Enabling Autonomous Space Mission Operations with Artificial Intelligence

Dr. Jeremy Frank

NASA Ames Research Center

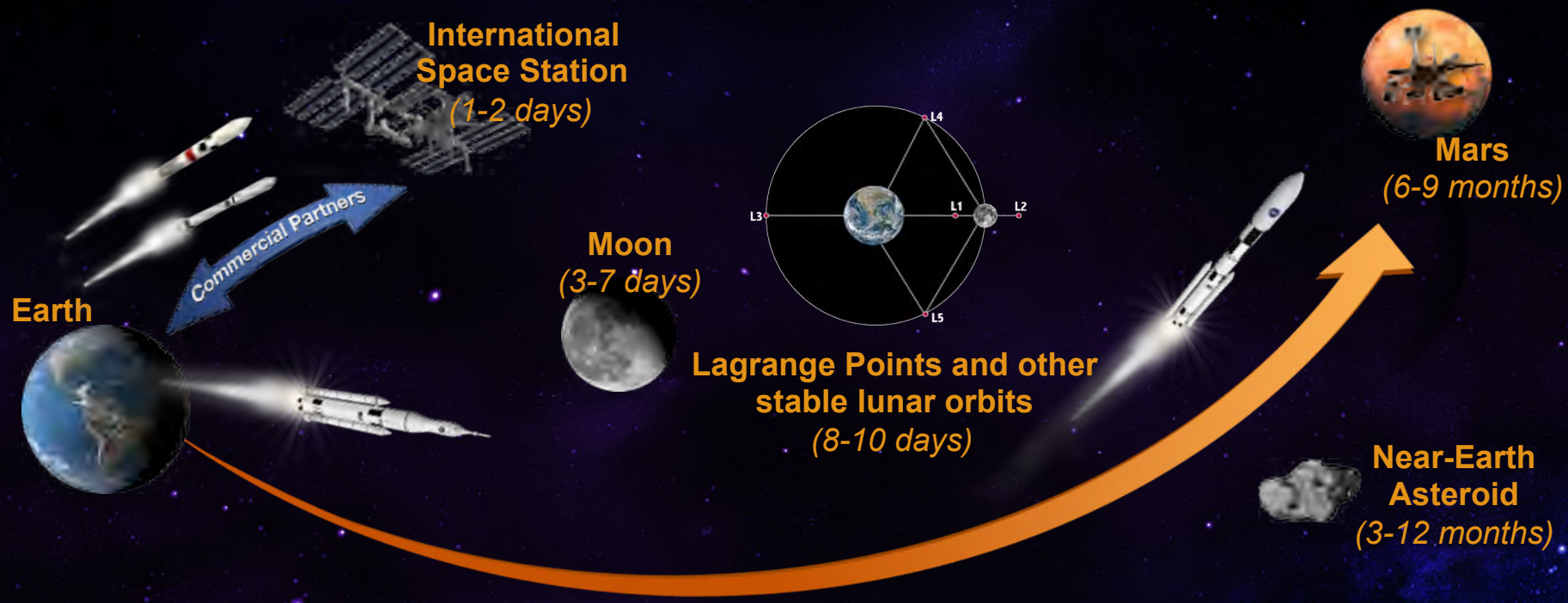
Outline

- Human Spaceflight Mission Operations
  - Motivations for Autonomy
  - AI as Autonomy Enabling Technology
- Autonomous Mission Operations: Projects
  - AMO TOCA SSC
  - AMO EXPRESS
  - ACAWS
- The AMO TOCA SSC Demonstration
  - Concept of Operations
  - Software Design
  - Demonstration Results
  - Lessons Learned
- Summary

Phobos, MRO, 2008.

Motivations for Autonomy

(one-way travel times)

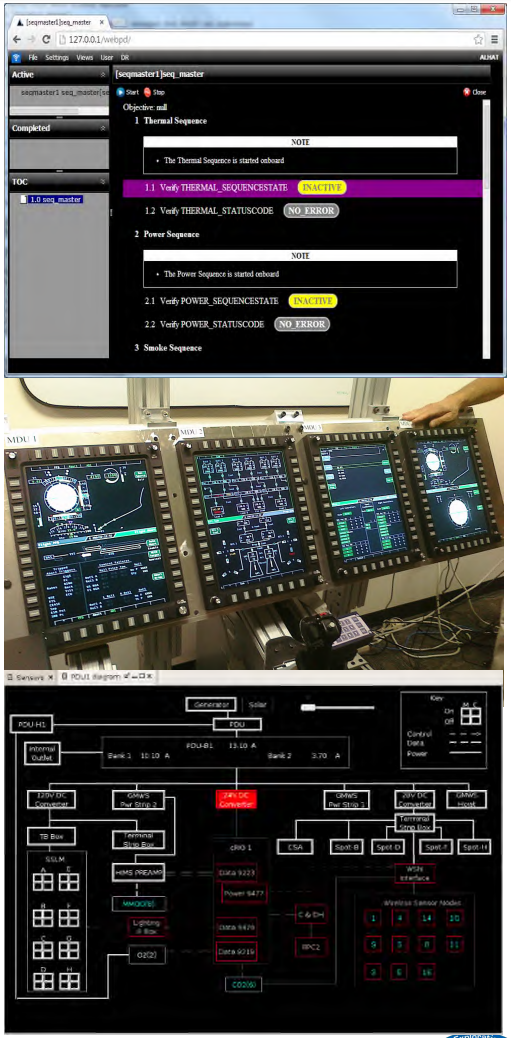


Future missions will be longer, more complex, & require new technology

Robotics and Mobility | Deep Space Habitation | Advanced Spacesuits | Advanced Space Comm | Advanced Propulsion | Resource Utilization | Human-Robot Systems

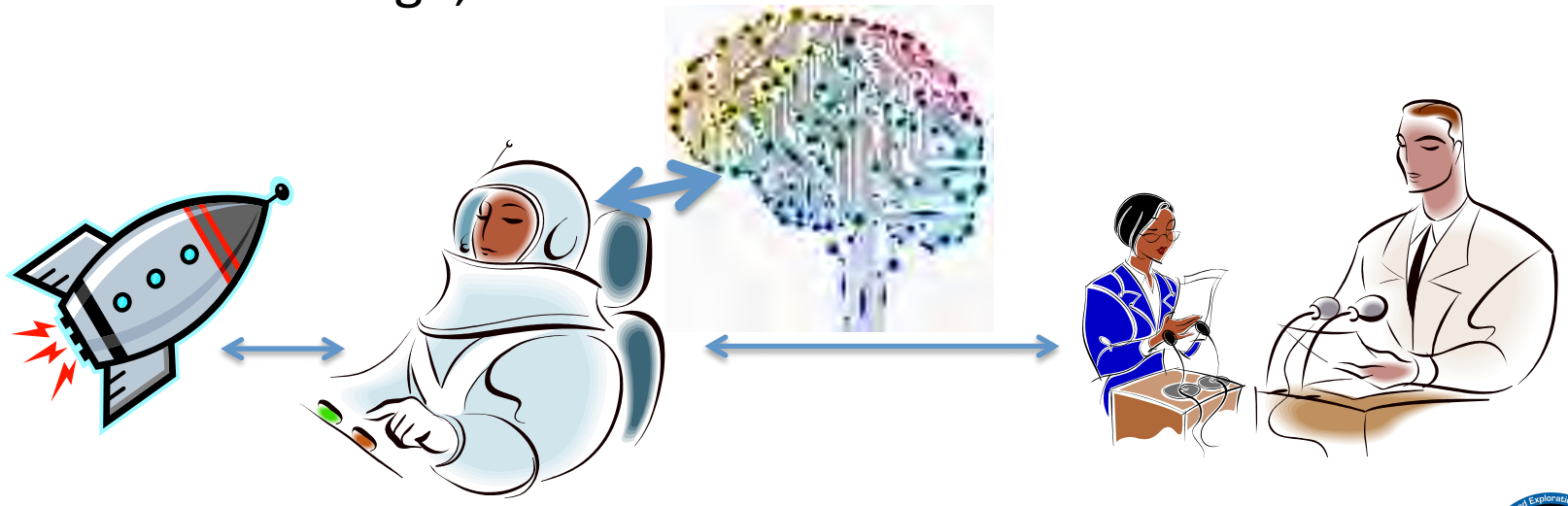
Motivations for Autonomy

- Monitoring
  - *What is the state of the spacecraft?*
  - Ensure the state of spacecraft systems, and the spacecraft's operating environment, are known.
- Planning and Scheduling
  - *What is the spacecraft doing and when?*
  - Understand current and future activities that the crew and spacecraft systems will perform.
- Execution
  - *What is the next activity to perform?*
  - Command spacecraft subsystems and ensure the results are as expected.
- Fault Management
  - *Is something wrong? What are the impacts?*
  - Detect and isolate faults, and determine the consequences.



Motivations for Autonomy

- Enabling human spaceflight autonomy requires:
  - A new balance of responsibility between crew and ground.
  - A new balance of responsibility between crew and vehicle.
  - New concepts of operations to fit new division of labor.
  - Application of AI technology to augment crew expertise and knowledge, and reduce crew workload.



Autonomous Mission Operations: Projects

Autonomous Mission Operations: Projects

- AMO TOCA SSC
  - Decision support for spacecraft habitation systems (life support, crew computers)
- AMO EXPRESS
  - System automation (powerup and configuration, fault detection and recovery)
- ACAWS
  - Spacecraft cockpit fault management

