Autonomous Planning System (APS) for an Onboard TCPED Pipeline

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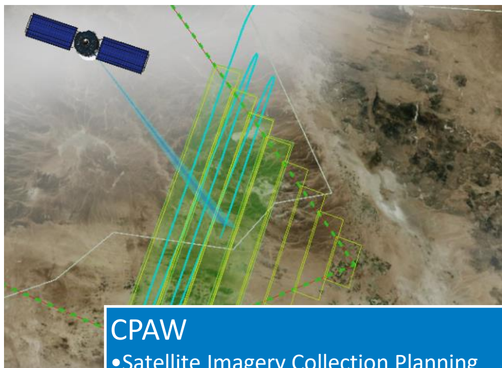
Dr. Kenneth Center, Orbit Logic Incorporated, Ken.Center@OrbitLogic.com
Ella Herz, Orbit Logic Incorporated, Ella.Herz@OrbitLogic.com
Evan Sneath, Orbit Logic Incorporated, Evan.Sneath@OrbitLogic.com
Sam Gagnard, Orbit Logic Incorporated, Sam.Gagnard@OrbitLogic.com
Rey Juarez, Orbit Logic Incorporated, Rey.Juarez@OrbitLogic.com
Dr. Neil Dhingra, Orbit Logic Incorporated, Neil.Dhingra@OrbitLogic.com

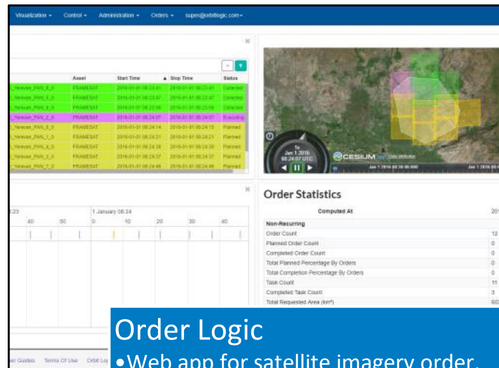
About Orbit Logic

Orbit Logic **specializes** in mission planning and scheduling software

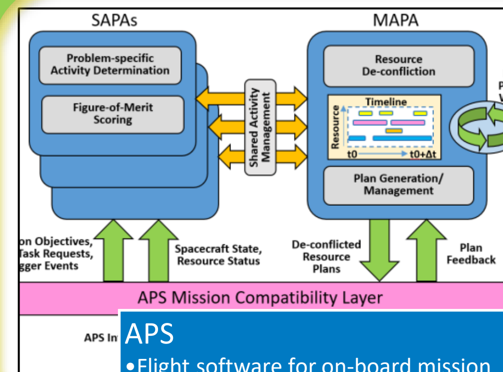
- Primary markets: aerospace and geospatial intelligence
- Off-the-shelf products, customized solutions, and services – since 2001
- Create better plans faster with fewer resources and more insight for all mission phases



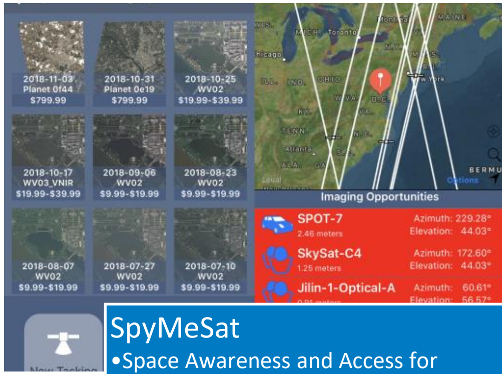
CPAW
- Satellite Imagery Collection Planning Software



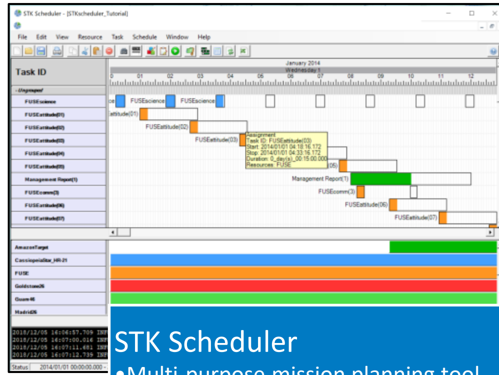
Order Logic
- Web app for satellite imagery order, asset, and observation management



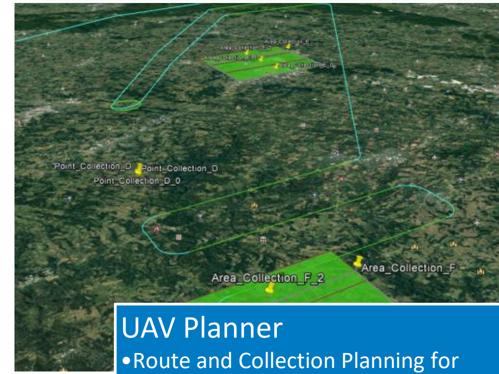
APS
- Flight software for on-board mission planning



SpyMeSat
- Space Awareness and Access for Everyone



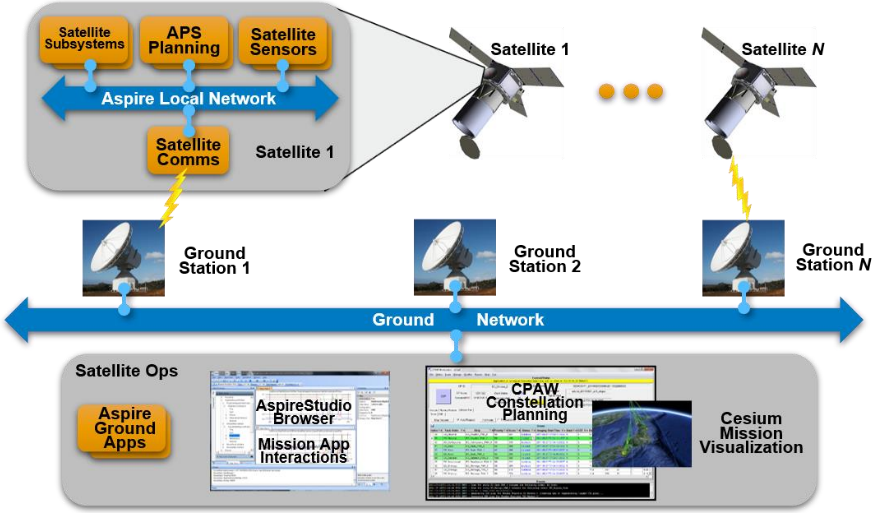
STK Scheduler
- Multi-purpose mission planning tool



