

# Cyberinfrastructure for Airborne Sensor Webs

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**Abstract - Since 2004 the NASA Airborne Science Program has been prototyping and using infrastructure that enables researchers to interact with each other and with their instruments via network communications. This infrastructure uses satellite links and an evolving suite of applications and services that leverage open-source software. The use of these tools has increased near-real-time situational awareness during field operations, resulting in productivity improvements and the collection of better data. This paper describes the high-level system architecture and major components, with example highlights from the use of the infrastructure. The paper concludes with a discussion of ongoing efforts to transition to operational status.**

**Keywords:** *airborne science, sensor webs, telepresence, telematics, extranet.*

## 1. INTRODUCTION

In 1960, computer networking pioneer J.C.R. Licklider envisioned a future in which people and computers would “cooperate in making decisions and controlling complex situations without inflexible dependence on predetermined programs” (Licklider, 1960). In simple terms, the long-term vision of this symbiotic relationship is the capability to establish and maintain situational awareness with time left over to take action.

As we entered the twenty-first century, Licklider’s vision thrived in many industries. Everywhere we looked, it seemed, were efforts to build network-centric, distributed, integrated, interoperable, adaptive, intelligent systems of systems that helped groups of people make decisions and get things done faster, better, or cheaper than could be done in any other way.

Incorporating sensors and instruments into decision support systems improves situational awareness. The term “sensor web” refers to the general convergence of data acquisition and network computing infrastructure. As sensor webs mature, *the network becomes the instrument* through which our observations are managed. Sensor webs, however, come with a long list of technical challenges and gaps. Computational resources may be limited because the instrumentation has size, power, and weight constraints. Dynamic physical topologies require self-organizing or adaptive behavior. New models of computation emerge. Trustworthiness – reliability, safety, security, privacy, and usability – must be designed into networked and ultimately autonomous sensor web systems. (NRC, 2001).

By 2003, the National Science Foundation (NSF) determined that the push of information technology advances combined with the pull of technical challenges in science and engineering research

had reached the point where it was advantageous to consider the development of *cyberinfrastructure*. Cyberinfrastructure is the aggregation of software, hardware, network communications, and assembled services that tie experimental facilities, instruments, and computational resources into dynamically composable end-to-end interactive digital environments (NSF, 2003).

In parallel with NSF recommendations, the Earth science and environmental monitoring research communities collectively emerged with their cyberinfrastructure vision to work toward a Global Earth Observation System of Systems (GEOSS). GEOSS would be comprised of a global and flexible network of providers that integrated their information and processing capabilities, resulting in delivering to decisionmakers, planners, and emergency managers the right data, in the right place, at the right time (Estrin, 2003; Battrick, 2005; CENR, 2005).

The primary objectives of the NASA Airborne Science Program are to gather in situ and remotely-sensed measurements, often to enhance or support calibration and validation of space-based measurements. In 2004 the program provided researchers with seed money to develop and demonstrate a general capability for science instrument developers to interact with their instruments on future unmanned aircraft systems (UAS). This “Suborbital Telepresence” project leveraged existing platforms as UAS surrogates and advocated evolutionary development of end-to-end connectivity and capabilities. Tele-observation, tele-control, and tele-computing capabilities were collectively envisioned as a logical path to airborne sensor webs for the entire airborne science community. General solutions for cyberinfrastructure useful to the airborne science platforms did not previously exist at NASA, so implementation of new airborne components, ground infrastructure, and end-to-end applications were required. This paper discusses the resulting system and its capabilities.

## 2. SYSTEM ARCHITECTURE

### 2.1 Concept of Operations

The concept of operations (Figure 1) involves one or more payload network(s) on each vehicle that support installed instrumentation as “powered cargo” physically isolated from avionics that influence vehicle flightpath. A single ground station supports one or more payload networks on multiple vehicles in a manner similar to an Internet service provider supporting multiple customers. Applications, along with network data servers and services, are needed beyond basic connectivity, so one or more *extranets* are employed for that purpose. An extranet is a network that is isolated from other corporate networks in order to properly manage access controls to and from external groups and organizations. Instruments, and possibly humans, in the aircraft interact in near-real time with each other and their counterparts on other aircraft or on the ground through the possibly unmanned ground station.