Status	Procedure	Rationale
This Week (GMT 2014/342 - 2014/348)		
Requested	ISTAR Total Organic Carbon Analyzer: TOCA - Waste Water Bag Changeout (Med Ops 6.3.350)	Required every 6 runs and prior to next run
Scheduled	ISTAR Total Organic Carbon Analyzer: TOCA - Water Sample Analysis Using TOCA Water Sample Hose (Med Ops 6.3.250)	Required weekly
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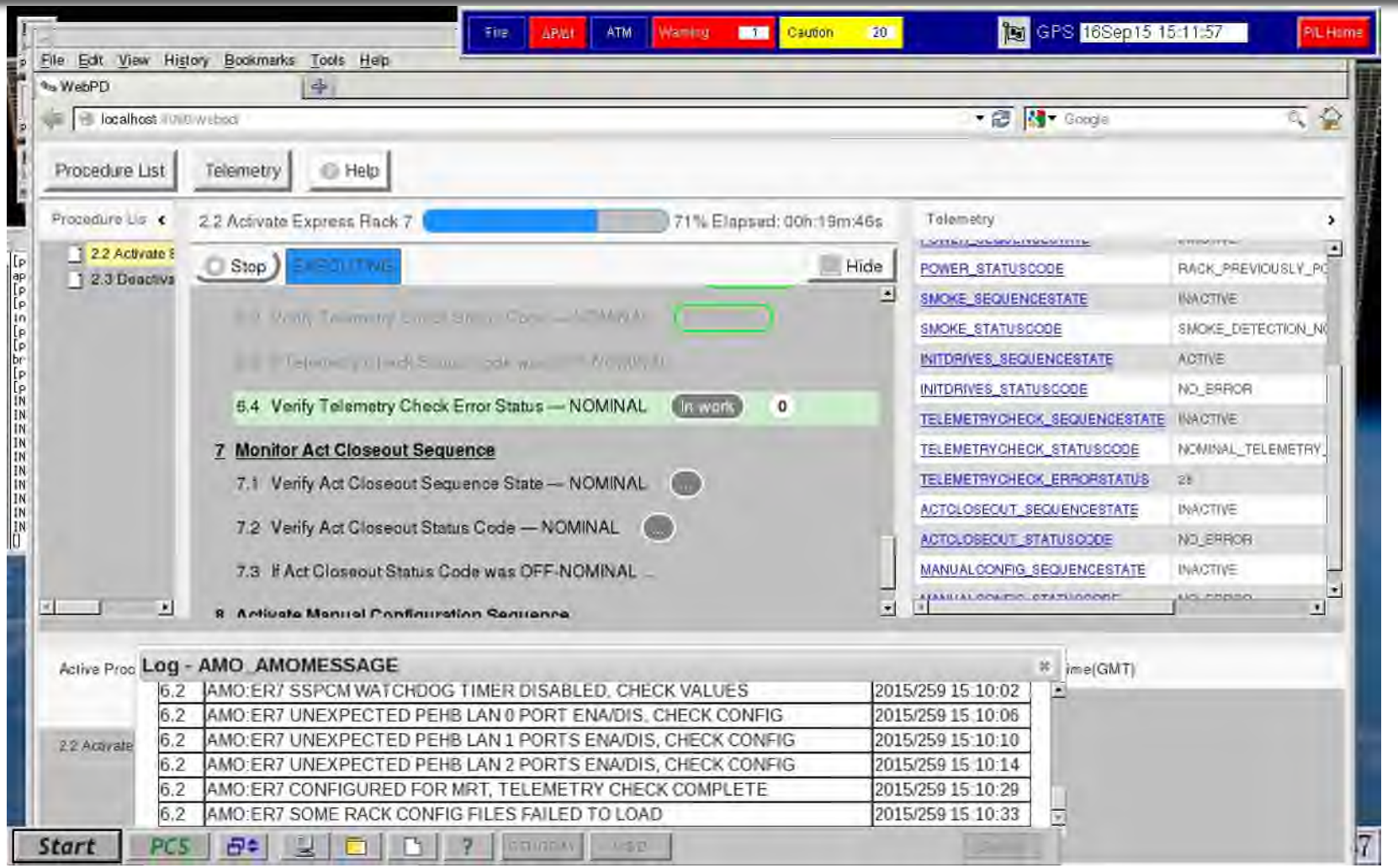
Future Week (GMT 2014/356 - 2014/362)		
Recommended	ISTAR Total Organic Carbon Analyzer: TOCA - Water Sample Analysis Using TOCA Water Sample Hose (Med Ops 6.3.250)	Required weekly
Recommended	ISTAR Total Organic Carbon Analyzer: TOCA - Water Sample Analysis From TOCA Sample Analysis Bag (Med Ops 6.3.300) (for Hot PWD)	Required monthly (alternating between the hot and ambient ports)

AMO EXPRESS

- EXPRESS=EXpedite the PRocessing of Experiments on Space Station
- Developed software to automate operation of ISS equipment.
  - Payload equipment racks operations is operator intensive, subject to many operational constraints.
  - These racks can be controlled by computers and plan execution software (Timeliner) onboard ISS.
  - We developed Timeliner scripts to implement conditional plans to power on the racks.
  - We developed displays to provide crew with situational awareness of state of executed state.

AMO EXPRESS


Fire
APU
ATM
Warning 1
Caution 20
GPS 16Sep15 15:11:57
P/L Home
File Edit View History Bookmarks Tools Help
WebPD
Procedure List
Telemetry
Help
2.2 Activate Express Rack 7
71% Elapsed: 00h:19m:46s
Stop
Hide
6.4 Verify Telemetry Check Error Status — NOMINAL
In work
0
7 Monitor Act Closeout Sequence
7.1 Verify Act Closeout Sequence State — NOMINAL
7.2 Verify Act Closeout Status Code — NOMINAL
7.3 If Act Closeout Status Code was OFF-NOMINAL
Telemetry
POWER_STATUSCODE
SMOKE_SEQUENCESTATE
INACTIVE
SMOKE_STATUSCODE
INITDRIVES_SEQUENCESTATE
ACTIVE
INITDRIVES_STATUSCODE
NO_ERROR
TELEMETRYCHECK_SEQUENCESTATE
INACTIVE
TELEMETRYCHECK_STATUSCODE
NOMINAL_TELEMETRY
TELEMETRYCHECK_ERRORSTATUS
ACTCLOSEOUT_SEQUENCESTATE
INACTIVE
ACTCLOSEOUT_STATUSCODE
NO_ERROR
MANUALCONFIG_SEQUENCESTATE
INACTIVE
Log - AMO_AMOMESSAGE
6.2 AMO:ER7 SSPCM WATCHDOG TIMER DISABLED, CHECK VALUES 2015/259 15:10:02
6.2 AMO:ER7 UNEXPECTED PEHB LAN 0 PORT ENA/DIS, CHECK CONFIG 2015/259 15:10:06
6.2 AMO:ER7 UNEXPECTED PEHB LAN 1 PORTS ENA/DIS, CHECK CONFIG 2015/259 15:10:10
6.2 AMO:ER7 UNEXPECTED PEHB LAN 2 PORTS ENA/DIS, CHECK CONFIG 2015/259 15:10:14
6.2 AMO:ER7 CONFIGURED FOR MRT, TELEMETRY CHECK COMPLETE 2015/259 15:10:29
6.2 AMO:ER7 SOME RACK CONFIG FILES FAILED TO LOAD 2015/259 15:10:33
Start
PCS

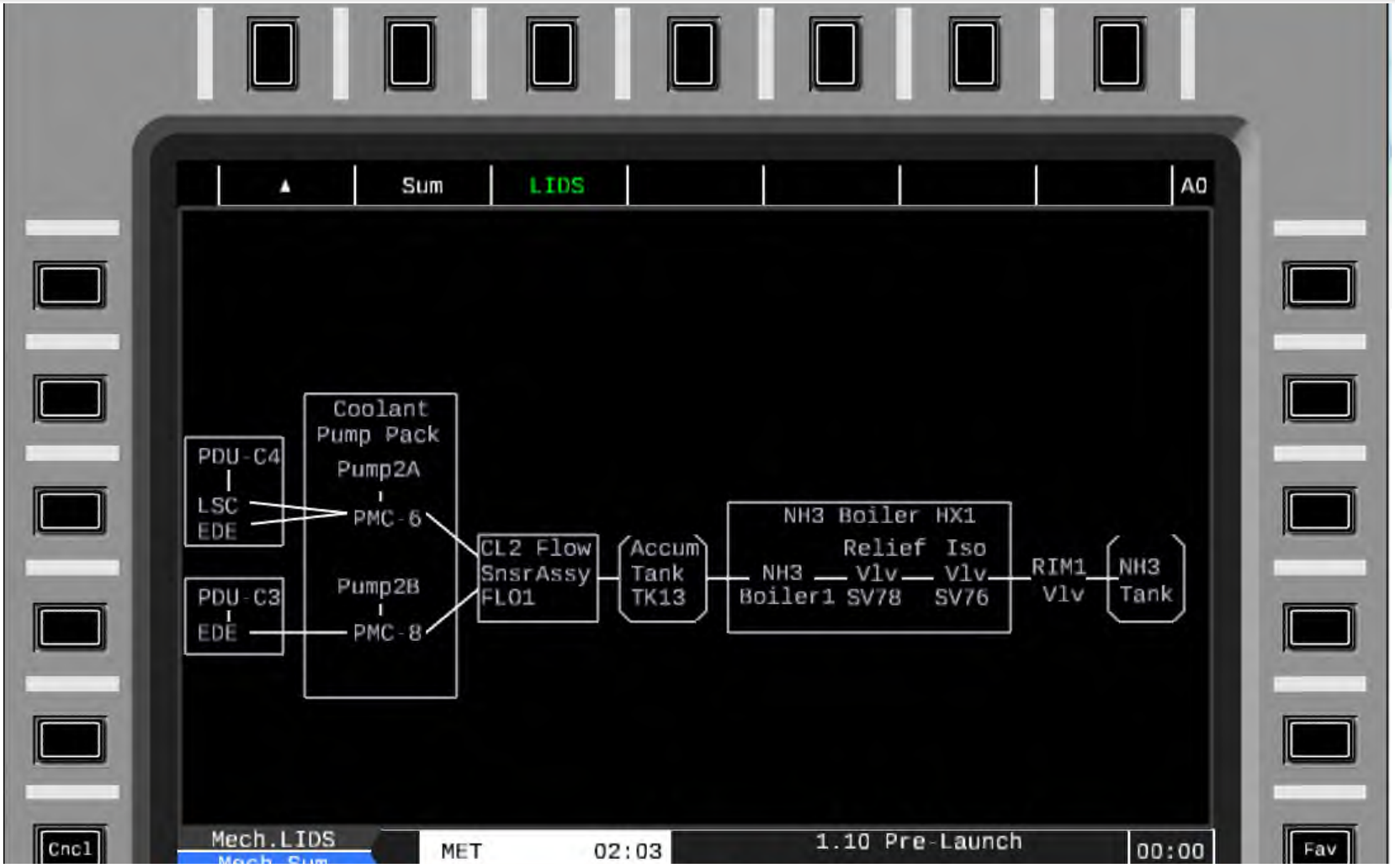
AMO EXPRESS

Advanced Caution and Warning System (ACAWS)

- NASA developed ACAWS to answer the needs for autonomous fault management.
- ACAWS was demonstrated with a large-scale model of Orion for the EFT-1 mission in December 2014
  - Executed on ground using the live downlink from pre-launch through post-landing
  - Model and architecture apply to on-board use
- Detected faults and determined effects of faults.
  - Loss of Capability
  - Loss of Redundancy

Advanced Caution and Warning System (ACAWS)

Advanced Caution and Warning System (ACAWS)