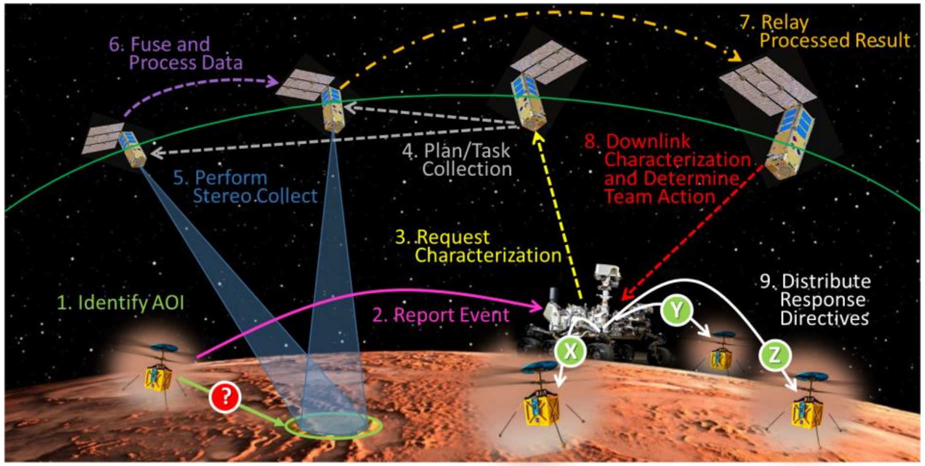
UAV Planner
- Route and Collection Planning for autonomous vehicles

Limitations of Centralized Control

- Some limitations of the traditional ground-based planning/tasking cycle:
  - Subject to link availability, latency, bandwidth limitations
  - Very limited view into satellite data
  - Significant delay sending directives to satellite
  - Ground station is single point of failure
  - **Ensuring timely responses to on-orbit events may not be possible…**

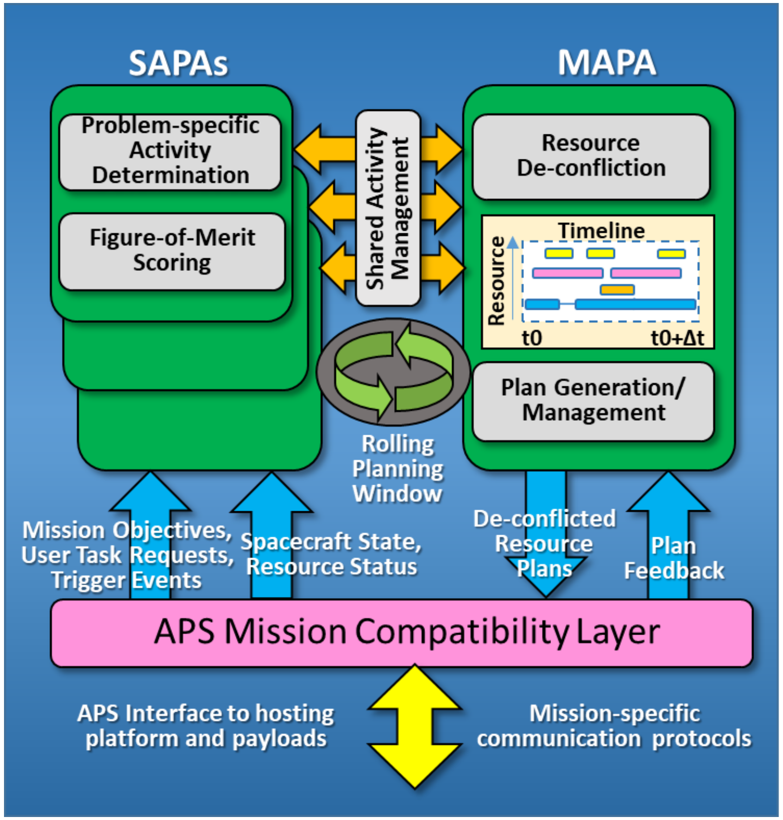


- Where would these limitations matter?
  - Time sensitive operations
    - Operations far from Earth
    - Autonomous rendezvous, collision avoidance, etc.
  - Large, distributed systems
    - Cooperating satellite clusters, constellations
    - Reactive tasking, cross-cueing other sensors
  - Large chains of dependent tasks
    - Tasking, Collection, Processing, Exploitation, and Dissemination (TCPED) pipeline



Autonomous Planning System (APS)

- Specialized Autonomous Planning Agents (SAPAs) address specific planning needs using of tailored approaches
  - Nominal and response planning
  - State- and Rules-based decision logic
  - Figure-of-Merit scoring of competing algorithms
- Master Autonomous Planning Agent (MAPA) de-conflicts local/global resources and creates a final plan
- APS is flexible and broadly deployable
  - Modular, plug and play architecture allows dynamic introduction/removal of SAPAs based on current mission needs, also facilitates extension/upgrade
  - Data sources used by planners obtained from local and remote sources
  - Messaging middleware provides XML-described abstract interfaces to services and system data
    - Translators map to native system formats/protocols
- APS is being applied to multiple mission domains
  - Earth – satellites and ground-based sensors for Space Situational/Domain Awareness (SSA/SDA), satellite protection, collaborative constellations
  - Heterogeneous collaborative maritime systems
  - Planetary and Lunar science/exploration swarms

