

# Infrastructure for Internet-Based Operations

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## Abstract

Global access to remote systems is becoming a reality through advances in the Internet. Applied to spacecraft operations, this provides the opportunity for spacecraft operators to access remote system resources from any location with Internet access. As part of its space operations research, Stanford University's Space Systems Development Laboratory (SSDL) is exploring the ability of Internet based operations to improve the cost effectiveness of space mission operation. It is developing a ground station control system to provide computer assisted console control, remote operation, and software agent-based autonomous control. Known as Mercury, the system has been implemented on SSDL's OSCAR-class amateur radio ground station and is in use to conduct operations on SSDL's first orbiting microsatellite, OPAL. This paper outlines various Internet based operation techniques and discusses the design of the Mercury prototype.

## 1 Introduction

Space missions are complex systems comprised of many components that are distributed, heterogeneous, and dynamic over time. These components collaborate together for a common purpose to complete the mission goals. Operation of a space mission includes managing all the hardware, software, people, procedures, and data used to control, retrieve, and analyze data from the space mission components, both on the ground and in space [1].

Mission operations are a costly component of a space mission. Typically, 60% of mission cost is devoted to operations [2]. Changes in operational paradigms are necessary for further competitive improvements [3]. Internet based operations (IBO) has the potential to improve the cost-effectiveness of mission operations through enhanced interconnectivity between space mission components.

This paper describes an exploratory IBO infrastructure developed at the Space Systems Development Laboratory (SSDL) at Stanford University for operating its space missions. It also discusses prototype design and lays a foundation for investigating the effects of IBO on cost, quality, and timeliness of space mission operation.

## 2 System Interconnectivity

Traditional space systems include space hardware and software, ground hardware and software, distributed technical and science teams, and archived data sources. The operations coordinates the components to control, retrieve, and analyze mission data and telemetry. The coordination and interconnectivity of the system is fundamental to the cost, quality, capability, and timeliness of operations.

Design of an interconnectivity scheme is dependent upon the requirements and characteristics of component input types, outputs types, and location. The diversity in the interconnectivity characteristics of space mission components can be quite large. For example, space borne components can be in a variety of trajectories from low earth orbits to interplanetary routes. This affects transmission latency, bandwidth, and received signal strength. The trajectories also place requirements on ground station resources. Antennas vary in size from small hand held devices for low earth orbits to large multi meter wide dishes for deep space missions. The human components are also diverse. From technical operators to principal investigators to the general public, a wide range of humans interact with space systems.

Methods of system interconnectivity must manage the diverse nature of the system components.

Desirable elements of interconnectivity include communication channels that are secure and reliable with low latency and adequate bandwidth, minimized human control and management, and flexible intuitive interfaces for human interaction.

Designers of Internet systems are engineering software and hardware infrastructure to support system connectivity with similar complexity. They are attempting to solve the problems of users with heterogeneous devices with varying link capabilities that are requesting the services of globally distributed Internet systems. These problems are similar to those of space systems. Application of Internet technology to space system connectivity has the potential to improve mission operations.

### **3 Internet Based Operations**

The goal of Internet based operations (IBO) is to leverage Internet technologies to improve the interconnectivity of space mission components. Three areas are being explored at SSDL: ubiquitous access to remote system components, a framework for composable services, and pipelines for distributed real time collaboration and software agent based operations.

#### *Ubiquitous Access*

Ubiquitous access is the ability to reach distributed system components from any Internet-connected computing device. By leveraging Internet communication frameworks such as email, ftp, HTTP, SSH, voice over IP, and other multimedia protocols, teleoperation of remote systems is becoming more cost-effective and more accessible.

Proxy systems are an integral part of Internet infrastructure. Proxies transform data from a remote component to the appropriate format for an end device, be it a desktop workstation or a small personal data assistant (PDA) [4]. Proxy systems also hide remote component location from connected users. Applied to space missions, proxy systems have the potential to provide improved integration of diverse, heterogeneous components and to reduce the location-based constraints on system components.

Ubiquitous access also entails flexibility in user interfaces. Internet systems often have command line interfaces (such as telnet) and/or graphical users (such as the web). This enables customization of interfaces for a given task and a given user. Applied to space missions, the diverse range of users, from

principal investigators to spacecraft operators, could benefit from diverse user interfaces that are tailored to meet their requirements.

