# Standards and Schematics for Intelligent Extensible Mission Architectures in Space

Evana Gizzi, Alan Gibson, James Marshall,
Shannon Bull, Timothy Chase Jr, Jonathan Davis,
Matthew Dosberg, Michael Johnson, Peter Knudtson,
John Lucas, Michael Monaghan, Chris Roberts, Daniel Rogers
*Engineering and Technology Directorate*
*NASA Goddard Space Flight Center*
Greenbelt, MD, USA
Email: evana.gizzi@nasa.gov

Bethany Theiling, Julie Breed,
Larry Kepko, Carrie Vuyovich
*Sciences and Exploration Directorate*
*NASA Goddard Space Flight Center*
Greenbelt, MD, USA
Email: bethany.p.theiling@nasa.gov

Connor Firth, Lily Clough
*Aurora Engineering*
Wilton, NH, USA

Aaron Woodard, Caleb Adams,
Brian Kempa
*Intelligent Systems Division*
*NASA Ames Research Center*
Moffett Field, CA, USA

Robin Onsay, Sam Pedrotty,
James Berck
*Engineering Directorate*
*NASA Johnson Space Center*
Houston, TX, USA

***Abstract*—As the space sector trends toward complex mission types, the demand for multi-asset, multi-generational, and multi-organizational paradigms has grown. It is critical that the spaceflight community builds the infrastructure needed to realize these mission architecture goals. To this end, we present a standard and schematic for intelligent extensible mission architectures, which will allow missions of the future to be distributed, heterogeneous, incremental, and interoperable for enhanced flexibility, adaptability, and responsiveness in space. We begin by describing a motivation for intelligent extensibility, followed by a review of related work in standards and autonomous multi-agent systems. Next, we present the theoretical definition and schematic of our standard, followed by an illustrative example and description of experimental results. We conclude with suggestions for adoption of our standards in future work.**

***Index Terms*—standards, autonomy, distributed systems, intelligence, space**

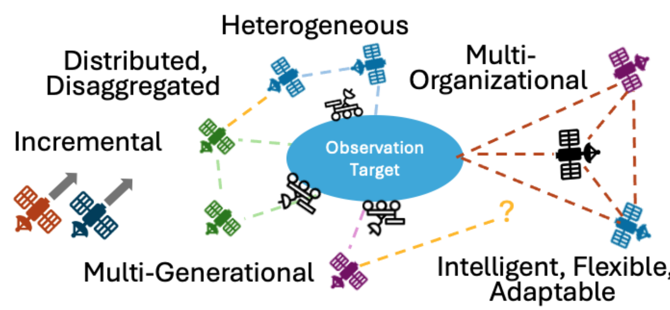


Fig. 1. Illustrative depiction of mission capabilities enabled by intelligent, extensible mission architectures. Intelligent, extensible architectures enable distributed, multi-organizational, multi-generational capabilities, resulting in increased science return, cost savings and increased programmatic flexibility.

## I. Introduction

Technological breakthroughs from the last 20 years have catalyzed major capability and programmatic shifts within the space industry. For example, the advent of miniaturized high-performance computers has enabled on-board autonomy (for both science and technology missions) [1], satellite-to-satellite communications in space [2], and an increase in the use of small satellites such as CubeSats and NanoSats [3]. The result has been an increased push toward advanced mission formats, such as distributed, disaggregated, and autonomous mission types [4], inciting missions at scale. For example, Earth observing satellites like NASA's A-Train fleet, and Planet Lab's SkySat constellation provide expansive temporal and spatial coverage of terrestrial phenomena such as hurricane tracking, containment detection, and even civic events such as protests and riots [5], [6]. Constellations like SpaceX's Starlink provide global mobile broadband coverage at scale for telecommunications applications [7].

In addition to their influence on mission formats, these technologies have lowered the barriers to entry of the global space economy. A once government-dominated space industry has witnessed a substantial increase in participation from private companies [8]. This metamorphosis of the space sector into a diverse, democratized ecosystem has created increased interest in the development of standards in space, especially those which support the multi-organizational collaboration [9] and general interoperability [10], agnostic to evolving communication protocols in space. To date, there exists a collection of solutions in the space sector for general interoperability,

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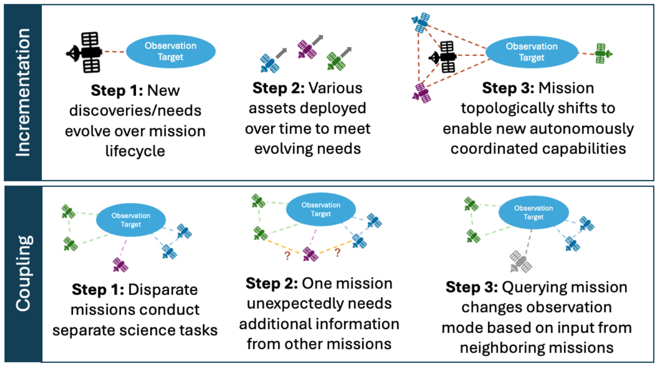