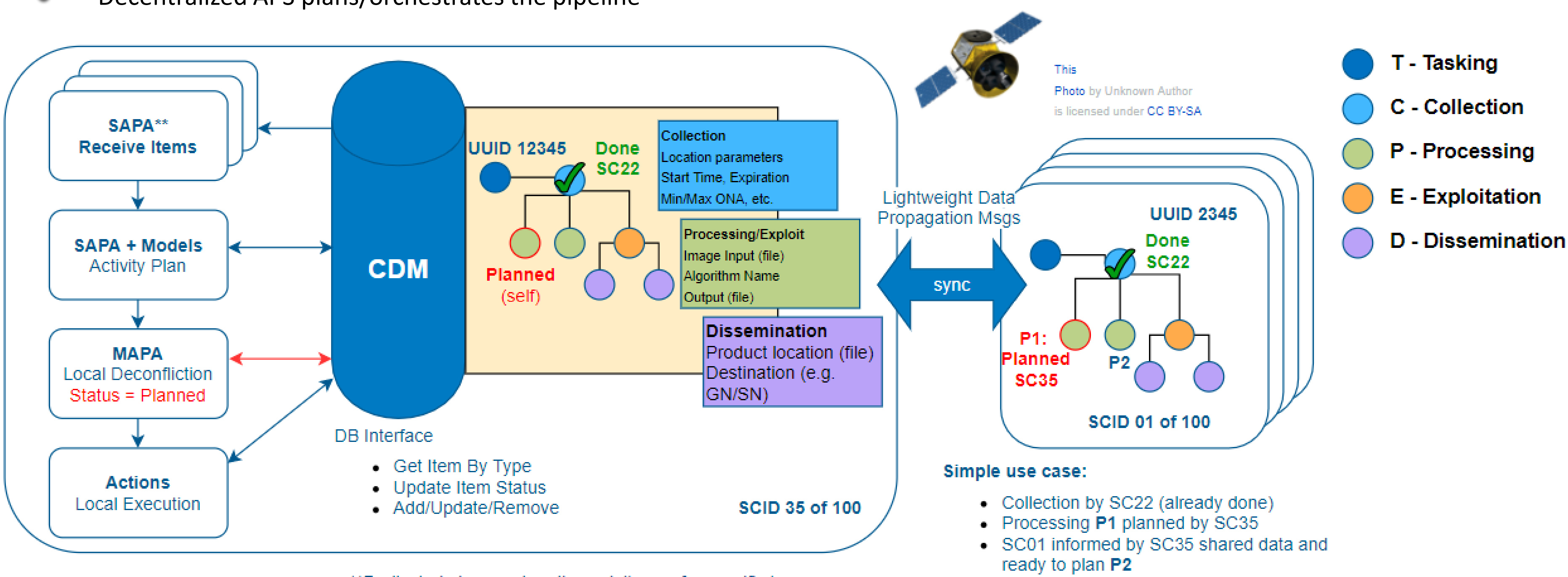


Primary Architectural Features

- APS can work off of a shared-world view, or Common Relevant Operating Picture (CROP), between assets
  - Facilitated by networked interoperability over communication links
  - Ensures all assets have local access to the information needed to make informed autonomous decisions
    - For solo activities that can be realized in full by a single asset
    - To meet mission-level objectives that require the support of multiple assets of differing capability (team collaborative)
- APS constitutes a fully decentralized approach to team-level planning
  - Bid-pass strategy on individual items in “work-pipelines”
  - Near-term receding time horizon planning on every asset
    - Greater opportunity for responsiveness to ad-hoc events
  - No single points of failure as with centralized planning
    - And resilient to failed/unresponsive nodes
  - Scales well to high-order autonomous teams
  - Reduce the computing resources needed by any given node

CDM Work Pipeline Management

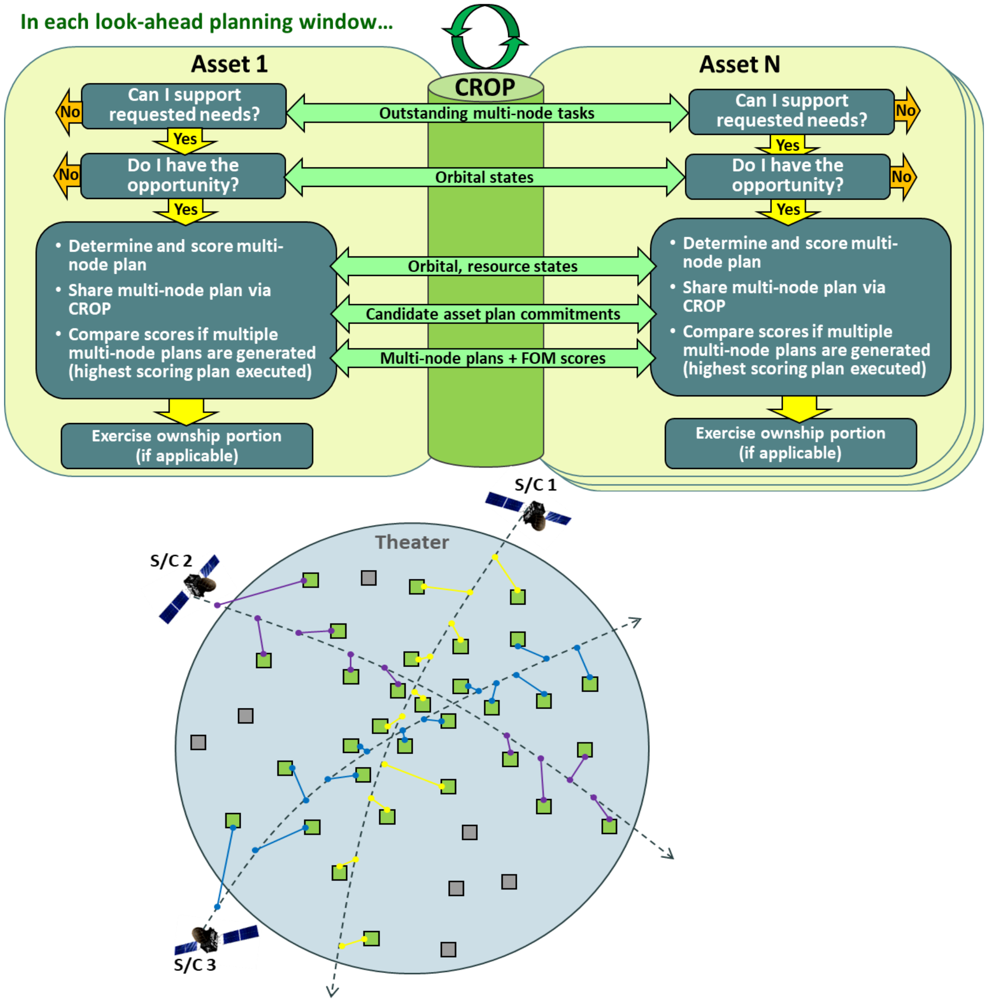
- **Constellation Data Manager (CDM) in APS architecture facilitates CROP sharing**
  - States of assets (orbits, ephemerides), required to support decisions involving asset interactions
  - SAPAs perform planning to satisfy “work items” in a “workflow pipeline”
  - Work items align with steps in the TCPED process flow
  - Pipelines define the steps required to accomplish mission objectives (end result typically delivery of a data product resulting from sensor collections followed by multiple processing stages)
  - Each work item can be accomplished by any asset with necessary equipment/capabilities and data access
  - Decentralized APS plans/orchestrates the pipeline