#### *Pipelines for Distributed Collaboration*

Multicasting is a powerful distribution capability of Internet systems that enables simultaneous reception of streaming data sources. Collaborative multicasting, such as chat systems, enable simultaneous multi-user interaction. Applied to space missions, a similar system would enable pathways for diverse data streams between distributed system components. These data pipelines would transform and filter data streams flowing between components. They would also provide interfaces for software agent interaction with the data flows. Multicast data channels have the potential to improve component collaboration and communication.

#### *Composition of Services*

The number of Internet services is growing rapidly and providing capabilities such as grocery shopping, bill reminders, and financial transactions. The composition of services involves connecting services that were not necessarily made to communicate with one another. This enables users to leverage existing services to develop custom services that are potentially more useful.

Applied to space systems, infrastructure for composable services could provide a mechanism for interconnecting legacy and COTS software/systems that were not designed to communicate with one another. It will also provide an Internet based framework for invoking distributed components and combining them into a functional service.

### **4 IBO Prototype**

The prototype IBO infrastructure, called Mercury, provides remote operation of SSDL's amateur radio ground station resources and enables real time command and control of SSDL satellite resources from any Internet connection. SSDL operators perform over ninety percent of all contacts with SSDL's first in-orbit satellite, OPAL [5], through the Internet. Mercury is also used to communicate with engineering models as well as a flight ready satellite, Sapphire [6], stored in SSDL's clean room. The Mercury/OPAL system provides a testbed to explore the issues of Internet based operations.

The following section provides an overview of SSDL's space systems and then describes the IBO infrastructure.

#### *OPAL Overview*

In January of 2000, SSDL's student built microsatellite, OPAL – the Orbiting Picosatellite Automated Launcher, roared into space on a modified Minuteman II rocket. SSDL students spent four years designing, fabricating, and testing the OPAL satellite in preparation for the launch.

OPAL's primary mission objectives were to explore a new mothership/daughtership mission architecture for distributed sensing, to characterize an off-the-shelf magnetometer, and to characterize a suite of off-the-shelf accelerometers. Six DARPA sponsored daughterships, also known as picosatellites, were deployed from OPAL. They were built by The Aerospace Corporation, Santa Clara University, and a team of amateur radio operators.

The OPAL satellite completely achieved its mission goals and is now in extended mission operations. Long-term characterization of the satellite bus, magnetometer, and accelerometers are underway. AMSAT assigned OPAL an amateur satellite number of OO-38. Figure 1 shows the OPAL spacecraft.

#### *SSDL OSCAR Station*

SSDL has a low-cost, small scale ground station fully equipped to contact OSCAR (Orbiting Satellite Carrying Amateur Radio) satellites in the 2m and 70cm amateur radio bands (140Mhz and 440Mhz). Equipment includes:

- A full duplex transceiver operating on the 2m band at 160W and the 70cm band at 40W.
- Two 13db gain Yagi antennas, one for each band, with preamplifiers and position control motors.
- A terminal node controller that serves as a modem and uses the packet radio protocol, AX 25, at rates up to 9600 baud.
- Several Pentium class computers providing computer control of equipment.
- Miscellaneous power control devices and RF equipment.

#### *Mercury – An IBO Prototype*

The Mercury prototype has evolved over the last year and a half from a single Windows program [7] to a multi process system residing on a Linux cluster of several commodity PCs. The first step in building

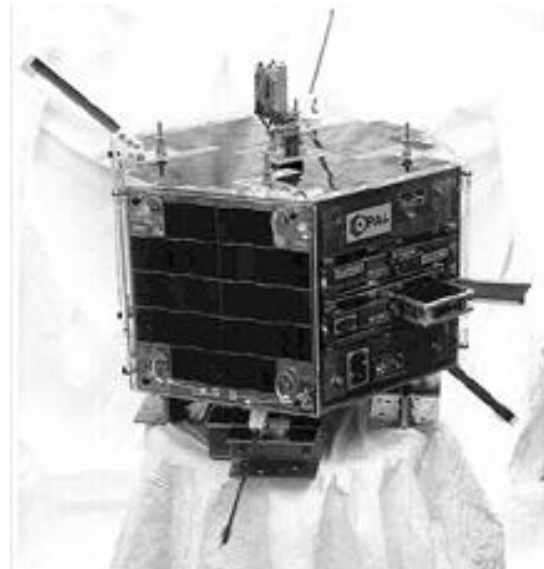


Figure 1 – The OPAL satellite on a pedestal in the clean room. OPAL weighed approximately 25 kg and was 23.5 cm in height.

Mercury was to provide Internet interfaces to all system components. All communication with SSDL satellites is via the SSDL ground station or similar OSCAR stations. Therefore, Internet access to the ground station enables access to satellite resources.

