Networking Technologies Enable Advances in Earth Science

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Abstract

This paper describes an experiment to prototype a new way of conducting science by applying networking and distributed computing technologies to an Earth Science application. A combination of satellite, wireless, and terrestrial networking provided geologists at a remote field site with interactive access to supercomputer facilities at two NASA centers, thus enabling them to validate and calibrate remotely sensed geological data in near real time. This represents a fundamental shift in the way that Earth scientists analyze remotely sensed data. In this paper we describe the experiment and the network infrastructure that enabled it, analyze the data flow during the experiment, and discuss the scientific impact of the results.

Keywords: Earth science application, field experiment, portable satellite dish, NREN

1. Introduction

The NASA Research and Education Network (NREN) team conducts research to enable the infusion of emerging network technologies into NASA mission applications. The NREN testbed peers with high-performance testbeds sponsored by other Federal agencies and with the university-led Internet2 Abilene testbed to provide a nationwide platform for conducting network research and for prototyping and demonstrating revolutionary applications.

The NREN team has partnered with NASA's Earth scientists in several endeavors in the past, including both application prototyping and technology development. Specific activities include QoS testing and experimentation between NASA Goddard Space Flight Center (GSFC) and NASA Ames Research Center (ARC), pre-launch checkout of

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instruments on the Aqua and Aura Earth Observing Satellites, helping to reduce the time-to-completion of large-scale ocean modeling for a project called Estimating the Circulation and Climate of the Ocean, support for international high-performance networking demonstrations at conferences sponsored by the Committee on Earth Observing Satellites (e.g., a multimedia teleseminar from Tokyo and Bangkok to Stockholm), and prototyping of a Data Grid application to process, distribute, and archive massive data sets from Earth-observing satellites.

In this paper we describe how networking technologies can significantly enhance scientific field activities. In June of 2003 NREN personnel joined a group of geologists in the desert near Vernal, Utah to conduct a Ground Truthing experiment. This experiment successfully prototyped near-real-time validation and calibration of satellite data by providing the geologists located at the remote site interactive access to NASA computational and storage facilities. These geologists collected reference data at the field site at the same time that the site was remotely sensed, and then interactively accessed supercomputing facilities for near-real-time analysis of the satellite and ground data. A combination of networking technologies provided the necessary communications infrastructure. A wireless LAN provided communications capabilities at the field site, a portable satellite dish enabled satellite connectivity between the field site and NASA Glenn Research Center (GRC), and the NREN WAN testbed provided terrestrial connectivity between NASA GRC and NASA ARC.

This paper presents details of the experiment and discusses its impact on the way Earth scientists analyze remotely sensed data. Section 2 presents background information about Earth science, to establish the context for the remainder of the paper. Section 3 presents details of the experiment, including a description of the network infrastructure. Section 4 analyzes the traffic flow generated by the experiment. Finally, Section 5 discusses possible enhancements to support future scientific field activities.

2. Earth Science Background

NASA's Earth Science Enterprise [1], a major science thrust within the Agency, is dedicated to understanding the Earth via remote observation from space. New technologies and strategies are being developed to improve the quality of remote-sensing instruments and the utility of the data that is collected. A series of satellites [2] are being launched throughout the current decade, containing a new generation of instruments that will produce higher resolution images of the Earth's land, oceans, plants, and atmosphere. These satellite instruments will generate terabytes of data daily, which must then be translated into useful information. This section briefly outlines the process of analyzing remotely sensed data, and then describes the specific instrument that was used in the Ground Truthing experiment.

2.1 Analyzing Earth Science Data

Along with new technologies and strategies to improve the quality of remote-sensing instruments, Earth scientists are exploring new techniques for analyzing the resultant

data. The traditional data path starts with downloading data from satellite instruments to a ground station. After instrument artifacts are removed at a Level One Processing facility, the data is transferred to one of the Distributed Active Archive Centers (DAACs) located throughout the country. Scientists then access data directly from the DAACs. This entire process from data collection to the scientist's desktop typically takes several days or even weeks.

Individual scientists then apply their own algorithms to the data. One useful computational technique for analyzing multi-spectral data is called *band ratioing*, a process wherein each pixel of one spectral band is divided by the same pixel of another spectral band. This is a technique for emphasizing the differences in images. Different band ratios are useful for highlighting different features of an image.

In order to complete the data analysis, the satellite data must be compared to reference data collected on the ground. This process, called *ground truthing*, is required to validate and calibrate the remotely sensed data. For example, remote sensing of a forest might reveal three different classifications of trees, while ground observation of the forest would be necessary to enable precise identification of the species of the trees in each of these classifications. Ground truthing should occur as close to the same time as the remote sensing as possible, to minimize differences that might occur in the scene and in the atmosphere over time. For detailed reference material on remote sensing and image analysis see [3].