**Dedicated planners handle work items of a specific type

APS Constellation/Team Planning

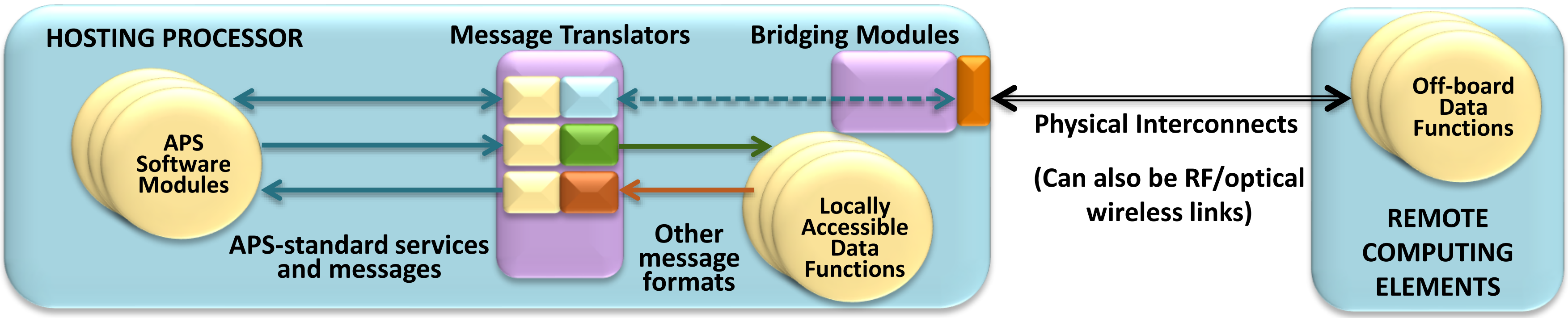
- **APS instances perform decentralized planning of activities**
  - SAPAs associated with a particular mission need are invoked on periodic/event basis
  - SAPAs determine opportunities to meet the need with activities (only a limited time into the future)
  - MAPA determines de-conflicted collection schedule, scores each by "goodness" (multi-factor Figure of Merit)
  - Plan metadata and scores are shared across asset team in CROP
  - Assets with lower scores than best stand down



State-aware coordinated planning
(Team Figure-of-Merit = 592.8)

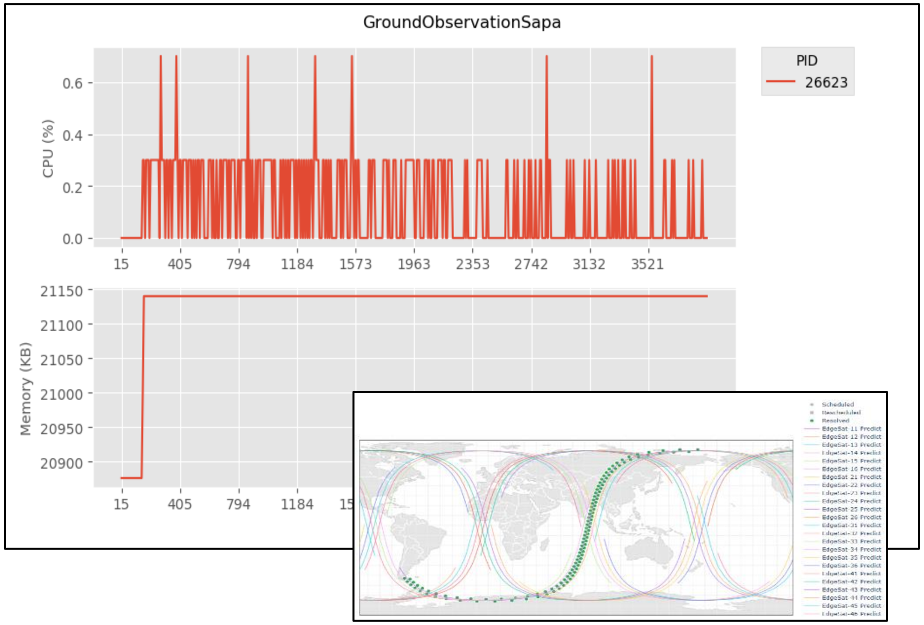
Mission Compatibility Layer

- For APS onboard architecture to be interfaced to existing/future systems, need flexibility in interfacing to variety of “native” data protocols and interconnects
  - Software might be hosted on mission processor, or on a separate “appliance” (co-processor)
- Compatibility Solution exposes service interfaces and messages to APS that can remain invariant when changing the hosting accommodation
  - Have already implemented support for several messaging standards (ROS, CFS, NATS, ProtoBuf, CCSDS, custom flight program protocols)
  - Over multiple transports/interconnects (sockets, Ethernet, RS-232/422, SpaceWire)
  - All C++ based for efficiency and use in constrained computing environments
  - Use of code generation to rapidly configure compatibility for given need