Control of primary ground station functions such as power control, radio tuning, and antenna pointing was computerized. This provided the basic building blocks for layering complex IBO control software on top of these low level drivers.

#### *Ubiquitous Access*

With the low level computer interfaces in place, focus turned towards ubiquitous access paradigms. Due to the high level of operator experience and comfort with Linux systems, the primary user interface is the command line. Shell scripts were written to command various setup tasks of ground station equipment. Software based on SatTrack [8] and Predict [9] is used to control antenna pointing and frequency tuning during satellite passes.

The OPAL spacecraft has a text based, telnet-like interface. Combined with the command line interface, this text interface enables simple computing devices (such as small personal data assistants or older terminal devices) to completely access the space system without sacrificing control capability of the system.

Flexibility in the user interface enhances the users computing experience by allowing customization to meet the user's needs. Graphical user interfaces are under development to provide a rich set of interfaces. Currently, web page and Java applet interfaces exist that provide alternates to the command line interface. The potential exists to create product generation web pages that allow high-level products to be specified and then transformed into low level automated commanding [10].

*Data Pipelines*

Data pipelines are fundamental to the Mercury IBO infrastructure. They serve as the communication backbones for most component interaction. Figure 2 shows a block diagram of a typical data pipeline for communication with OPAL.

The primary communicating components are  $E_S$ , the satellite, and  $E_O$ , the operator. The operator is commanding the satellite through an Internet/ground

station link.  $E_{A1}$  is a software agent that monitors the satellite contact watching for downloaded data files and archiving them in a web accessible database.  $E_{A2}$  is a software agent that assists in the security login sequence of the satellite by parsing the OPAL generated login key and generating the appropriate password phrase.  $E_{A3}$  is a software agent that parses OPAL's time stamp and generates a difference with real time. This difference is used to adjust OPAL's clock to real time. An additional agent not shown in the diagram logs all contacts and publishes the log files to a web accessible database. A complete history of all contacts is generated by this agent.

The filters,  $F_1$ - $F_3$ , transform the data traveling through the pipeline.  $F_3$  parses the data looking for the download file tags from OPAL. It then pipes information between the tags to  $E_{A1}$ , a program that decodes OPAL data and stores the downloaded files in a web accessible database.  $F_1 - F_3$  add semantic labels that contain time stamps and data packet originators.

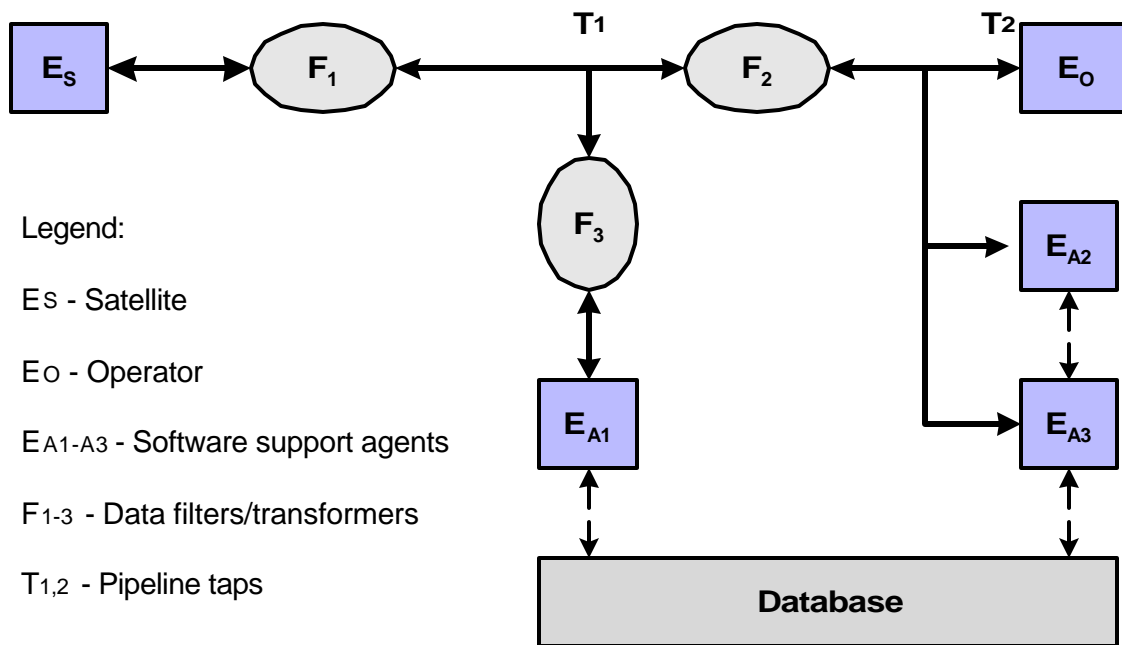


Figure 2 – Diagram of data pipeline used during Opal communication.