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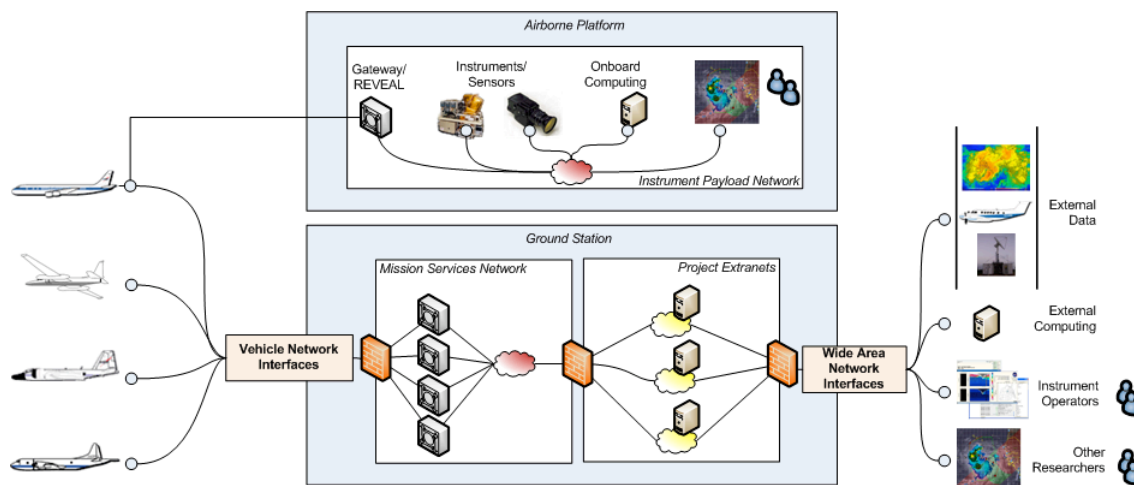


Figure 1. High-level cyberinfrastructure architecture for airborne science sensor webs.

A ground station has at least two network segments: an internal aircraft-facing network, and an extranet network providing web-oriented applications and services for data sources and destinations on the wide area network. The ground station provides a point of presence on the terrestrial network for the airborne payloads while also providing a set of end-to-end services that may constitute a complete solution for some customers. In concert with the GEOSS vision, however, there is a basic assumption that the ground station is one node that is part of a larger and loosely-coupled system of systems.

Connectivity to and from the aircraft is enabled via one or more wireless network links. Constrained bandwidth makes it important to control access for different classes of users. Instrument operators may have preconfigured connections that enable interactive communication directly with their instruments or other onboard resources, while other system users have read-only access to ground systems and cannot impact the flow of data to and from the vehicle.

Major systems components that are readily defined by physical system boundaries include airborne and ground-station components. Network-distributed services and end-to-end applications can be considered layers that are distributed across the boundaries of the physical system.

## 2.2 Airborne System Components

In order to enable uniform approaches to managing multiple instruments across multiple aircraft platforms, mechanisms for providing basic services on the airborne network were required. These services included acquisition and processing of vehicle-specific data sources, and network gateway management.

Vehicle-specific data acquisition and processing were enabled through a Research Environment for Vehicle-Embedded Analysis on Linux (REVEAL). REVEAL is an ongoing project at the NASA Dryden Flight Research Center (Edwards, California, USA) to evaluate the feasibility and benefits of using Linux as a network-attached data system for measurement and telemetry network research (Sorenson, 2003). The software architecture features simple XML files specifying system resources and dynamically-configurable user jobs. A prototype hardware system was designed and built using modular PC/104 components.