Execution on Flight Computers

- APS Performance Benchmarking
  - Routinely performed for several programs
    - AFRL SaFIRE
    - DARPA Blackjack
    - Large Aerospace Prime Customer
  - Frugal utilization of processing and memory



Innoflight CFC-400 Flight Computer equivalent

Hardware Configuration

Item	Details
Board Type	Xilinx Zynq UltraScale+ MPSoC ZCU102 Evaluation
Processor(s)	Quad-core Arm® Cortex®-A53 Dual-core Cortex-R5F*
GPU	Mali™-400 MP2*
System Memory	DDR4 SODIMM – 4GB 64-bit w/ ECC attached to processing system (PS) DDR4 Component – 512MB 16-bit attached to programmable logic (PL)*
Operating System	Linux iSpace-Host1 4.14.0-rt1-ispace-v2018.1 (ARM64)

** Components marked with asterisk are not currently utilized by APS flight software*

Benchmark Scenario

25 collaborating agile satellites

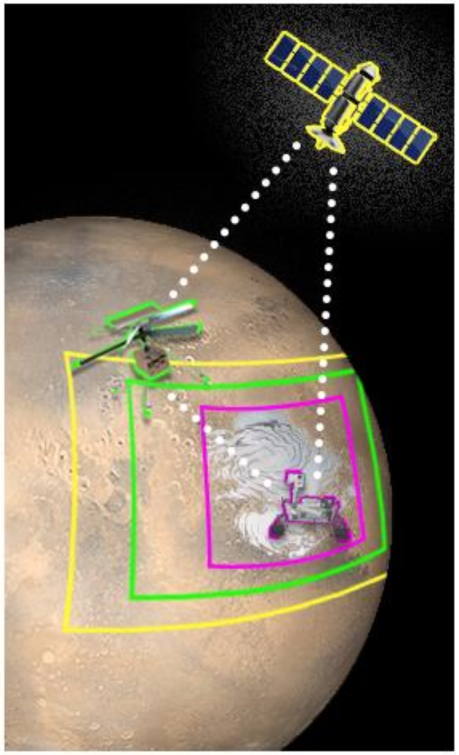
Each hosting EO sensor

120 surface targets accessible to all satellites over course of orbit

Plot represents resource utilization on one satellite

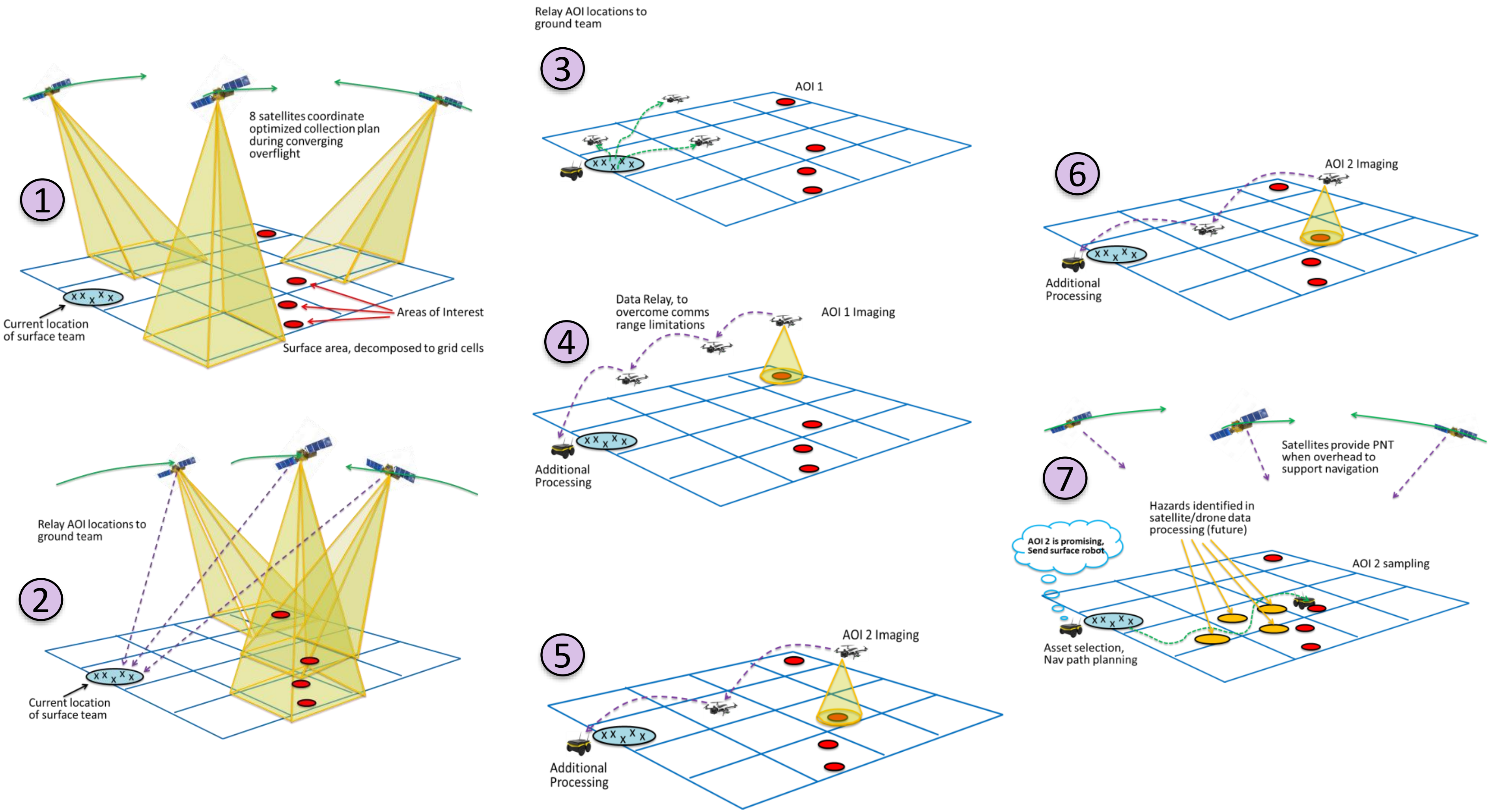
APS for Robotic Space Exploration