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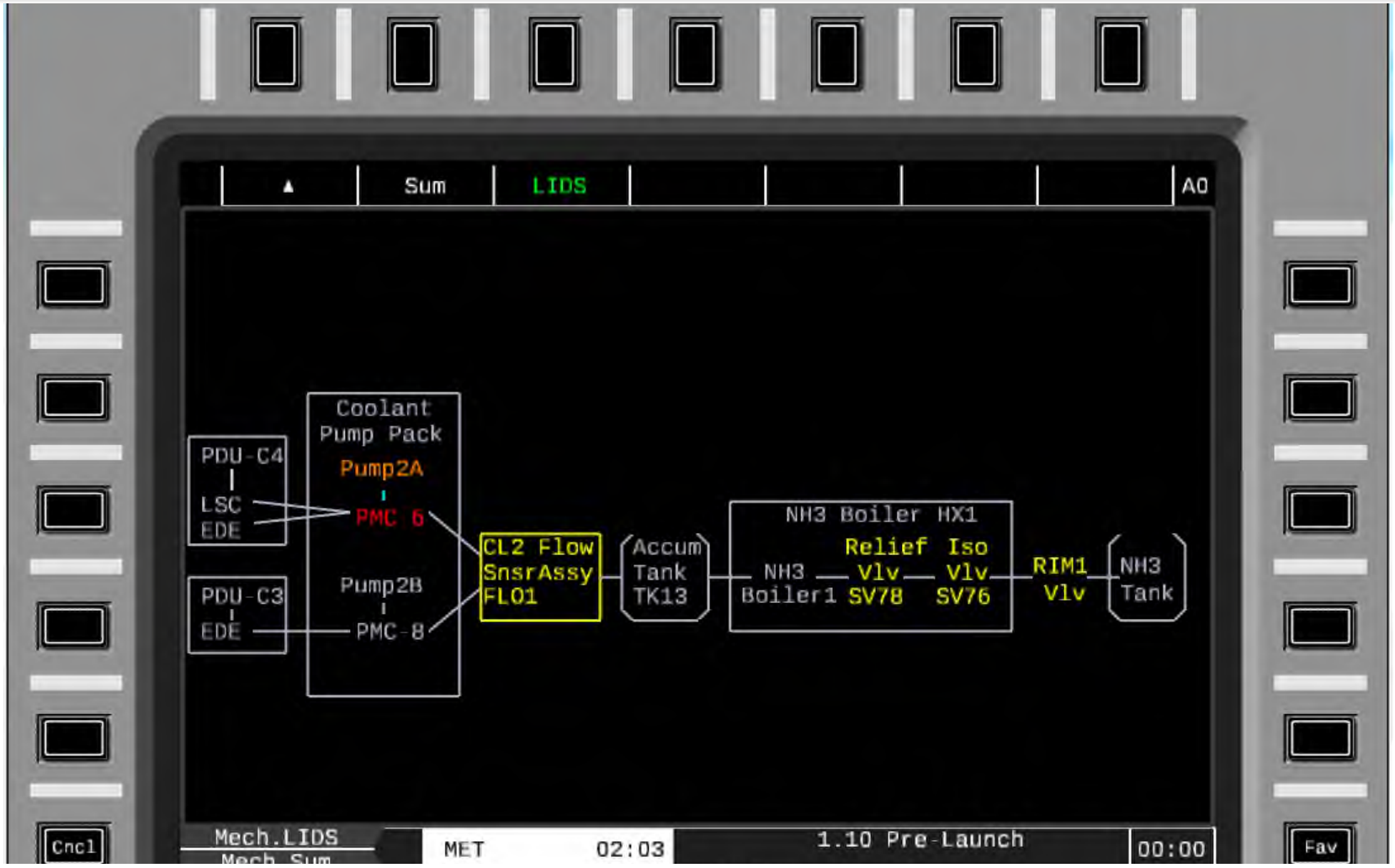


Advanced Caution and Warning System (ACAWS)

Advanced Caution and Warning System (ACAWS)

The AMO TOCA SSC Demonstration

Concept of Operations

Total Organic Carbon Analyzer (TOCA)

Station Support Computers (SSCs)

Concept of Operations

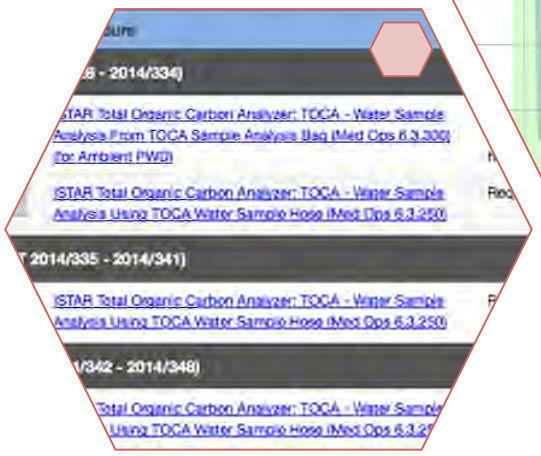
- ISS Hardware: TOCA
  - Water Quality analyzer
  - Analyses take place 1-2 times / week
  - Periodic maintenance activities (bimonthly – annually)
  - Several fault modes, some experienced regularly on orbit
- ISS Hardware: SSC
  - Crew non-critical (office) computers used for multiple functions
  - Housekeeping performed weekly
  - Problems require management (e.g. network connectivity, over-temperature, disk space)

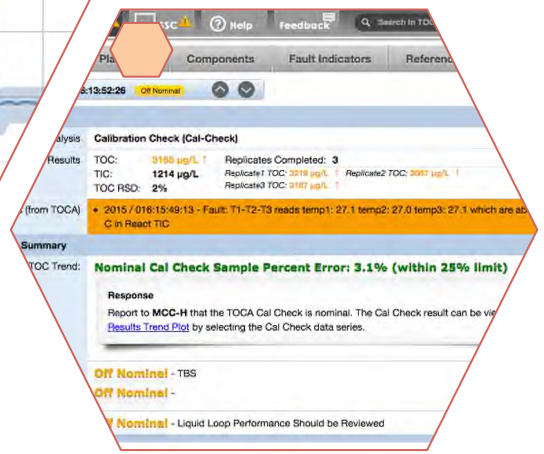
Concept of Operations

Planning: Provides list of required crew activities

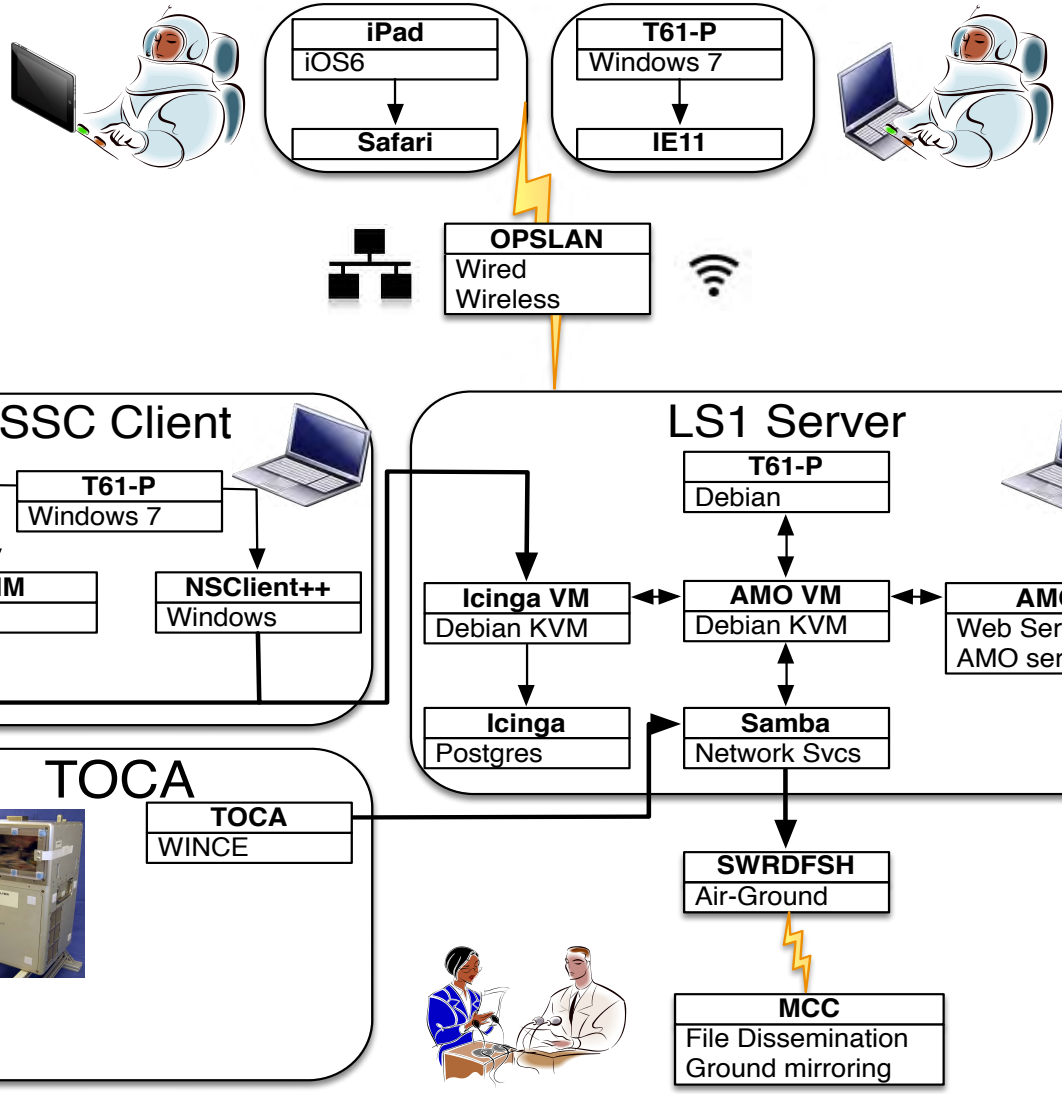
Monitoring: Perform hardware performance analysis and trending