For anytime, anywhere network connectivity to and from the aircraft, a fundamental requirement existed to operate in both

polar regions. Additional considerations included operating costs, on-demand scheduling, and constraints in size, power, and weight that would be imposed on many platforms. The nearly-polar-orbiting Iridium satellite constellation provided the only feasible approach for a generic prototype given these constraints. Iridium functions using small patch antennas and a few watts of power, enabling installation on all but the smallest of aircraft.

Since a single Iridium modem provides a nominal 2400 baud, it makes sense to combine multiple Iridium modems in parallel for greater, albeit still limited, bandwidth. These modems were integrated into REVEAL components as well as independent gateway systems for aircraft not requiring additional acquisition and processing services. It is envisioned that other data-link technologies can be added over time, providing multiple paths in a disruption-tolerant adaptive communication architecture.

## 2.3 Ground Infrastructure Components

Airborne science payload networks, like any other mobile system, require ground infrastructure to support the terrestrial end of the wireless connection. Scalable and affordable ground infrastructure should accommodate multiple data-link technologies, including third-party communications infrastructure. Both one-directional telemetry and two-directional command/query of the payload network must be supported. Global airborne science deployments require flexibility in the physical location of the ground infrastructure. The flexibility to research ad hoc communication protocols, tailor access controls, and manage information security must be addressed.

These requirements were addressed for the Iridium data links by implementing several link termination options. Traditional “dial-up” connectivity enables authenticated point-to-point connections via the public switched-telephone network (PSTN). The PSTN landlines can be avoided by replacing the traditional landline modem with one or more Iridium modem/antenna assemblies. These antenna assemblies were implemented in a “Global Test Range” development laboratory as well as in a transportable ground station. Finally, virtual private networks and other router-based options from the Iridium constellation gateway facilities to NASA Dryden enabled additional configuration options useful in certain scenarios.

From a network perimeter perspective, ground infrastructure is divided into a mission network segment and an “extranet”

segment. The mission network supports the systems that communicate with the payload networks while the extranet supports the exchange of information with authorized users and data sources obtained from wide area networks such as the Internet.

#### 2.4 Applications Development

Over the last decade, the need for advancements in all aspects of software services and tools for sensor webs and related cyberinfrastructure has grown tremendously. Rather than promote creation of a centralized “one-stop-shop” solution, the Suborbital Telepresence Project fostered a loosely-coupled heterogeneous system-of-systems approach to enabling applications development.

In the mid-1990s, researchers at NASA Dryden collaborated with industry on solutions for network-distributed signal processing in aircraft flight-testing applications. Those efforts led to the development of DataTurbine, a middleware cache server for stream-oriented data management in distributed test and measurement applications. While a detailed discussion is beyond the scope of this paper, the basic technology gap closed with DataTurbine involves managing data buffers for acquisition and processing of continuously changing instrumentation data streams across network links (Miller, 2003; Tilak, 2007).

DataTurbine middleware was chosen as the foundation for establishing terrestrial cyberinfrastructure for airborne science under the Suborbital Telepresence Project. A DataTurbine server on the ground was a natural choice for caching health and status data streams from different instruments, including REVEAL. Processing modules, possibly running on separate computers, can demultiplex these packets and perform various calculations; additional modules can monitor and act on the results, forming a network-distributed process chain. An “Intelligent Network Data Server” organized as a hierarchy of DataTurbine servers on separate computers enabled resource management by platform or project. On larger aircraft with onboard research teams, an additional onboard DataTurbine server enables on-board processing that compliments the terrestrial processing and helps eliminate unnecessary bandwidth consumption.

The network integration facilitated by DataTurbine was easily leveraged by third-party applications and collaborators using standard network transport protocols. In 2005, support for on-demand generation of real-time flight tracks using Keyhole Markup Language (KML) ushered in rapid and widespread use of the Google Earth application as a situational awareness display. A Realtime Mission Monitor emerged in 2006 that delivers sophisticated integrated mission-level views of measured, predicted, and other status information from aircraft, instruments, satellites, and forecast models (Blakeslee, 2007).