2.2 The NASA Grid

Algorithms for analyzing Earth science data are often computationally intensive, requiring the use of supercomputer facilities. NASA's primary supercomputer facilities are located at only a few selected NASA centers. To facilitate access by scientists who are located throughout the country, NASA is currently integrating its large-scale computing and storage facilities into a grid infrastructure [4]. Components of the NASA Grid are the supercomputers and mass storage facilities, the network that connects these distributed resources, and the middleware that makes the distributed system look like a single, large virtual computer to the user. When the Grid is fully developed, a user will be able to log on to the Grid and run his application without knowing (or even caring about) the location of the specific resources that are being used. The Grid will locate and allocate resources, schedule jobs, stage data at the proper locations, manage jobs and resources, and return processed data files to the user.

Application developers from multiple disciplines are working with grid developers to ensure that the NASA Grid will be a useful tool to enable advances in NASA science. Earth scientists, both within the NASA community and within the broader international community, are currently prototyping several applications for grid computing in order to investigate the benefits of the technology and to drive its development. It is envisioned that future Earth scientists will routinely use the NASA Grid to analyze their data sets.

2.3 Hyperion Imaging Spectrometer

The Hyperion imaging spectrometer was the focus of the Ground Truthing experiment. This is one of three instruments located on NASA's Earth Observing One (EO-1) satellite [5], which was launched in November 2000.

The Hyperion instrument provides a new class of Earth observation data for improved Earth surface characterization. Hyperion, the first civilian hyperspectral sensor to image the Earth from a space platform, operates by measuring reflected solar radiation from the Earth's surface. It collects information in 220 spectral bands, from the visible to shortwave infrared, at approximately 30-meter spatial resolution (i.e., each pixel represents an area that is 900 square meters in size). Hyperion captures images in a swath 7.5 kilometers by 180 kilometers with twelve bits of data per pixel.

Detailed classification of land assets through the Hyperion imaging spectrometer improves the ability to detect and identify surface characteristics. The Hyperion's large number of spectral bands and the high number of bits per pixel enable high-resolution images of the Earth, providing increased accuracy of remote sensing data for many applications, such as mining, geology, forestry, agriculture, and environmental management. Resulting benefits will include, for example, better mineral identification and more effective selection of sites for exploration and mining, better predictions of crop yield, and improved forest management. More information about the Hyperion imaging spectrometer can be obtained from [6].

3. The Ground Truthing Experiment

NREN personnel from NASA's Ames and Glenn Research Centers joined university and US Geological Survey (USGS) geologists at a remote site in the Utah desert in June 2003 to demonstrate how real-time access to the NASA Grid can enhance Earth science in the field. Geologists calibrated and validated hyperspectral data from the Hyperion sensor onboard the EO-1 Earth observation satellite in near real time by processing this data on the NASA Grid and comparing it to spectral data that was collected from an instrument in the field.

3.1 On-site Equipment

NREN provided hybrid network capabilities to support the experiment, including both wired and wireless technologies. Wireless networks connected facilities at the field site. An NREN portable satellite dish enabled satellite connectivity between the experiment site and NASA GRC. The NREN testbed provided the terrestrial wide-area network communications infrastructure. In addition the PCMon monitoring and measurement tool [7] that has been developed by the NREN team was used to collect application performance data. Details regarding each of these networking components are presented in Section 3.2 below.

Scientists at the field site used a field spectroradiometer to make observations at the site, for comparison with the Hyperion instrument data. This spectroradiometer, which was attached to a laptop to record and store observational data, was mounted on a science trailer pulled by an all-terrain vehicle (ATV). A web camera was also mounted on the science trailer to take pictures of the terrain as the spectroradiometer collected data. For convenience, the field team parked a recreational vehicle (RV) at the site to serve as an office. Using software packages to remotely control and view the data on the computer screens, scientists could sit inside the RV and control instruments and view data and images from the remote laptops while the equipment was being pulled around on the science trailer. Alternatively, the spectroradiometer could be mounted on a backpack and carried by a scientist. Whether carried by a scientist or mounted on the science trailer, the spectroradiometer could easily be transported to sites of interest for data collection.

The NASA Grid provided storage and processing facilities at both NASA ARC and GRC. Specific NASA Grid facilities that were utilized during the Ground Truthing experiment include:

- Mass storage facility, called *lou*, at the NASA Advanced Supercomputing (NAS) facility, NASA ARC
- Mass storage facility, called *gmass*, at NASA GRC
- Computing cluster, called *aeroshark*, at NASA GRC

The computing cluster was used to compute band ratios, while the mass storage facilities were used to store both the raw data collected by the instruments and the band ratio results.