- **Mars/Interplanetary Swarm Design and Evaluation Framework (MISDEF)**
  - Swarms in the Martian environment
    - Using decentralized planning approach to meet mission goals with cooperating heterogeneous assets
  - Rovers, satellites, and rotorcraft
- **Intelligent Navigation, Planning and Awareness for Swarm Systems (IN-PASS)**
  - Swarms in the Lunar environment with Astronauts-on-the-Loop
    - Formal methods approach to rover operations planning balancing mission performance and safety
  - Rovers, satellites, and Astronauts
- **On-board Swarm Control for Autonomy and Responsiveness (OSCAR)**
  - Extensions to facilitate a decentralized planning approach to autonomous satellite formation flying
  - Adapt the formation based on dynamic mission needs



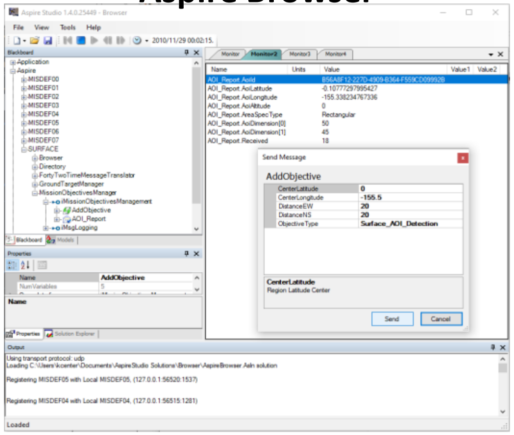
Collaborative Planetary Exploration/Survey Using A Variety of Science Sensors on Satellites, Rovers and Atmospheric Craft

Mars Exploration Demo Scenario

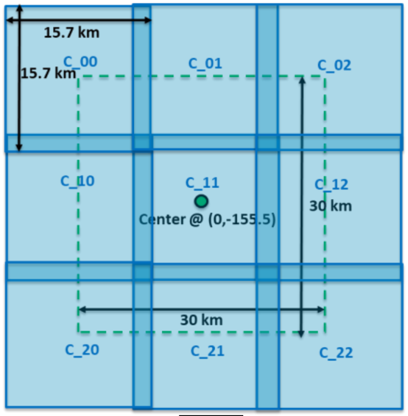


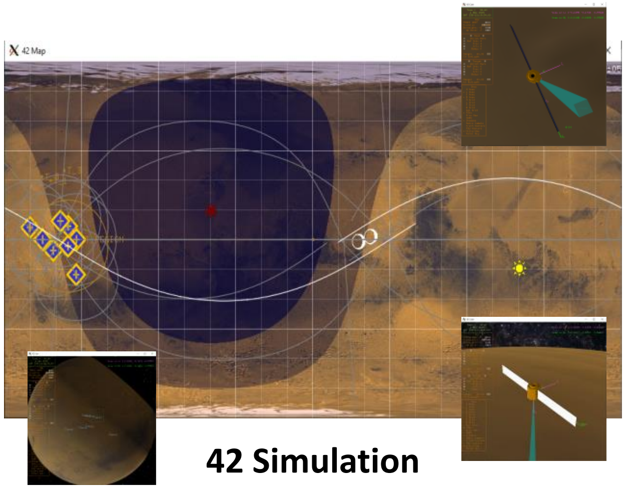
Satellite Constellation Planning/Orchestration