A significant extension of DataTurbine’s value to Earth science cyberinfrastructure was realized in 2007 when the National Science Foundation sponsored the Open Source DataTurbine (OSDT) Initiative. The objective of the OSDT Initiative is to facilitate the development of complex distributed streaming data applications, including real-time virtual observatories and telepresence collaborative laboratories. Over a dozen other cyberinfrastructure efforts involving DataTurbine were under way in the first year of the open source project (Tilak, 2008).

### 3. FIELD DEPLOYMENT SUPPORT

Evolutionary development of end-to-end capabilities was accomplished via supporting as many airborne science field operations with as many platforms as was feasible within funding, manpower, and schedule constraints. Table 1 provides a chronological view of major activities.

Table 1. Highlights of airborne science mission support.

2004	<ul style="list-style-type: none"> <li>• Suborbital Telepresence Project started. Inaugural flight of multichannel Iridium gateway on DC-8.</li> <li>• Inaugural test of prototype capabilities on ER-2.</li> </ul>
2005	<ul style="list-style-type: none"> <li>• Inaugural deployment of capabilities on Altair. UAV/NOAA Demo, spring and fall.</li> <li>• Supported Tropical Cloud Systems and Processes (TCSP) mission on the ER-2.</li> <li>• Introduced web-based time indexing service and dynamic KML generation.</li> </ul>
2006	<ul style="list-style-type: none"> <li>• Inaugural use of Intelligent Network Data Server.</li> <li>• Inaugural use of Realtime Mission Monitor.</li> <li>• Introduced Linux multichannel Iridium gateway.</li> <li>• Supported ER-2 for CALIPSO/CloudSat Validation Experiment (CC-VEx).</li> <li>• DC-8 deploys to Africa on the NASA African Monsoon Multidisciplinary Analysis Mission.</li> <li>• Supported secondary payloads during Western States Fire Mission on the Altair UAS.</li> <li>• Supported Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) on ER-2.</li> </ul>
2007	<ul style="list-style-type: none"> <li>• Inaugural deployment of capabilities on WB-57F.</li> <li>• Supported Tropical Composition, Cloud, and Climate Coupling (TC4) with capabilities on three aircraft simultaneously.</li> <li>• Supported additional deployments on ER-2: Large Area Collector (LAC), Cloud and Land Surface Interaction Campaign (CLASIC), and others.</li> </ul>
2008	<ul style="list-style-type: none"> <li>• Inaugural deployment of capabilities on P-3B.</li> <li>• Integration of NASA B-200 and several NASA-external aircraft into situational awareness displays.</li> <li>• Major two-phase deployment Arctic Research of the Composition of the Troposphere from Aircraft and Satellites (ARCTAS) involving P-3B and DC-8. Includes studies for the California Air Resources Board (CARB).</li> <li>• Supported ER-2 campaigns: AVIRIS/MASTER; LAC.</li> <li>• Supported Soil Moisture Active Passive Validation Experiment (SMAPVEX08) involving P-3B and Twin Otter.</li> <li>• Inaugural installation of capabilities on NASA’s G-III in support of UAVSAR, a synthetic aperture radar for differential interferometric observations.</li> <li>• Begin capability development for NASA’s Global Hawk platform.</li> </ul>

The chronological view of Table 1 is augmented with three anecdotal stories demonstrating how the cyberinfrastructure is delivering value for the science community:

In 2005 the ER-2 and its veteran NASA pilot, overflew the most powerful hurricane of their career on a moonless night while studying Hurricane Emily. The ER-2 recorded frequent lightning and captured startling Doppler radar imagery of Emily, including "eye wall" storms rising to a rarely-observed height of 18 kilometers (60,000 feet). The prototype real-time mission monitor displays superimposing the flight track onto the satellite imagery helped flight operations personnel keep the pilot a safe distance from the dangerous conditions near the eye wall of the hurricane.