Manage Faults: Answer questions, recommend actions





Software Design



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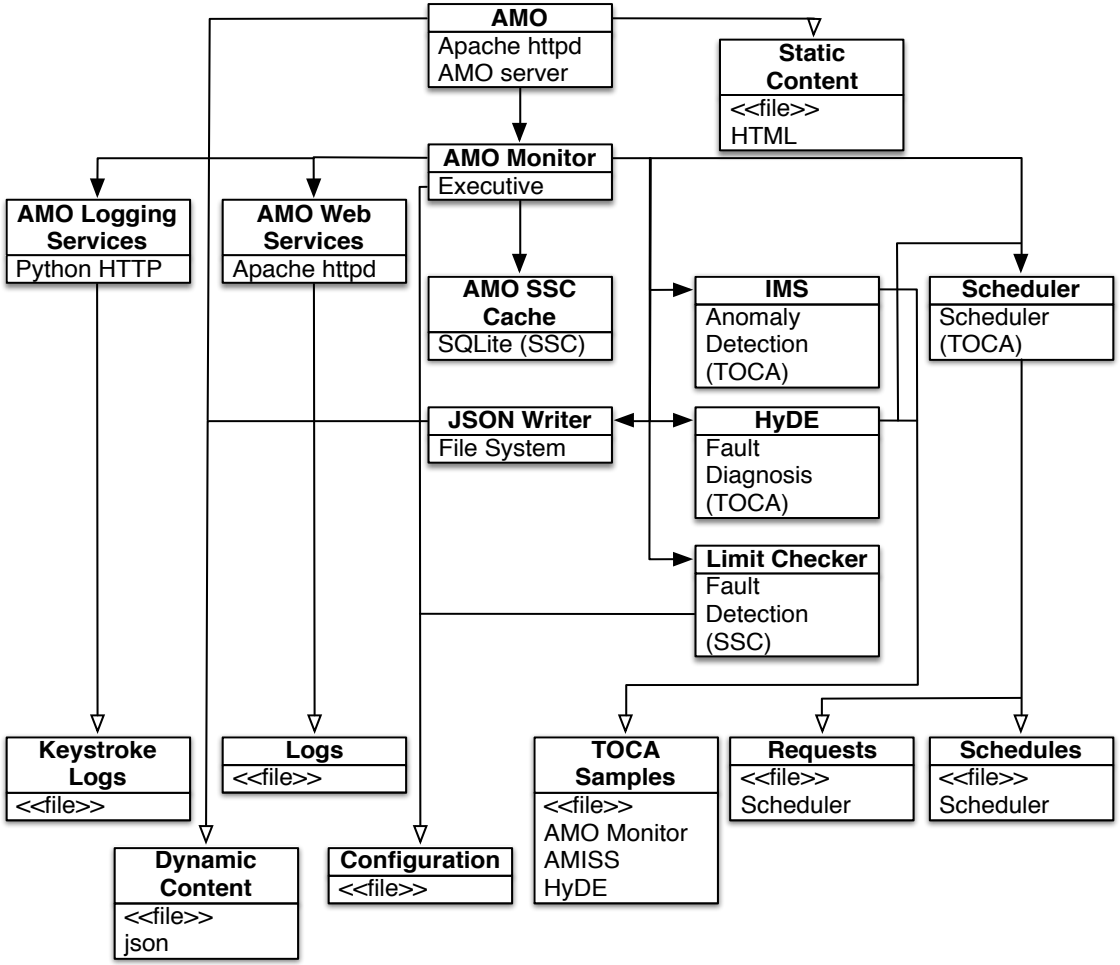

Software Design

- Monitor
  - Invokes other functions in response to new TOCA data
  - Invokes TOCA scheduler in response to new information uplinked from ground or crew recommendations
  - Pulls SSC data and invokes processing on schedule
  - Marshalls logs and state for downlinking on schedule
  - Ensures activities terminated if they take too long

Software Design

- Scheduler
  - Recommends next 2 weeks of TOCA activities
  - Crew can accept recommendations or add tasks
  - Schedule recomputed when new schedule uplinked

Activity	Type	Frequency
Hose Sample	Nominal	Weekly
Bag Sample (Hot)	Nominal	2 Months
Bag Sample (Ambient)	Nominal	2 Months
Cal Check	Maint.	3 Months
Waste Bag Changeout	Maint.	6 Runs
Buffer Container Changeout	Maint.	47 Runs
Calibrate	Maint.	Cal Check Fails

Software Design

- Scheduler

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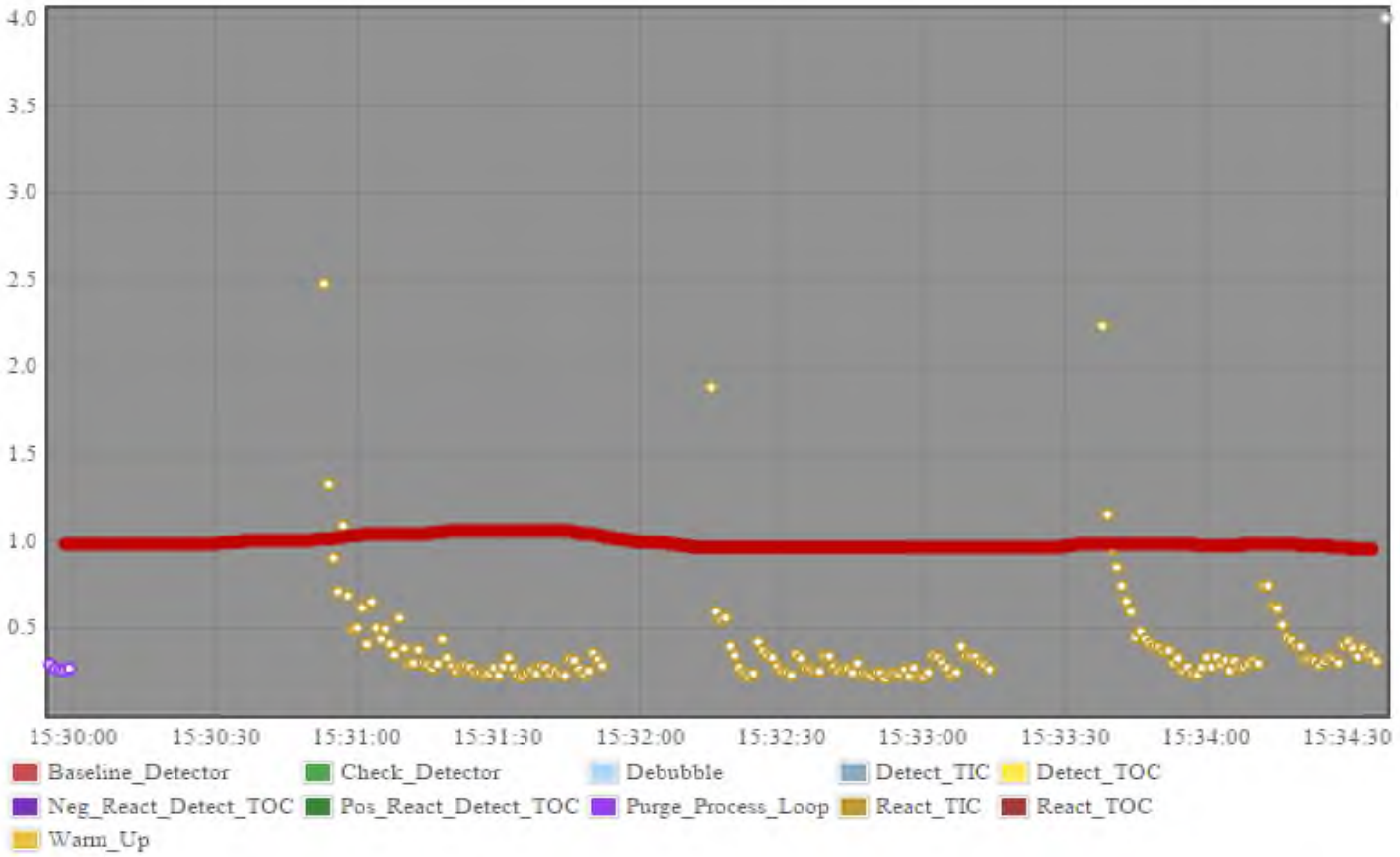
Software Design

- Inductive Monitoring System
  - Monitors TOCA performance to detect *anomalies*
  - Anomalies are differences in device performance when compared to a profile of normal performance
  - Profile developed for one subsystem of TOCA based on parameters identified by system experts
  - If the new behavior differs too much from normal (in a formal mathematical sense) an anomaly is reported
  - Challenges: TOCA has many processing phases, profiles or normalcy required for each, and transitions between phases introduce hard to characterize transients

