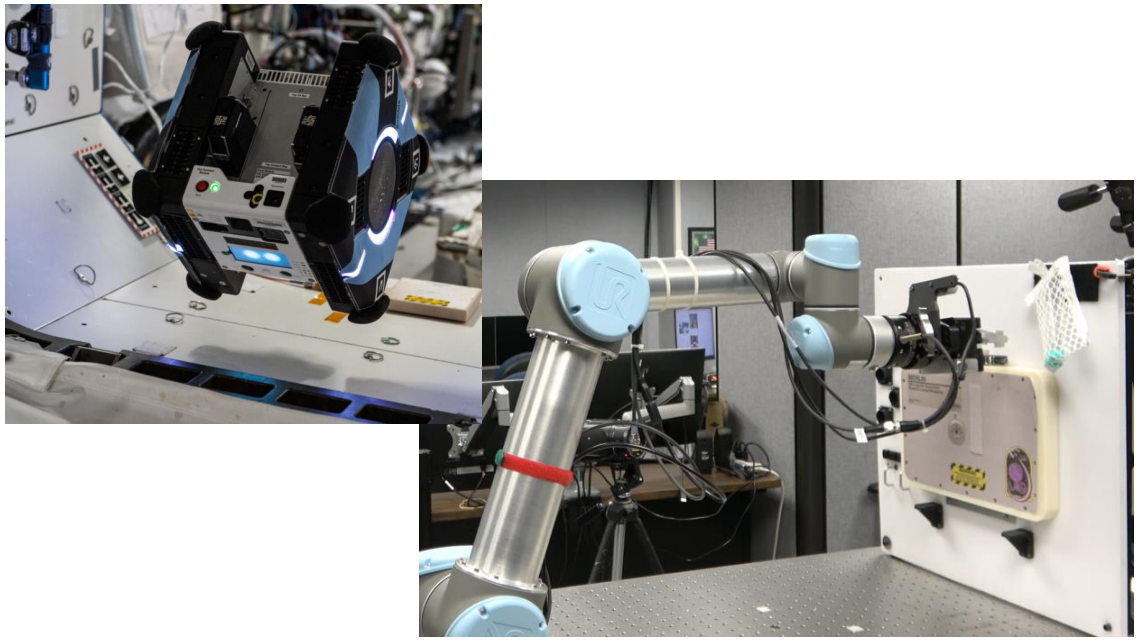
EPO Calendar Outlook (High Priorities):

6 Month Look-Ahead	
ISAAC plans FY24 ISS activities that may be newsworthy (see previous slides)	Exact dates TBD

ISAAC-mentored interns so far in FY23

Name	Institution	Level	Program	Topic	Period
Holly Dinkel	UIUC	Ph.D.	NSTGRO	Flexible object perception	Ongoing
Ian Miller	Penn	Ph.D.	NSTRF	Semantic robot localization	Defended Summer ’23
Eric Chang	Columbia	Ph.D.	NSTGRO	Tactile sensing	Ongoing
Jamie Santos	CUT Goth., Sweden	M.S.	OSTEM	Change detection in 3D models	Spring ’23
Astroberth team	Florida Atlantic U	Undergrad x 5	N/A	Free-flyer cargo transfer	AY 22/23
Thermal IR team	Florida Atlantic U	Undergrad x 5	N/A	Free-flyer thermal sensing	AY 22/23
Morgan Sun	U Michigan	M.S.	OSTEM	Localizing objects with CNNs	Summer ’23
Rachel Lu	MIT	Undergrad	OSTEM	Search for label text in ISS panos	Summer ’23
Luisa Mao	Carnegie Mellon U	Undergrad	OSTEM	Improved relocalization with semantic filtering	Summer ’23

Project Summary





Phase 1XX

- ARC: ISS demo: Astrobee close-up targeted inspection of hatch seals
- JSC: Ground lab demo: Mobile manipulator inspection of freezer seals

Technology

- Close-up targeted inspection
- Change & anomaly detection
- Mobile manipulator
- Compliance/admittance control

Phase 3

- ARC: ISS demo: Coordinated ISS interior survey with multiple Astrobees

Technology

- Multi-robot coordination
- Begin migrating to ROS 2
- Map-building and navigation