In September 2006, the chief scientist for the NASA African Monsoon Multidisciplinary Analysis mission leveraged the Suborbital Telepresence cyberinfrastructure to permit his graduate-level tropical meteorology class in Utah to actively participate in a live mission studying the growth of tropical storms off the west coast of Africa. With little expense or preparation, the students viewed the same information that was displayed to the scientists flying aboard the DC-8 Airborne Laboratory, and the students could interact with the scientists by text messaging.

On the Altair UAS in October 2006, a secondary instrument failed shortly after takeoff. Cyberinfrastructure enabled the research team to diagnose and repair the instrument software on a noninterference basis with the primary flight activity, and the instrument was functional in time for a live demonstration in Japan while the Altair platform flew its mission over Yosemite National Park in California.

#### 4. CURRENT STATUS

Airborne components have been deployed and tested on NASA's core fleet (DC-8, P3B, ER-2, WB-57F, G-III) and technology demonstrators (Altair, with Global Hawk in work). Integration of some catalog aircraft (B-200, Twin Otter) has also been accomplished. Approximately 1500 mission support hours on REVEAL components have been accumulated to date.

The Arctic Research of the Composition of the Troposphere from Aircraft and Satellites (ARCTAS) mission in the spring and summer of 2008 relied on significant inter-aircraft coordination amongst the researchers, including realtime distribution of measured results amongst aircraft that optimized decision-making during the flight operations. Despite the constrained bandwidth of Iridium, cyberinfrastructure capabilities enabled significantly greater quantities of better research data to be acquired. Demonstrated capabilities were deemed valuable and required for most future field missions, and a commitment was made to transition to an operational capability.

An operational system implies long term planning for NASA-wide infrastructure. Ongoing strategic planning is considering many factors such as the relationship of the airborne science sensor web with other GEOSS-relevant sensor webs, and myriad challenges in keeping costs low while effectively supporting multiple globally deployed teams.

The commitment to transition to operational status does not imply a set of fully mature components or components that currently don't depend on a few highly skilled individuals. Ongoing work steadily expands use of emerging web services technology and service-oriented architecture as mechanisms to improve usability. Web service interfaces are currently evolving within the DataTurbine environment to facilitate distributed process management, and harmonization of display tools that produce KML-based integrated views (RTMM, DataTurbine modules, and others) is ongoing.

Expansion of terrestrial extranet infrastructure to include server and storage virtualization technologies is also a facet of current strategy. Computing resource virtualization is sometimes referred to as *cloud computing*. Virtualization can help implement enterprise-class scalability and flexibility without significant cost growth that could otherwise make the infrastructure too expensive to operate. This approach is aligned with NASA's strategy for evolving network architecture and should facilitate interoperability with other sensor web activities at NASA.

#### 5. FUTURE WORK

Project plans target an initial operational capability by 2010. This transition includes training operations personnel while the research staff continues to implement and deploy innovations at all levels of the cyberinfrastructure problem. Near-term innovation efforts include miniaturization of REVEAL hardware systems for smaller classes of vehicles, higher bandwidth network connectivity to the aircraft, and new capabilities via federated systems and web service-oriented architecture. Longer-term research involves integration of multiple-link technologies into intelligent and disruption-tolerant communications over which airborne instruments evolve toward autonomous intelligent observation systems.

#### 6. SUMMARY

Cyberinfrastructure for airborne science sensor webs has been bootstrapped through global reach network access, combined with flexible end-to-end processing that delivers situational awareness in various forms for reasonable cost. Five years of focused effort has resulted in a critical mass of airborne science customers who now expect these capabilities to be affordable and available. Operational transition is under way.