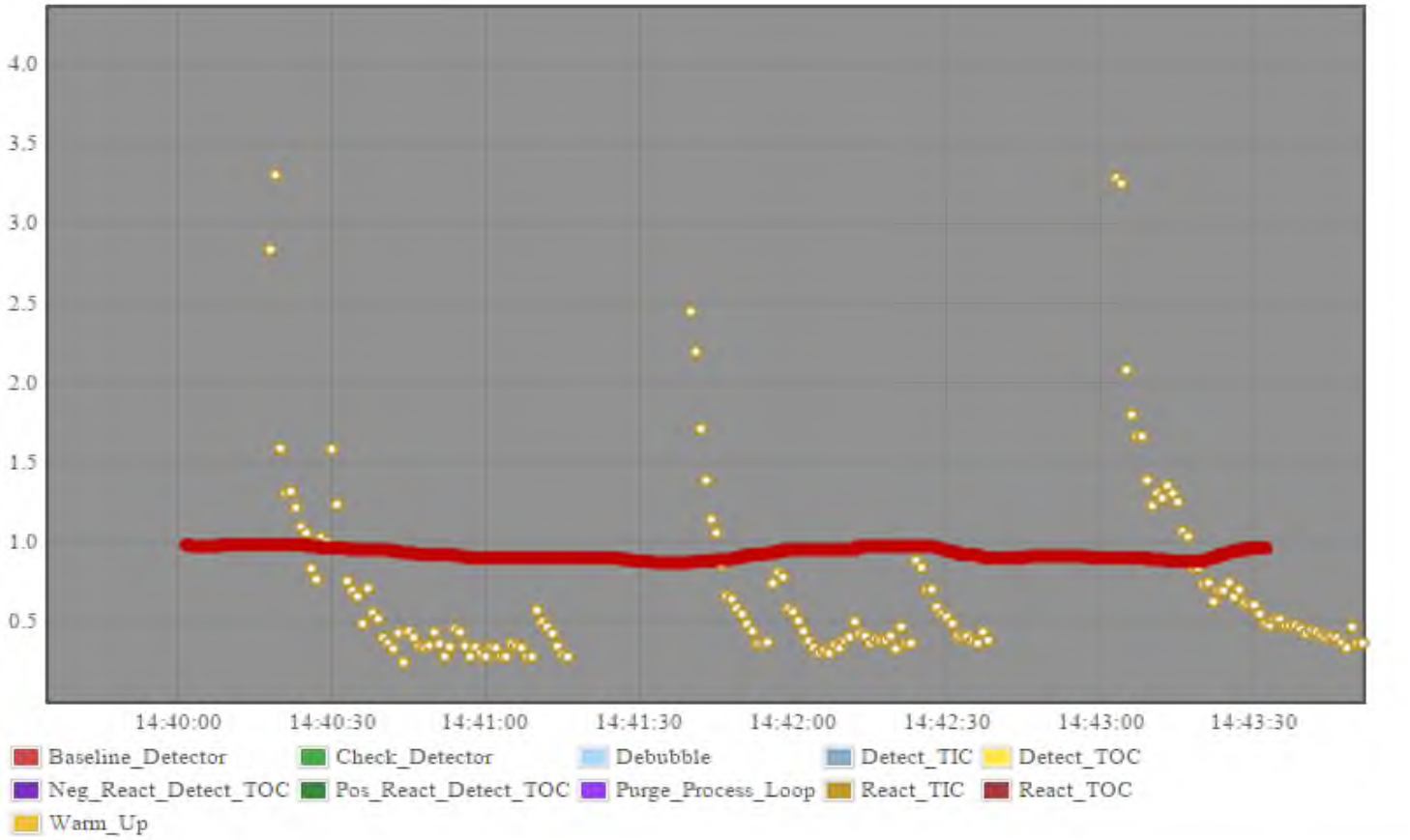
Software Design

- Inductive Monitoring System



Software Design

- Inductive Monitoring System



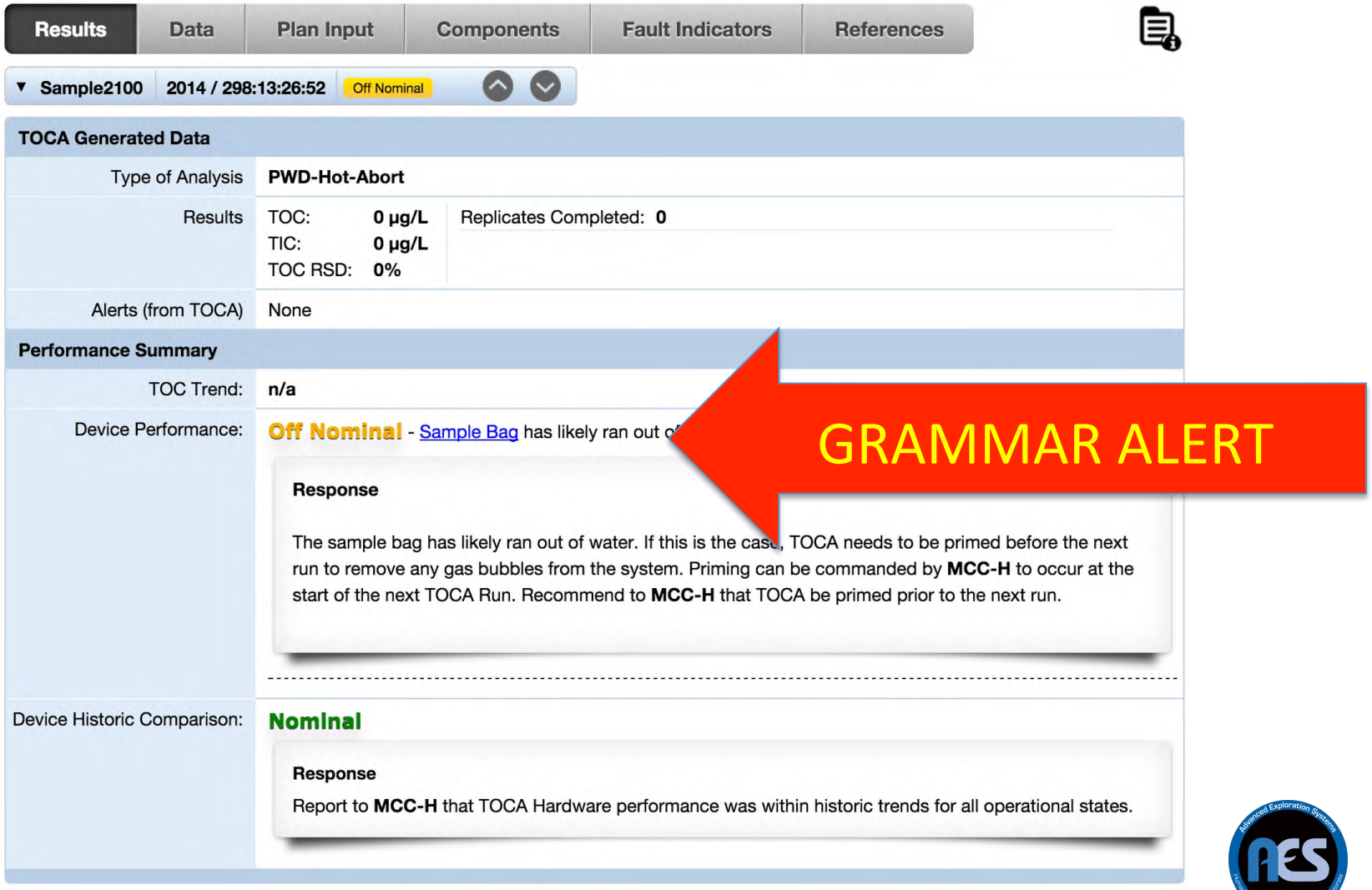
Software Design

- Hybrid Diagnosis Engine (HyDE)
  - Monitors TOCA performance to detect *faults*
  - Model consists of states (normal and faulty) and state transitions (events, including faults, and commands)
  - HyDE searches for faults that explain discrepancies between model (predictions) and world (data)

Fault Type	# Faults	Fault Type	# Faults
Sensor Faults	27	Acid Dispenser	1 (failed)
Valve Stuck	12 (open/closed)	Circ Pump	1 (failed)
Sample Bag	1 (underfilled)	Reactor	1 (failed)
Hose	1 (valve closed)	Chiller	2 (hot/cold)
Waste Container	1 (full)	Pipe	1 (clogged)

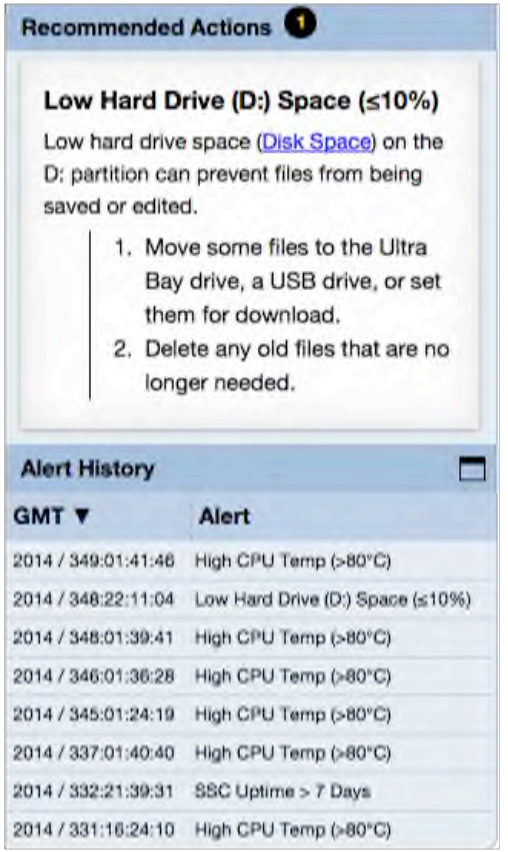
Software Design

- TOCA Results (HyDE and IMS)



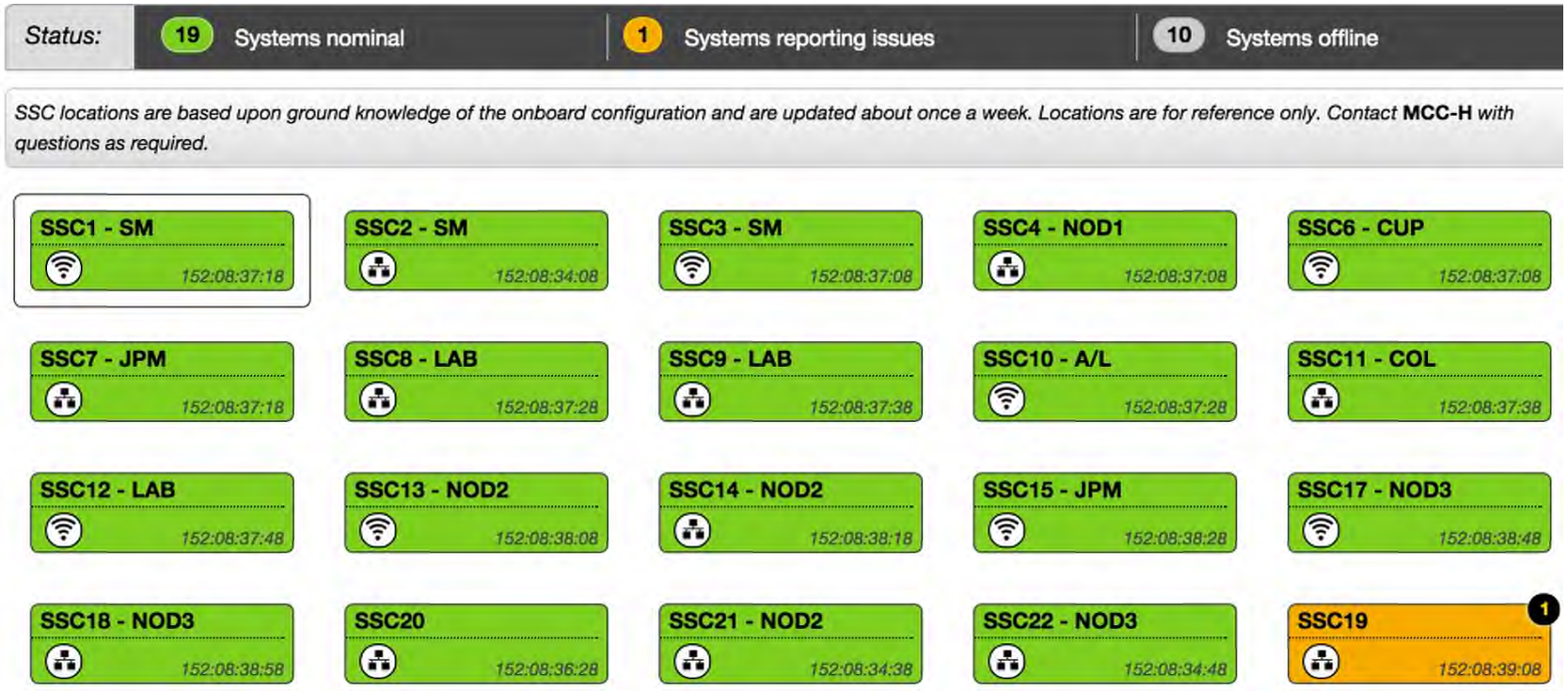
Software Design

- Limit Checker
  - Checks for SSC limit exceedances
  - Also checks SSC connection status
  - Produces alerts for UI
  - History of alerts stored for 5 weeks