Assertion of Mission Objective using Aspire Browser

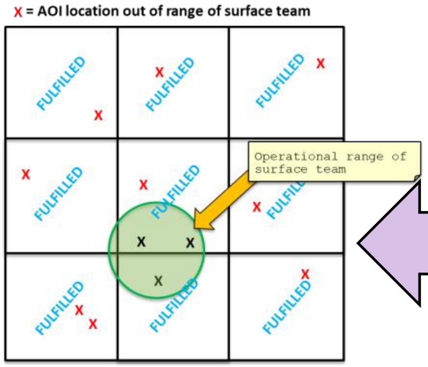


Gridding of region of interest

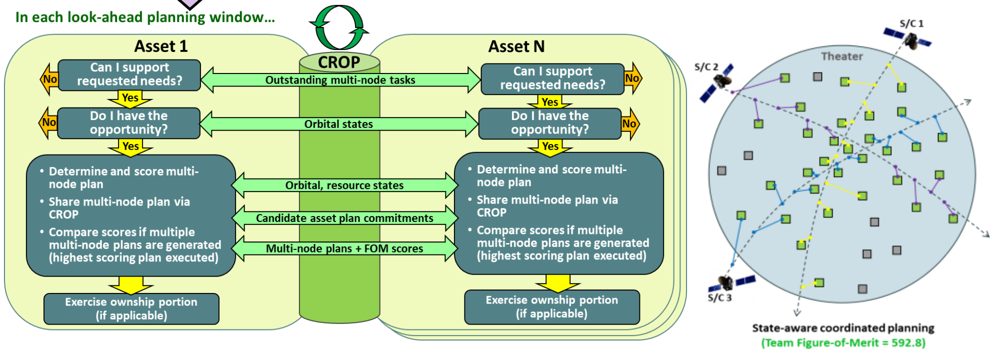




42 Simulation



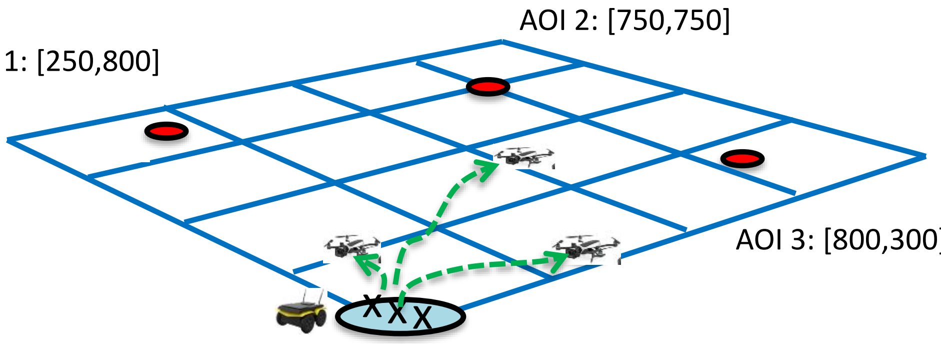
Processing and Dissemination of AOI locations to Surface Assets

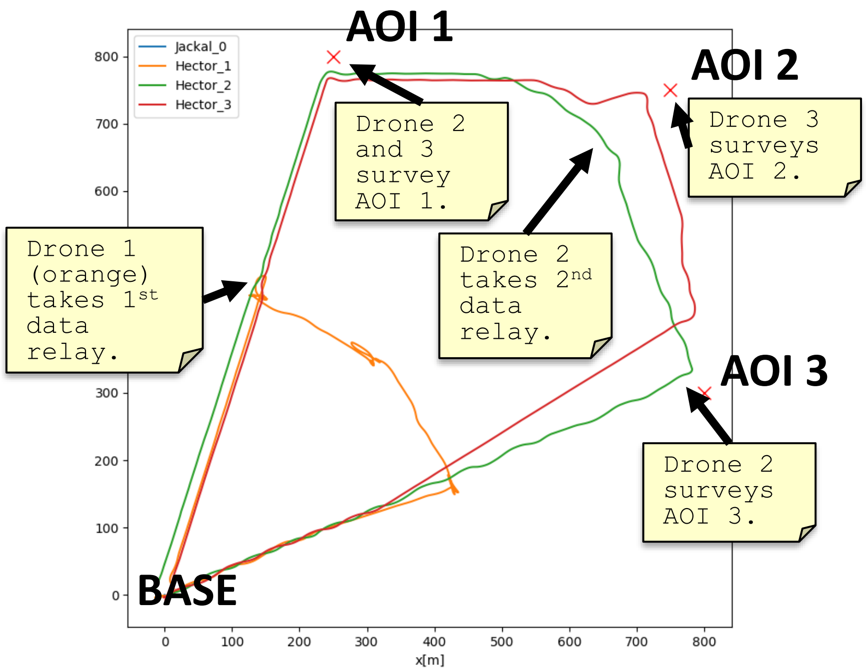


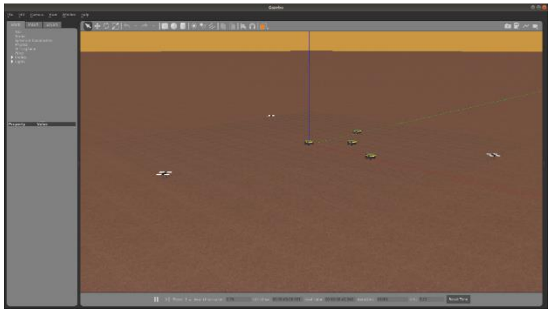
Decentralized planning of sub-region collection by APS

Planning of Drone Collects

- **Simulation Outline**
  - **3 drones, parked by rover**
  - **Tasked to sequentially provide hovering data collection**
  - **3 areas of interest within 1500m of base station (AOI 1→AOI 2→ AOI 3)**
- **Mission Objective**
  - **Optimal positioning of assets**
  - **Relay streamed sensor data back to base station during collects**
- **Notes**
  - **All real-time, not pre-planned**
  - **Accurate navigation is enabled by state-sharing**
  - **Exchanged on the same communication paths used to transport mission data during excursions**