Licklider's vision of the value of networked computing for managing complex time-constrained decision-making activities has materialized for the Earth sciences community as a vision for building a global Earth-observing system-of-systems. The work presented in this paper directly addresses the seamless participation of suborbital observation platforms in that future system. Interoperability with other Earth observation infrastructure is facilitated via the use of open-source tools such as DataTurbine and data integration standards such as Keyhole Markup Language. The list of work yet to be done is long, but the modest efforts described herein have already demonstrated that rapid understanding of distributed information is achieved through decision support systems integrating measurements and analyses over networks.

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# Cyberinfrastructure for Airborne Sensor Webs

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## 1. BACKGROUND

Visionaries advocating for computer networking fifty years ago envisioned a future in which people and computers "cooperate in making decisions and controlling complex situations without inflexible dependence on predetermined programs". By 2003, the push of technology advances combined with the pull of technical challenges in science and engineering had reached the point where it was advantageous to consider the development of *cyberinfrastructure*. Cyberinfrastructure is the aggregation of software, hardware, network communications, and assembled services that tie experimental facilities, instruments, and computational resources into dynamically composable end-to-end interactive environments. The cyberinfrastructure vision for Earth science is a Global Earth Observation System of Systems (GEOSS) comprised of a flexible network of interoperable providers delivering the right data, in the right place, at the right time. In 2004 the NASA Airborne Science Program provided researchers with seed money to develop and demonstrate a general capability for science instrument developers to interact with their instruments on future unmanned aircraft systems (UAS). This "Suborbital Telepresence" project leveraged existing platforms as UAS surrogates and advocated evolutionary development of end-to-end connectivity and capabilities. Tele-observation, tele-control, and tele-computing capabilities were envisioned as a logical path to airborne sensor webs for the entire airborne science community. General solutions for cyberinfrastructure useful to the airborne science platforms did not previously exist at NASA, so implementation of new airborne components, ground infrastructure, and end-to-end applications was required.

## 2. CONCEPT OF OPERATIONS

One or more payload network(s) on each vehicle support installed instrumentation as "powered cargo" physically isolated from avionics that influence vehicle flightpath. A single ground station supports one or more payload networks on multiple vehicles in a manner similar to an Internet service provider supporting multiple customers. One or more extranets support needed applications beyond basic network connectivity. An *extranet* is a network that is isolated from other corporate networks in order to properly manage access controls to and from external groups and organizations. Instruments, and possibly humans, in the aircraft interact in near-real time with each other and their counterparts on other aircraft or on the ground through the possibly unmanned ground station. A ground station has at least two network segments: an internal aircraft-facing network, and an extranet network providing web-oriented applications and services for data sources and destinations on the wide area network. The ground station provides a point of presence on the terrestrial network for the airborne payloads while also providing a set of end-to-end services that may constitute a complete solution for some customers. In concert with the GEOSS vision, however, there is a basic assumption that the ground station is one node that is part of a larger and loosely-coupled system of systems. Connectivity to and from the aircraft is enabled via one or more wireless network links. Constrained bandwidth makes it important to control access for different classes of users.

## 3. AIRBORNE SYSTEM COMPONENTS

Managing multiple instruments across multiple aircraft platforms require basic services such as acquisition and processing of vehicle-specific data sources, and network gateway management. Vehicle-specific data acquisition and processing were enabled through a Research Environment for Vehicle-Embedded Analysis on Linux (REVEAL). REVEAL is an ongoing project at the NASA Dryden Flight Research Center (Edwards, California, USA) to evaluate the feasibility and benefits of using Linux as a network-resident data system for measurement and telemetry network research. A prototype hardware system was designed, built, and deployed using modular PC/104 components. A fundamental requirement existed to operate inexpensively, anytime, and anywhere (including both polar regions). The Iridium satellite constellation provided the only feasible approach for a generic prototype given these constraints. Since a single Iridium modem provides a nominal 2400 baud, multiple Iridium modems in parallel offered greater but still limited bandwidth. These modems were integrated into REVEAL components as well as standalone gateways. Other data-link technologies would be added over time, providing multiple paths in a disruption-tolerant adaptive communication architecture.