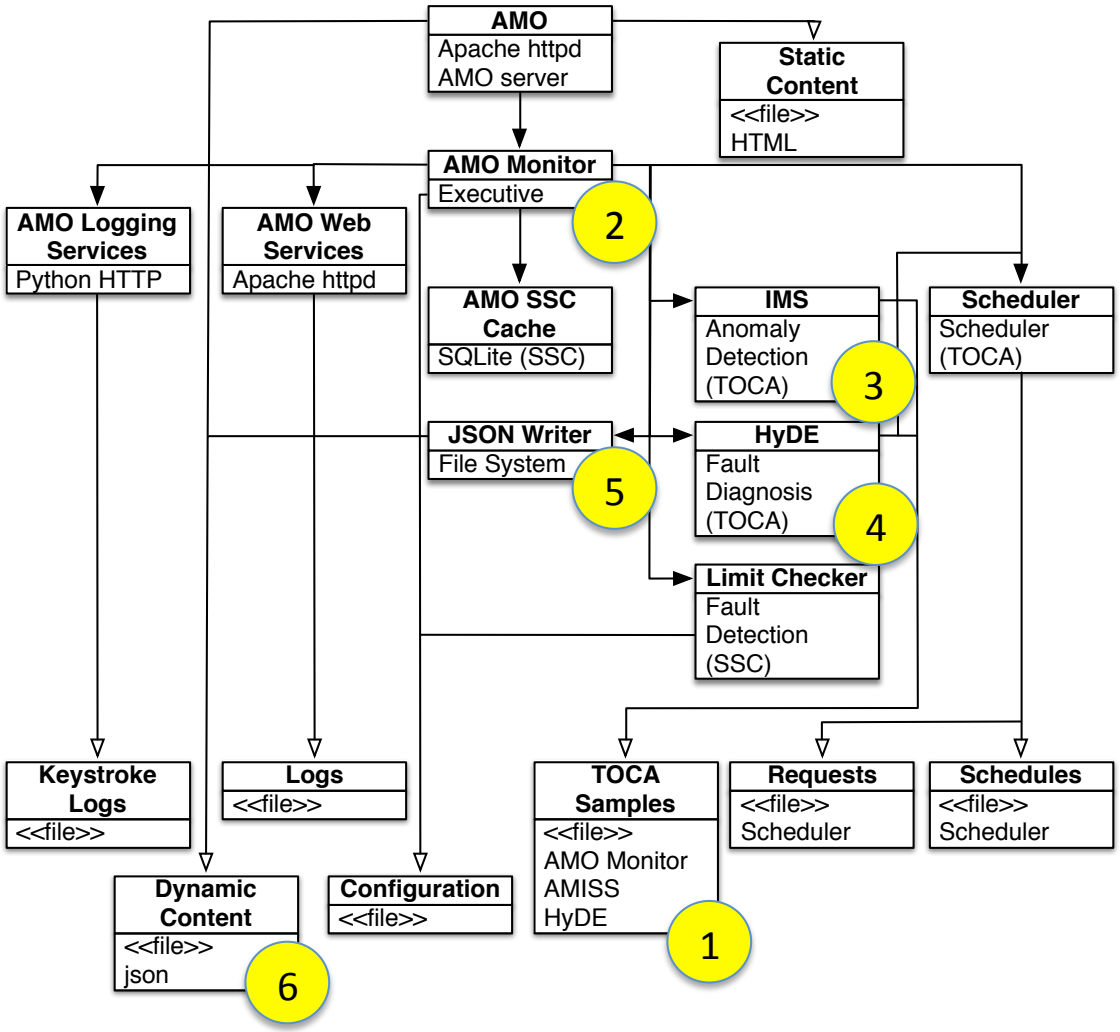


Software Design

- Limit Checker
  - SSCs with alerts in latest processing phase are flagged on SSC Overview



Software Design



Demonstration Results

- Summary
  - Project start: December 2012
  - Software completion and delivery: June 2014
  - Deployment: August 2014
  - 7 months on orbit (Sept. 2014 – April 2015)
- Usage Statistics
  - 59 TOCA samples processed
  - 31 uses of Scheduler on orbit
  - 15 uses of IMS and HyDE for analyzing TOCA performance
  - SSC data processed once / hour for 7 months

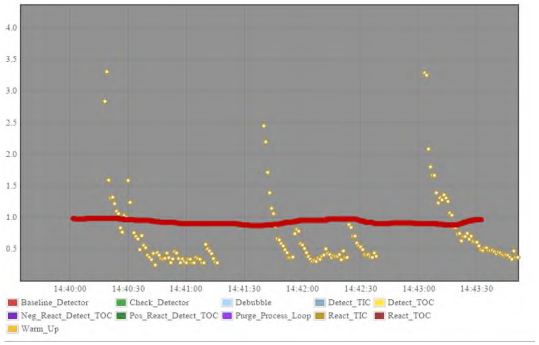
Demonstration Results

- Software Performance Summary
  - Focus on TOCA, system for which ground truth available

Function	Analyses	Correct	Score
Scheduler	31	28	90%
IMS	59	52	88%
HyDE (detect)	59	59	100%
HyDE (diag)	59	57	50%

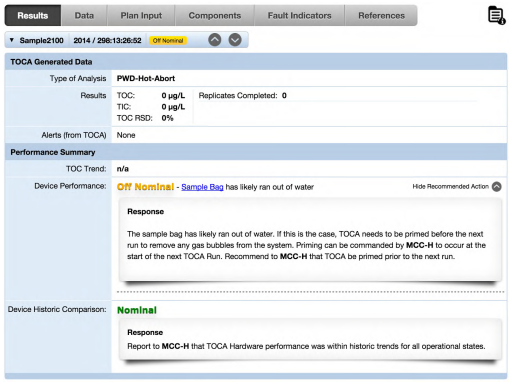
Demonstration Results

- IMS Performance
  - Focus on one TOCA component (liquid loop)
  - 12 anomalies detected
  - 5 False positives (as judged by flight controllers and SMEs)
  - 2 False negatives (TOCA aborts)
  - Transients were hard to model
  - No retraining after deployment for flight



Demonstration Results

- HyDE Performance
  - Fault detection accuracy was perfect
  - Diagnosis was not (2/4 correct diagnoses)
  - First error due to modeling omission (unexpected error)
  - Second due to lack of data and modeling omission
    - Cabin over-temperature led to TOCA over-temperature
  - At least one modeling error seen pre-flight (sensor failure)



Demonstration Results

- Scheduler Performance
  - 31 crew uses, so 31 evaluations of scheduler
    - Scheduler ran onboard many more times
  - 2 process errors
    - Crew use of Scheduler but no current schedule uplinked
  - 1 software design error
    - Failure to account for scheduled activity just outside 3 week 'window'

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Demonstration Results

- What Worked Well:
  - AMO reasoning algorithms performed well
  - Flexibility of model-based systems enabled software reuse and reduced redesign time
  - Early identification of operating environment and virtual machine solution for software isolation
  - Systems integration was relatively easy due to clean interfaces of pre-existing components

Demonstration Results

- Lessons Learned:
  - Unmodeled TOCA failures, lack of complete data concerning external events, and incomplete coverage of TOCA hardware meant performance was not perfect
  - Lack of time during experiment to change onboard configuration to address errors found during operations
  - Process issues for TOCA scheduling led to some errors
  - Manual extraction of TOCA activity detail needed
  - Early problems with uplink-downlink due to onboard resource limitations and communications coverage
  - Lack of understanding of onboard data processing time, coupled with latent software bug, caused early problems

AMO On Orbit
(R. Wiseman, Sept. 2014)


Summary

Summary

- AMO TOCA SSC
  - Decision support for spacecraft habitation systems (life support, crew computers)
- AMO EXPRESS
  - System automation (powerup and configuration, fault detection and recovery)
- ACAWS
  - Spacecraft cockpit fault management

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Summary

AI Applications Used in Demonstrations

	AMO TOCA SSC	AMO EXPRESS	ACAWS
Model-based Fault Management	HyDE	Timeliner (simple limits)	TEAMS
Anomaly Detection for Fault Management	IMS		
Model-based Planning and Scheduling	Custom-built dispatch scheduler		
Discrete Control / Plan Execution		Timeliner	
Intelligent User Interfaces	Schedule Display	Procedure Display	Fault Display

Summary

	TOCA	SSC	EXPRESS	EFT1
Data items	22	161	276	4,000
Displays	13	185	0	0
Procedures	12	7	0	0
Plan Steps	6	0	57	0
Constraints	10	0	0	0
Faults	70	207	35	3,500

Summary

Scaling Up…

	TOCA	SSC	EXPRESS	EFT1	ISS (USOS)
Data items	22	161	276	4,000	170,000
Displays	13	185	0	0	5,000
Procedures	12	7	0	0	4,000
Plan Steps	6	0	57	0	500
Constraints	10	0	0	0	200
Faults	70	207	35	3,500	13,000

…is a work in progress!

Acknowledgements

The work described in this presentation was performed by a cross-NASA center team (ARC, MSFC, JSC).

The work described in this presentation would not have been possible without NASA astronauts and flight controllers, who participated in our demonstrations, and provided critical feedback into the design of our software, both prior to and during our demonstrations.