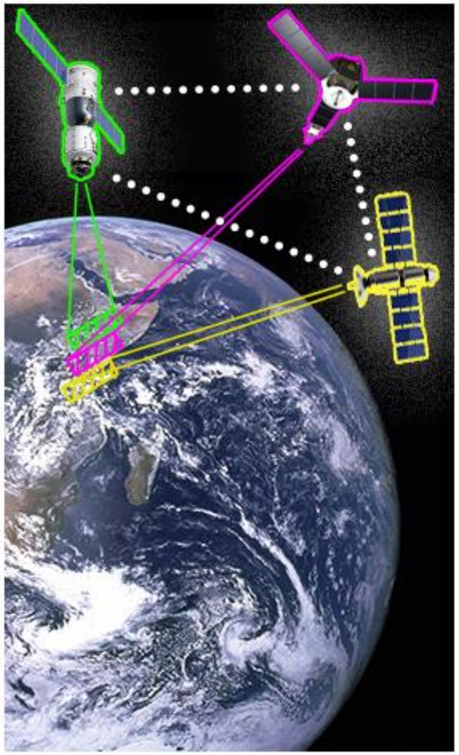




Gazebo Simulation Visualization

APS for Satellite Operations

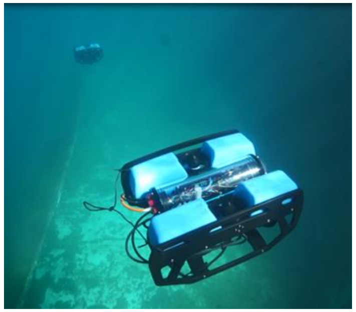
- **APS is scheduled to fly on two satellites – one in June 2021 and one in early 2022**
- Satellite Fusion, Inference & Response Engine (SaFIRE) - AFRL
  - Satellite enhanced Space Situational Awareness and Self-protection
    - Federated teams of satellites and ground-based sensors
- DARPA Blackjack Pitboss (SSCI Team Sagittarius)
  - Proliferated LEO constellations of heterogeneous sensing/processing
    - All planning and decision-making in the constellation
    - Demonstration mission to be flown in June 2021 on Loft Orbital satellite
- APS as Part of an Orbit Logic Enterprise Solution
  - Developing cloud-based satellite constellation targeting intel community needs
  - Hybrid centralized/de-centralized planning system and 2022 flight demonstration



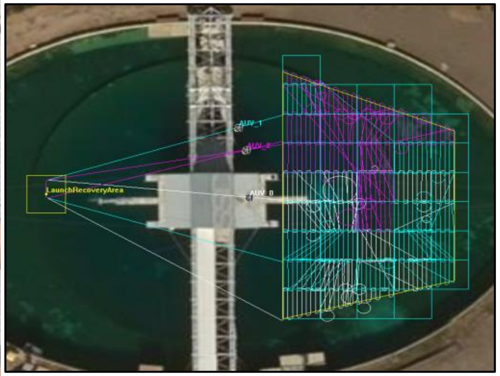
Collaborative Satellite Imaging with Rapid Reaction to Events

APS for Underwater Operations

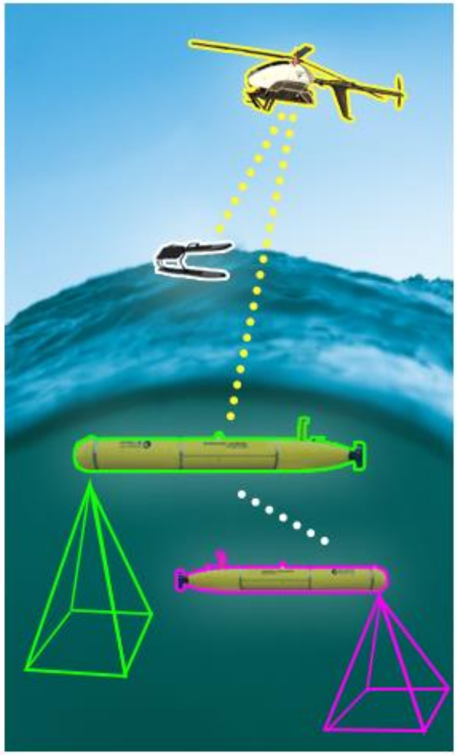
- **MinAu**
  - Collaborative Teams of maritime assets (UUVs, unmanned surface craft, supporting UAVs)
    - Unpredictable operating environments and challenging communications
  - Currently undergoing in-water testing



Calibrating onboard sensors for SeaRover pool testing



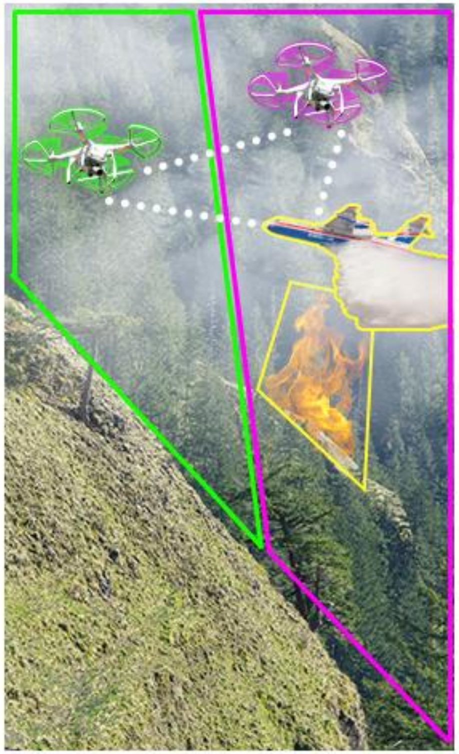
Nominal mission navigation plan for NIWC-PAC TRANSDEC Pool



Collaborative UUV Bottom Mapping or Patrol/Detect/Track with UAV Data Ferry Facilitating Communication to USV Mothership

Conclusions

- Autonomous Planning System (APS)
  - On-board software for autonomous operations
  - Networked, for seamless interoperability between nodes and cooperative constellation control
  - Modular architecture, for configurability to meet specific mission needs
  - Plug & play features, to facilitate systems with dynamic networks where nodes can come and go
  - **APS is a flexible platform that enables collaborative autonomy**
- Deployment
  - APS was originally developed for the autonomous control of satellites and satellite constellations
    - Will fly on two demonstration missions in 2021-2022
  - APS was applied for underwater surveying and search missions
    - Currently undergoing in-water testing
  - APS is being applied for robotic space exploration
  - **APS can be applied to any swarm of autonomous agents!**



Collaborative UAV Forest Fire Hot Spot Detection and Fire Suppression Tasking

Orbit Logic Contact Information

Primary POC: Ken Center Ken.Center@OrbitLogic.com

Orbit Logic Incorporated
7852 Walker Dr., Suite 400
Greenbelt, MD 20770

www.OrbitLogic.com

Email: info@OrbitLogic.com

Phone: (301) 982-6232

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