## 4. GROUND INFRASTRUCTURE COMPONENTS

Airborne science payload networks require ground infrastructure to support the terrestrial end of the wireless connection. Scalable and affordable ground infrastructure should accommodate multiple data-link technologies, including third-party communications infrastructure. Both one-directional telemetry and two-directional command/query of the payload network must be supported. Global airborne science deployments require flexibility in the physical location of the ground infrastructure and in protocols supported. From a network security perimeter perspective, ground infrastructure is divided into a mission network segment and an "extranet" segment. The mission network supports the systems that communicate with the payload networks while the extranet supports the exchange of information with external data sources and authorized users.

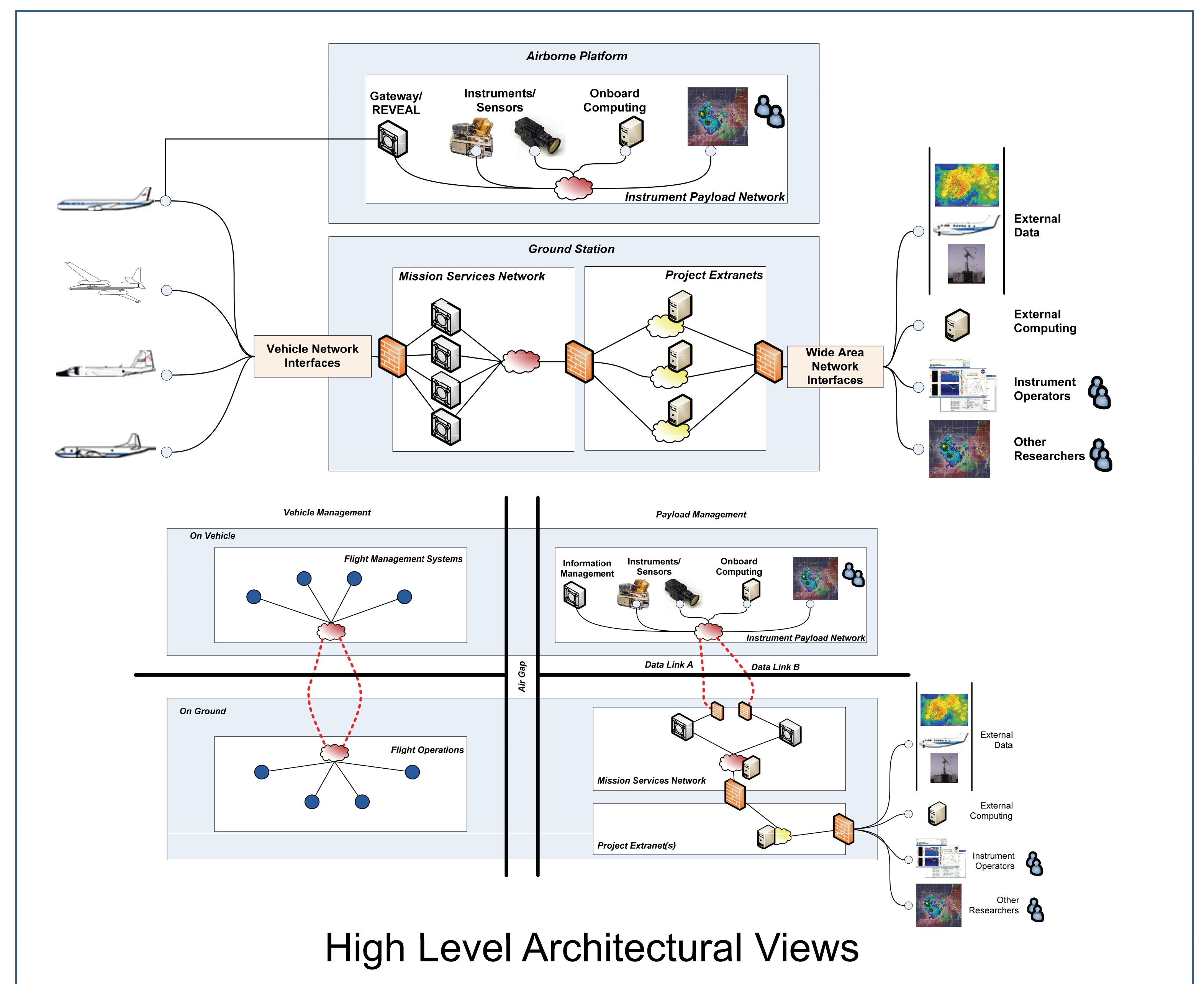
## 5. APPLICATIONS COMPONENT DEVELOPMENT