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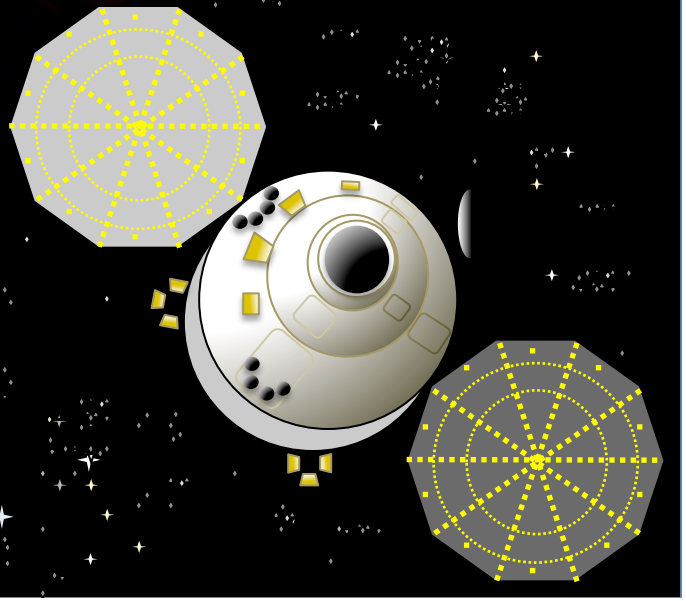
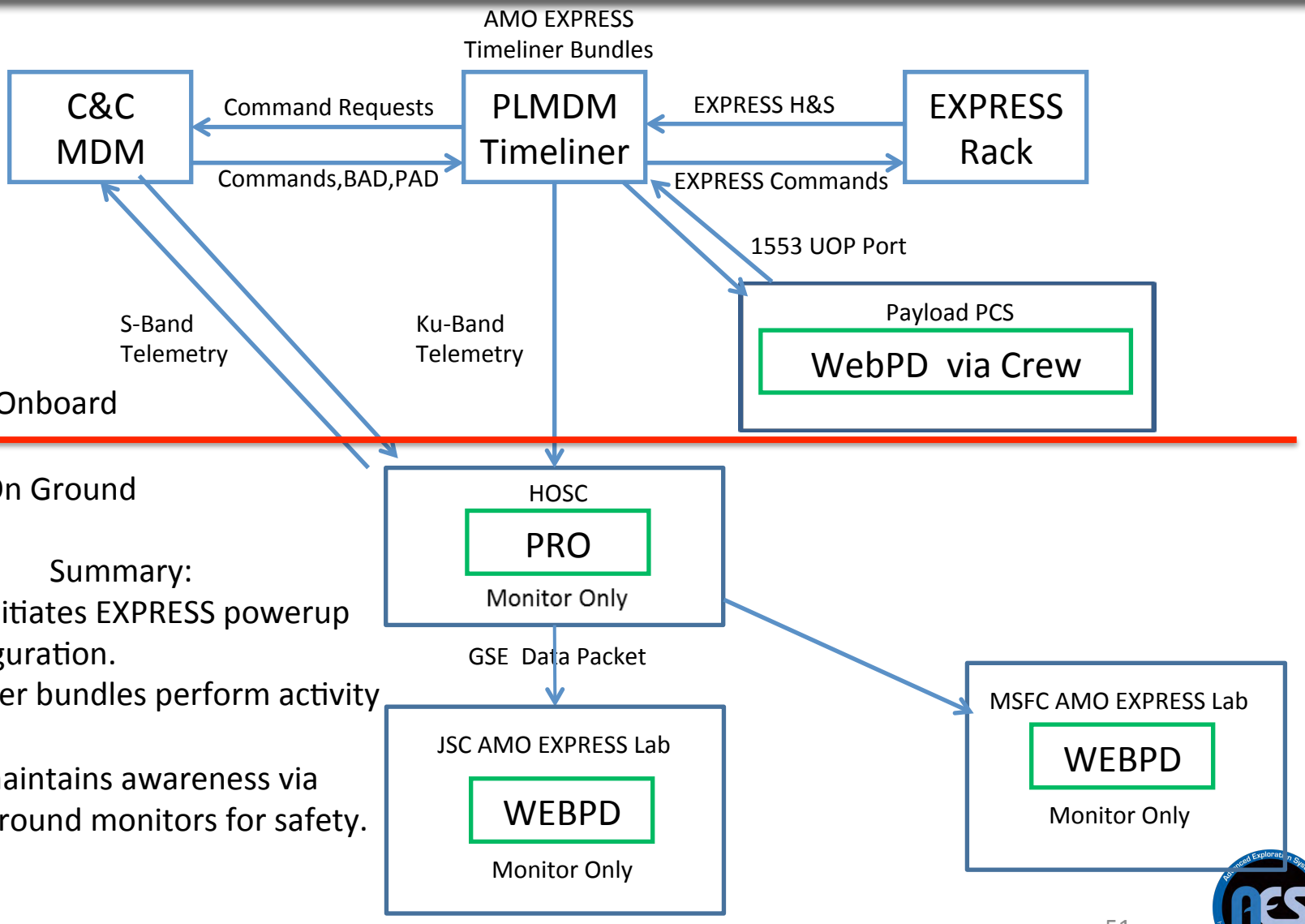
Autonomous Mission Operations

Thank you!



AMO EXPRESS



Summary:

1) Crew initiates EXPRESS powerup and configuration.
2) Timeliner bundles perform activity onboard.
3) Crew maintains awareness via WebPD; ground monitors for safety.

Definitions: Mission Operation Function

- Monitoring
  - **What is the state of the spacecraft?**
  - Process and abstract data from sensors.
  - Group resulting information into displays.
  - Displays are specific to major spacecraft system and/or phase of mission.
  - Monitoring ensures plans are being performed as expected, and spacecraft state is known.
- Planning and Scheduling
  - **What is the spacecraft doing and when?**
  - Plans are created to achieve specific objectives.
  - Plans are created days to weeks ahead of time.
  - Plans are often created for major spacecraft subsystems separately, then integrated.
  - Unexpected events or faults may require replanning on shorter time scales.

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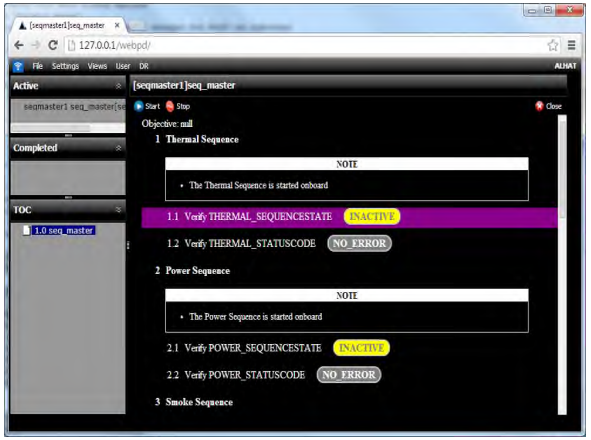
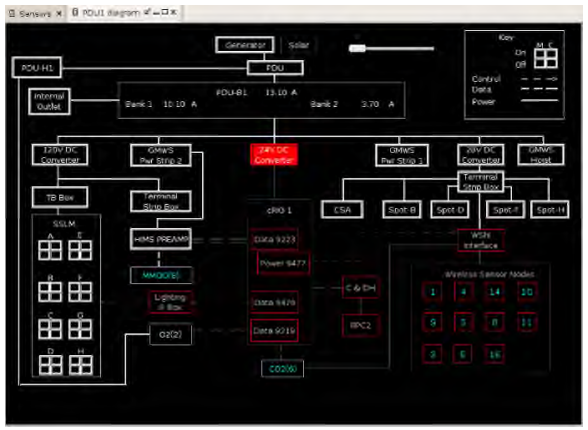
Definitions: Mission Operation Function

- Execution
  - **What is the next activity to perform?**
  - Execution involves issuing commands to spacecraft subsystems and ensuring results are as expected. (See Monitoring)
  - If unexpected events occur, replanning may be needed. (See Planning and Fault Management)



- Fault Management
  - **Is something wrong? What are the impacts?**
  - Fault management involves the detection and isolation of faults (See Monitoring).
  - Fault management also involves determining the consequences of faults.
  - Recovering from or mitigating faults involves replanning. (See Planning)

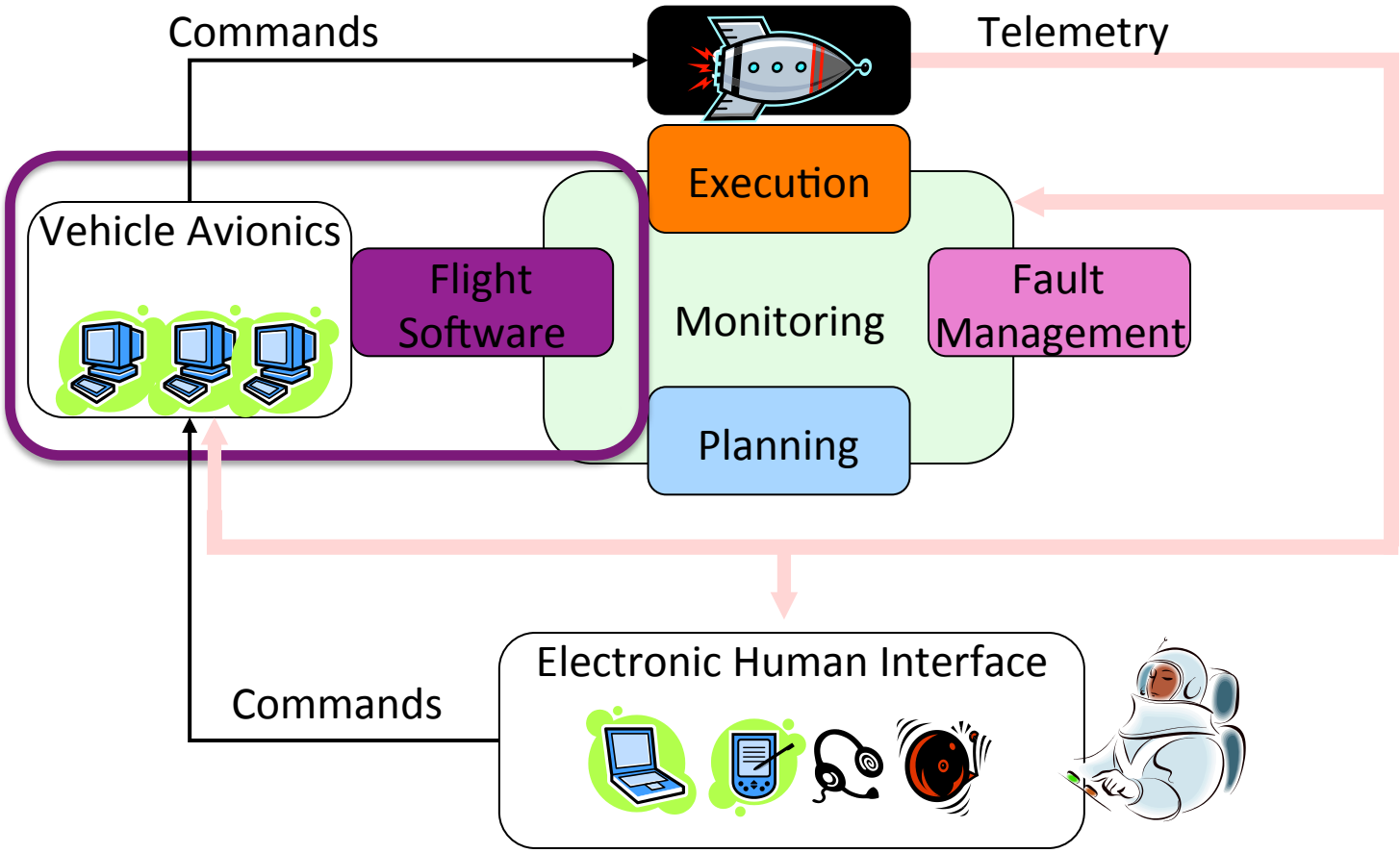


Definitions: Autonomy and Automation

- Autonomy
  - The state of existing or **acting separately from others.** (Webster's)
  - Able to independently choose how to act in order to achieve goals (perhaps provided by another entity).
  - Autonomy is a **relative** term: Autonomous from **whom?** for **what purpose**? and **when**?
- Automation
  - **Automatically controlled operation** of an apparatus, process, or system by mechanical or electronic devices that take the place of human labor. (Webster's)
  - Able to perform a **pre-specified set of instructions** on its own.
  - Automation is a **tool** that enables (supports) autonomy.