Data pipelines also exist to interconnect hardware drivers with automation software. Tracking software is connected to the antenna and radio drivers through a pipeline. This facilitates integration of software components by abstracting the interface to a common TCP/IP socket and enable COTS components to be connected.

### *Composable Services*

Mercury provides a framework for composing services based on system components. The data pipeline in figure 2 is an example of a composable service for operator contacts with a satellite. Currently, the services are built manually using command line functions. Work is underway to develop an XML framework for specifying services. The XML service specification will then be parsed by Mercury to automatically build and run the service. Another example of a composable service involves the magnetometer experiment onboard OPAL. Principle investigators requested comparison of magnetometer measurements made by OPAL to predicted values. A website was found that calculated magnetic field values based on location and time. A software agent was written that connected to the pipeline in figure 2 to automate this comparison. When the agent detected magnetometer measurements in the pipeline from OPAL, it obtained location and timing information from the tracking software and sent this to the magnetometer web site. It then compared the results from the web site with OPAL's data and published the data online.

### *Security*

Security is an integral element of Internet based operations. Any component accessible via the Internet is open to attack and abuse. Careful risk assessment must be made of potential misuse of the system. However, systems such as this need not be on the Internet. Many of the system components work well within an isolated intranet and are therefore immune to outside attacks.

Outside access of the Mercury system is restricted to encrypted connections through secure shell [11]. Secure shell (SSH) is a standard, cross platform Internet application that encrypts logins, passwords, and data flows. It also enables encrypted X11 forwarding of applications.

The graphical user interfaces are experimental and are only enabled during functional tests. Security features such as encryption and restricted access are necessary before the interfaces are deployed full time.

### *Implementation*

The Mercury prototype is currently implemented on a small cluster of three Pentium-class PCs running Linux. Software is written in a variety of languages including C, Perl, and Java. Low level details on the Mercury implementation are found online at <http://ssdl.stanford.edu/mercury/>.

## **5 Related Work**

The NASA Goddard Space Flight Center and the University of Surrey have been exploring operating missions as nodes on the Internet (OMNI) [12]. Experiments with the microsatellite UO-12 have uploaded networking protocols to the satellite and assigned the satellite an IP address. A router installed at the Surrey ground station has enabled pinging and ftp access to the satellite. Their goal is to lower operations costs by leveraging use of standard Internet protocols.

Goddard and the Center for Human-Machine Systems Research at the Georgia Institute of Technology are researching human interaction with automated systems. They have determined that in "lights out" systems, as operators move from controllers to managers, the automation must be human-centered in design. The designs must facilitate rapid human inspection, comprehension, intervention, repair, and maintenance [13]. These design features are important for remote operation and should be considered in IBO designs.

The Internet based operations work with Mercury has grown from SSDL's Automated Space Systems Experimental Testbed (ASSET). The purpose of this testbed is to develop and validate innovations for improving the cost-effectiveness of space operations. Current research work is focusing on model-based techniques for anomaly management, a blackboard architecture for software control, a high level product specification interface, and a beacon system for efficient anomaly detection and notification [10].

The Software Infrastructure Group at Stanford University is researching Internet infrastructure software. They are exploring ways in which software systems can be structured to achieve high dependability, availability, reliability, safety, and security. Their work on appliance digital services (ADS) is developing infrastructure to facilitate web publishing of data from digital devices such as handheld cameras and scanners [14]. This is similar to the web publication features of Mercury.

## **6 Conclusions**

The rapid growth and development of the Internet has highlighted the Internet's ability to provide global connectivity to distributed systems and services. Techniques and standards from the Internet world may potentially decrease the component connectivity costs of space systems, as well as provide new modes and methods of operations.

The Mercury system has been prototyped by SSDL to explore Internet based operations. It is an integral component of the OPAL space mission where over ninety percent of the spacecraft contacts are performed over the Internet.

Future work will continue to research various IBO technologies. Software strategies are under development to provide reliable and sustainable platforms for mission critical applications. Hardware and software infrastructure is under expansion to incorporate multiple space missions and global ground stations. The Mercury IBO prototype will continue as a testbed to explore the viability and applicability of Internet based operations in space missions.

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