Rather than promote creation of a centralized "one-stop-shop" solution, the Suborbital Telepresence Project encourages a loosely-coupled heterogeneous system-of-systems approach to enabling applications development. An open source middleware product called *DataTurbine* was chosen as a foundation component for caching health and status data streams from different instruments, including REVEAL. Processing modules, possibly running on separate computers, can demultiplex these packets and perform various calculations; additional modules can monitor and act on the results, forming a network-distributed process chain. On larger aircraft with onboard research teams, an additional onboard *DataTurbine* server enables on-board processing that complements the terrestrial processing and eliminates unnecessary bandwidth consumption. *DataTurbine* was easily leveraged by third-party applications and collaborators using standard network transport protocols. In 2005, support for on-demand generation of real-time flight tracks using Keyhole Markup Language (KML) ushered in rapid and widespread use of the Google Earth application as a situational awareness display. A Realtime Mission Monitor emerged in 2006 that delivers sophisticated integrated mission-level views of measured, predicted, and other status information from aircraft, instruments, satellites, and forecast models.

## 6. FIELD DEPLOYMENT EXPERIENCE

Evolutionary capabilities development was accomplished via supporting as many airborne science field operations with as many platforms as was feasible within funding, manpower, and schedule constraints. The adjacent table provides a chronological view of major activities. Three anecdotal stories demonstrate how the cyberinfrastructure is delivering value: (1) In 2005 the ER-2 and its veteran NASA pilot overflew the most powerful hurricane in their career on a moonless night while studying Hurricane Emily. The ER-2 recorded frequent lightning and captured startling Doppler radar imagery of Emily, including "eye wall" storms rising to a rarely observed height of 18 kilometers (60,000 feet). The prototype real-time mission monitor displays superimposing the flight track onto the satellite imagery helped flight operations personnel keep the pilot a safe distance from the dangerous conditions near the eye wall of the hurricane; (2) In September 2006, the chief scientist for the NASA African Monsoon Multidisciplinary Analysis mission leveraged the Suborbital Telepresence cyberinfrastructure to permit his graduate level tropical meteorology class in Utah to actively participate in a live mission studying the growth of tropical storms off the west coast of Africa. With little preparation, the students viewed the same information being displayed to the scientists flying aboard the DC-8 Airborne Laboratory, and the students interacted with the scientists by text messaging; (3) On the Altair UAS in October 2006, a secondary instrument failed shortly after takeoff. Cyberinfrastructure enabled the research team to diagnose and repair the instrument software on a noninterference basis with the primary flight activity, and the instrument was functional in time for a live demonstration in Japan while Altair flew its mission over Yosemite National Park in California.

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High Level Architectural Views

REVEAL System

Ground Station

Transportable Ground Station

DataTurbine Network Server

Realtime Mission Monitor

TCSP, 2005

Altair/WFSM, 2006

TC4, 2007

NAMMA, 2006

Year	Key Events
2004	<ul style="list-style-type: none"> <li>Suborbital Telepresence Project started. Inaugural flight of multichannel Iridium gateway on DC-8.</li> <li>Inaugural test of prototype capabilities on ER-2.</li> </ul>
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Components

Experience