Fig. 2. Intelligent extensible mission architectures enable the flexibility needed for adaptable mission types. For example, (top) multi-generational incremental mission types, which allow for the addition of assets over the lifetime of a mission, and (bottom) coupling of disparate, multi-organizational mission types to address time sensitive priorities.

but none with built-in artificial intelligence support that is streamlined with advancements from the general artificial intelligence research community. Moreover, these solutions are often proprietary and challenging to use at all stages of development; they are thus counterproductive to the multi-organizational goal.

## II. Intelligent Extensible Mission Architectures

To address the described desires and limitations of the space economic and research sector, this paper highlights the design of software standards for intelligent extensible mission architectures for earth and space systems. Broadly, *intelligent extensible mission architectures (IEMAs)* are protocols which enable high-level modularity and reconfiguration of mission assets, both within a mission and across disparate missions. This emergent architectural standard enables flexibility in missions of the future to realize new and complex mission paradigms, especially as they concern disaggregated autonomy. For example, IEMAs enable incremental mission types (See Figure 2, top), where assets can be added or subtracted from a fleet over time as mission needs evolve. IEMAs also enable the coupling of disparate missions to amplify constituent and joint capability in salient scenarios where additional resources may be needed (See Figure 2, bottom). The impact of such missions would result in cost savings, increased science return and programmatic flexibility. The standard presented in this paper was developed through literature review, market research and through a series of prototypes and experiments (described at length in [11]). The presented standard is agent-, domain-, and communication protocol-agnostic, as discussed in detail in Section V.

## III. Related Work

Building intelligent extensibility in space is a multi-layered problem which necessitates networking standards and protocols for asset-to-asset communication in space (See Figure 3). Several organizations have made contributions toward building networking standards in space. The European Space Agency

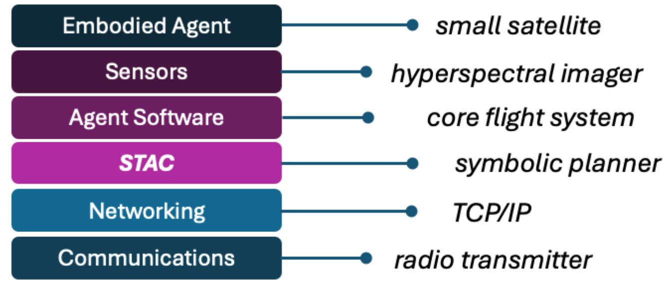


Fig. 3. Example of the technology stack of an agent in a constellation, used to highlight the role of our extensibility architecture, which is used to connect agent-specific software with networking protocols.

(ESA) and the European Cooperation for Space Standardization (ECSS) has developed several standards for data link protocols in space [12]. Similarly, NASA has developed a suite of standards for space networking, including the Delay Tolerant Network (DTN) [13] and standards for coordination within Tracking and Data Relay Satellite System (TDRSS) [14], both of which are mission operational. The Open Geospatial Consortium (OGC) is a multi-organizational group focused specifically on interoperability standards for geospatial data [15]. The Consultative Committee for Space Data Systems (CCSDS) is a multinational forum for the development of standards in space regarding data handling and communications [16]. More recently, the United States Department of Defense (DoD) has highlighted the criticality of developing standards to amplify swarm satellite capability at a multi-organizational and multi-national level [17], [18].

While the listed projects and programs provide vital support toward intelligent extensible architectures and/or their application, they do not explicitly provide the tools for generalized intelligent extensibility. Alternatively - and in a complementary vein - the contributions in this paper aim to provide an explicitly simple public standard for enabling generalized intelligent extensibility spanning both autonomous and space systems. We recommend consideration, use, and feedback of these standards, presented in Section VII.

## IV. Preliminaries

Within the field of artificial intelligence, there exists a body of research in distributed systems called multi-agent systems, which focuses on the interaction of autonomous agents in real-world systems of varying fidelity, with sub-fields spanning low level control theory to high level cooperative control. Popular applications include computer networks [19], warehouse logistics (robot operators) [20], and drone swarms [21]. For any multi-agent system, it is critical to consider the leadership paradigm, physical topology, agent-to-agent communication parameters, etc. [22].