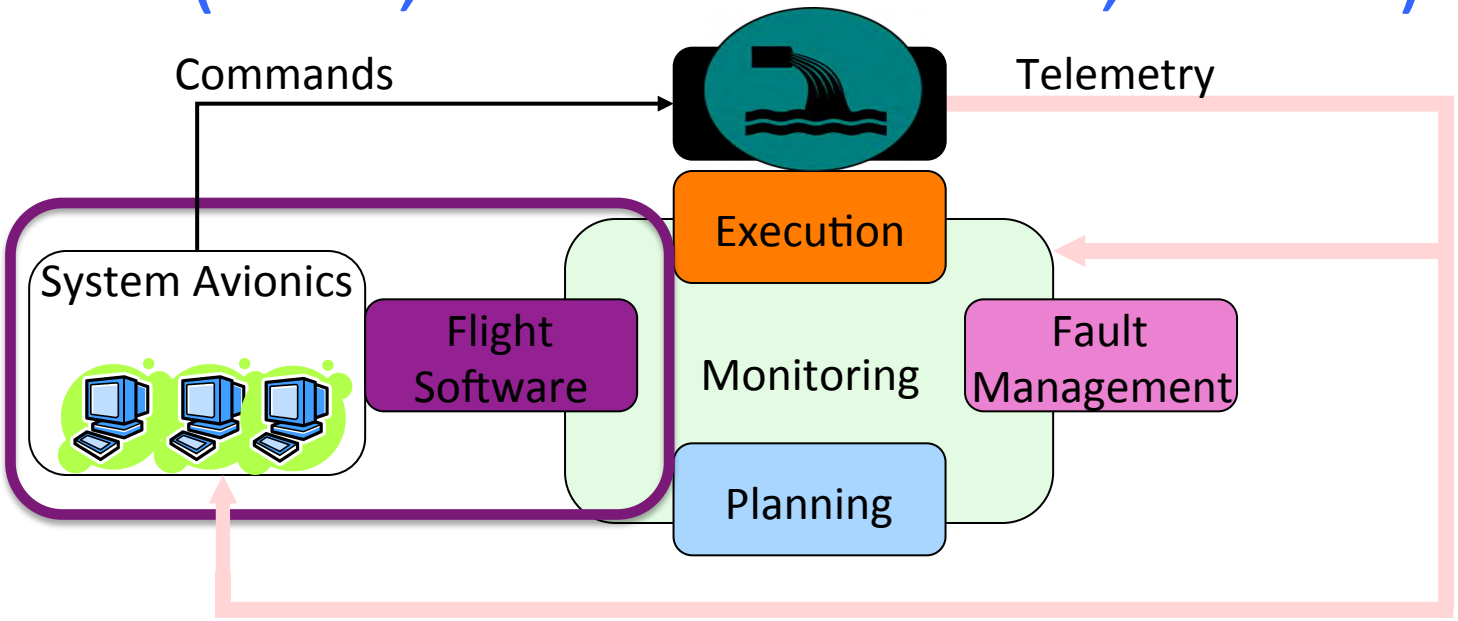
Where is Autonomy Applied?

Vehicle Systems Management (Workload Reduction and Dormancy)



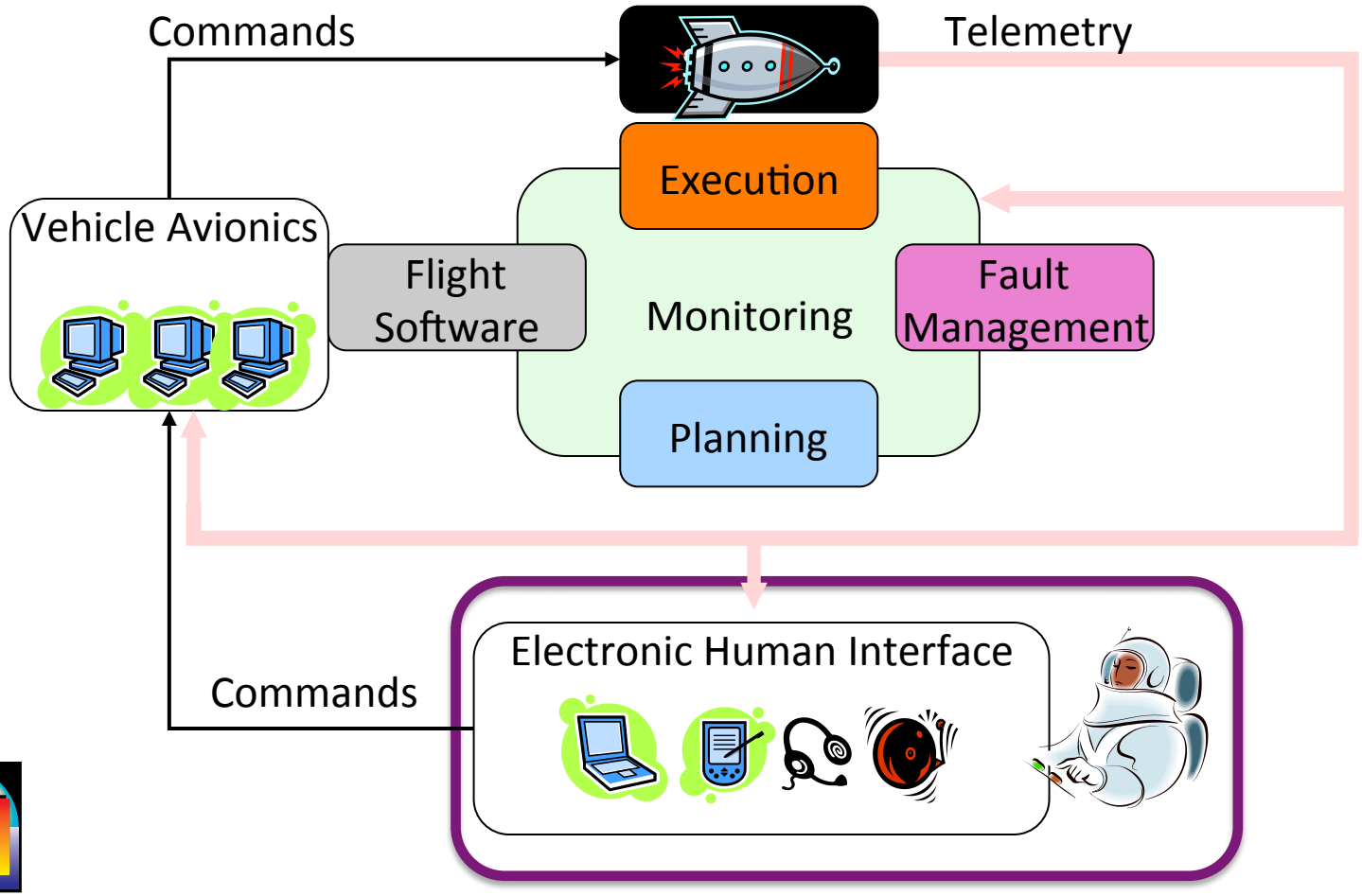
Where is Autonomy Applied?

Surface Assets
(ISRU, Communications, Power)

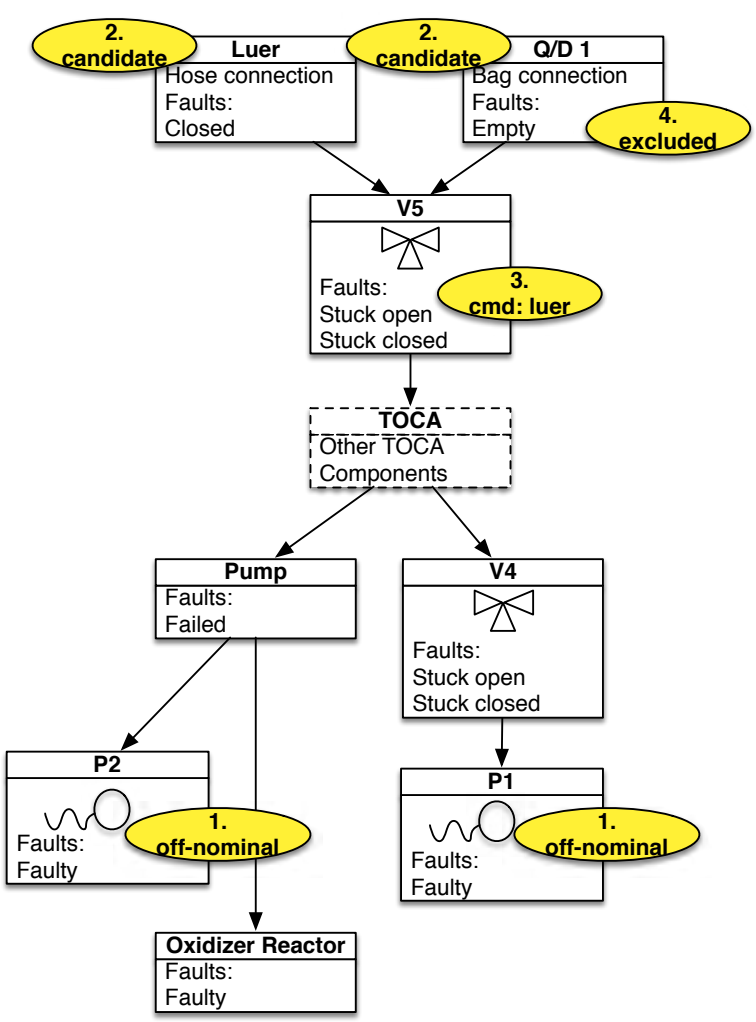


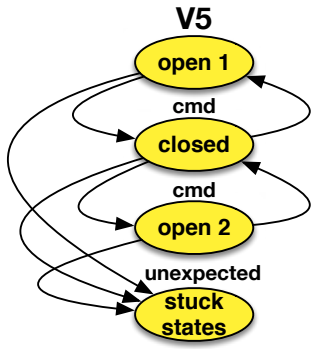
Autonomous Mission Operations: Projects

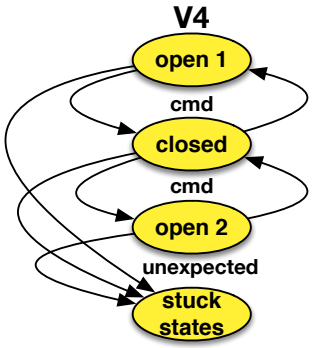
Software Architecture of Decision Aids

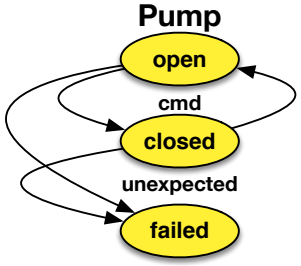


Software Design









Concept of Operations

Crew Planning

Crew autonomously recommends activities for the following week.

- Planning
- Procedure Recommendation
- Constraint tracking

Crew Plan Execution

Crew tries to resolve any questions themselves before calling MCC.

- System Expertise
- Failure Recognition
- Procedure Recommendation

Crew System Analysis

Crew analyzes both hardware performance and results of activities autonomously

- Failure Recognition
- Analysis and "Go for Ops"
- Systems Expertise

AMO TOCA SSC by the Numbers

70 million miles traveled by ASO software.
4016 SSC data analyses performed.
251 days onboard.
123 data downlinks.
106 flight controllers used the software.
59 TOCA samples analyzed on orbit.
41 schedule updates.
38 uses of Scheduler by astronauts.
15 TOCA sample status checks by astronauts.
12 notifications of TOCA anomalies.
4 ISS astronauts used AMO software.
4 ISS increments software was in use.
4 TOCA fault notifications.
3 ASO software updates on-orbit.
2 countries' astronauts.
1 awesome team.