While many formalizations of both single and multi-agent problems exist, we take inspiration from Russell & Norvig's notion of a rational agent in our formalization of standards for intelligent extensibility, which defines a rational agent as an entity that is able to sense, perceive and act in the world

[23]. For many implementations of rational embodied agents - such as reinforcement learning, classical planning, expert systems, and search problems - an agent is able to generate behaviors by traversing over its own notion of states, actions, and constraints. States include an agent's own state (including current and/or desired goal states), the states of others, and the state of the world, typically acquired through sensing and perception. Actions include an agent's own actions and the actions of others. Constraints include spatial, temporal, visual, and mechanical constraints, etc.

In addition to Russell & Norvig's notion of a rational agent, we derive our standards by examining the unique features and needs of the space domain. For example, computational resources in space are much more limited than they are on Earth due to the radiation-intensive environment. Additionally, space does not have the same communication infrastructure that Earth does, especially beyond low earth orbit, which is vital in supporting disaggregated missions in space. Moreover, building out infrastructure in space requires launches, resulting in fewer opportunities to put assets into space. Lastly, this launch prerequisite imposes constraints on size, weight and power (SWaP) for satellites, which furthers limitations of space development.

## V. Suggested Standards

We recommend that the space research community adopts a streamlined, de-centralized, multi-agent system standard where assets (satellite, ground, etc.) exchange information regarding three core elements: their own state, their own actions, and their own constraints.

### A. Theoretical Formulation

We represent a given multi-agent system containing $n$ assets (referred to here as elements and/or assets) as $\mathcal{E} = [e_1, e_2, \dots e_n]$. A given element in $e_i \in \mathcal{E}$ is composed of a set containing its state $s_i$, a list of its actions $\mathcal{A}_i = [a_1, a_2, \dots a_n]$ and a list of its constraints $\mathcal{C}_i = [c_1, \dots]$. At time $t$, an agent $e_i$ can share a data packet containing its current state, its currently available actions, and its current constraints as the set $e_i(t) = \{s_i(t), \mathcal{A}_i(t), \mathcal{C}_i(t)\}$, where $\mathcal{A}_i(t) \subset \mathcal{A}_i$ and $\mathcal{C}_i(t) \subset \mathcal{C}_i$. We reference this set as an agent's StAC (state, action, constraints). While it is assumed that an agent's StAC is a function of time, it should be noted that an agent's StAC can also be contextualized/scoped based on another agent's requests for information, described in detail in the illustrative example in Section V-C.

### B. Data Schematic

In this section, we describe a high-level schematic of an agent's STAC, which can be instantiated in a variety of ways depending on the application. We recommend employing a symbolic representation for an agent's stack. For example, when using a symbolic planning representation, an agent's stack may take a string-based format, shown below.

```
string[] state
string[] actions
string[] constraints
```

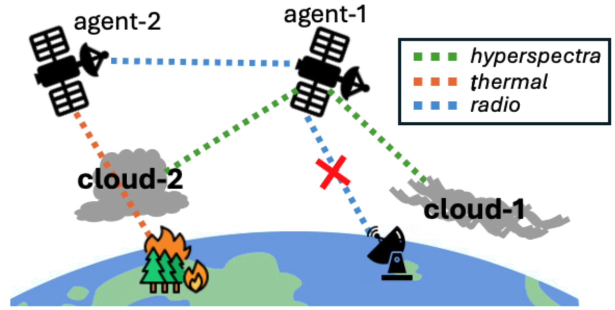


Fig. 4. In complex, time-sensitive scenarios such as wildfires, multiple satellites can collaborate to overcome hurdles such as communication outages and limitations on onboard instrumentation.

This schematic shows a minimum spanning set of information that would be required to enable intelligent extensible mission architectures. However, an individual client to this standard may chose to fill in more details or requirements on their own schematic. For example, a set of users who want to explicitly share time stamped information outside of an agent's individual state information may require the following schematic:

```
string time
string[] state
string[] actions
string[] constraints
```

It should be noted that an agent can use the StAC representation to either i) share its own information or ii) request information from other agents. In Section V-C, we review these options using an illustrative example.

### C. Illustrative Example

In this section, we review the scenario depicted in Figure 4 to illustrate the utility of intelligent extensible mission architectures. Suppose a satellite (`agent-1`) in low earth orbit is tasked with detecting and characterizing clouds using a hyperspectral imager. At a given time $t$ = `2025-03-28` and GPS location of `42,71`, the satellite is able to identify two clouds in its hyperspectral data (`image-1`), where `cloud-1` is a cirrus cloud, and `cloud-2` is a cumulus cloud. Moreover, suppose that at at time $t$, the satellite is able to perform one of the following actions in reaction to the cloud identification: `save-data`, `downlink-data`, `delete-data`. In this case, the StAC of `agent-1` can be represented as follows (with `s = state`, `a = actions`, and `c = constraints` for brevity):

```
s = [time(2025-03-28),
     agent_id(agent-1),
     location(42, 71),
     artifact(cloud-1, cirrus),
     artifact(cloud-2, cumulus)]
a = [save-data,
```

```
        downlink-data,
        delete-data]
    c = [valid(save-data, 20s)]
```

Suppose that due to a communication limitation, `agent-1` is unable to down link its hyperspectral imagery data to the ground for further analysis of the cause of the cloud formations. For example, a cumulus cloud could indicate a series of phenomena of varying urgency, such as a non-critical hot spot, or a more critical developing wildfire (called a pyrocumulus cloud). In this case of an unexpected critical event, `agent-1` may request that a downstream orbital asset equipped with a thermal imager, called `agent-2`, observe the fire-related phenomena and provide insights to the ground (See Figure 4). Here, `agent-1` may send the following StAC to `agent-2`:

```
    s = [request]
    a = [observe(site_id, (42,71)),
        downlink-data(site_id)]
    c = [valid(observe, 20s)]
```

Here, `agent-2` can extend the capabilities of `agent-1` by using an alternative asset to i) make diversified/amplified observations which are not available on `agent-1`'s payload and ii) to help with the operational constraints associated with communication limitations.

## VI. Experiments and Planned Missions

The StAC standard has been developed through a series of iterative prototypes used in applications with environments of increasing fidelity, starting with software-only experiments, and transitioning into operational infusion during two planned NASA-led research missions in 2025. All experiments have leveraged the NASA On-Board Artificial Intelligence Research (OnAIR) platform [24] as a prototyping tool for enabling single agent intelligence, where OnAIR instances are connected by a fleet interface object passing StAC information for intelligent extensibility.

### *A. Drone Field Campaign*

In summer 2025, a NASA field campaign involving coordinated adaptive decision-making between autonomous drones and humans will study opportunistic science events at a domestic site which is rich with biogeochemistry phenomena, serving as an ocean world analogue. Coordinated decision-making will enabled by StAC data transmitted between assets to drive inter-asset cooperation on the fly. Each asset will use OnAIR as a central tool to enable on-board autonomy.

### *B. Satellite Flight Experiment*

In the Fall of 2025, intelligent extensible standards will be used in an on-board flight experiment, hosted on Johnson Space Center's Realizing Rapid, Reduced-cost high-Risk Research (R5) satellite fleet [25]. The experiment will leverage the NASA Ames Research Center's Opportunistic Software Experiments for Spacecraft Autonomy Testbeds (OSE-SAT), which is a technology to enable containerization of onboard processes. The experiment uses StAC to communicate between two onboard agents, hosted in two separate OSE-SAT containers, independently checking star tracker imagery for anomalies. StAC messages are used to establish anomaly consensus. Since the mission is highly data limited, this consensus is used to autonomously mark high-priority data for downlink.

The experiment will use the intelligent extensible architectures standard to augment down-link constricted satellites scenario with the ability to "extend" their duties, leveraging ground assets for fault diagnosis. Additionally, OSE-Sat will host multiple OnAIR containers traversing over star tracker imagery, each equipped with their own machine learning-based anomaly detection method.

## VII. Discussion and Future Work

The goal of this paper is to establish a high-level vision and corresponding architectural standard for realizing an "internet of things" future in space. This future space ecosystem will welcome contribution from, and benefit, all application areas, organizations, and generations of science and technology. We encourage an open use and conversation around intelligent extensible architectures - which we believe to be a cornerstone of the future "interoperable space" ecosystem.

In the near term, we urge researchers and space community members to use our presented standards in prototyping distributed mission concepts, gradually increasing maturity toward mission operational use. We recommend the use of the NASA OnAIR platform as a prototyping tool for single agent intelligence (available publicly at https://github.com/nasa/OnAIR) and which can be used in concert with a StAC interface to enable agent-to-agent communication as described in Section VI.

In the long term, we encourage the development of mission concepts which can be realized through the use of intelligent extensive mission architectures. For example, large responsive terrestrial sensor-webs can provide near real-time reaction to natural disasters and long term insights for important earth science questions regarding global hydrological cycles, the planetary boundary layer, and surface vegetation and topography [26]. Additionally, incrementing infrastructure in space to build large space weather networks will provide alerts to astronauts exploring the surface of the Moon and Mars [27]. Similarly, incrementing assets observing deep-space planetary environments on an "as needed" basis will enable multi-shot observation of possible life on other planetary bodies like Enceladus and Europa [28]. This is particularly important in communication limited environments of planetary exploration. Lastly, being able to capture celestial events by connecting large telescopes and observatories through responsive observation will unlock insights into universe formation questions and habitable worlds [29]. Enabling intelligent extensible architectures will require participation from the entire space community at large. We look forward to a new generation of space exploration for all and welcome feedback and conversation on the presented work.

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