3.2 Networking Infrastructure

This section presents details about each of the networking components that supported the field activity. Figure 1 is a diagram of the end-to-end networking infrastructure.

3.2.1 NREN WAN Testbed

The NREN testbed is a high-performance testbed that connects several of the NASA centers, providing a research platform for the development of emerging network technologies and for prototyping of next-generation NASA mission applications. The current testbed configuration, presented in Figure 2, connects five NASA centers via a combination of ATM (Asynchronous Transfer Mode) and POS (Packet Over SONET) circuits, with bandwidths ranging from OC-3 (155 Mbps) to OC-12 (622 Mbps). Specific application and project requirements are used to determine how much capacity to provide for each individual link. The testbed is frequently upgraded, reflecting advances in technology. When NREN was first developed in 1993, the links were 45 Mbps DS3; we plan to investigate the use of optical wavelengths to enable gigabit wide-area networking in the future.

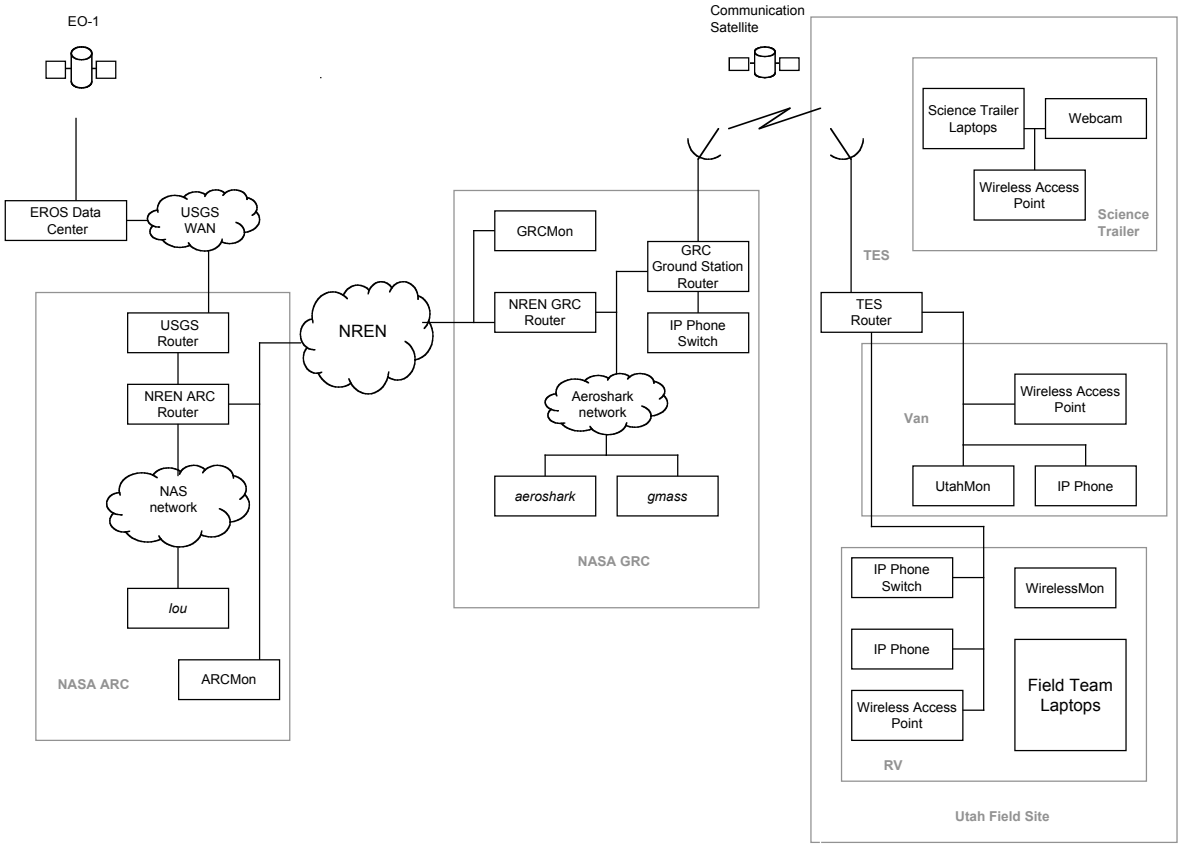

Figure 1. Networking infrastructure to support the experiment

Satellite connectivity to the testbed is available via ground station facilities at NASA GRC. The NREN testbed peers with high-performance testbeds sponsored by other Federal Agencies (e.g., the Department of Energy's Energy Sciences Network (ESNet) and the Department of Defense's Defense Research and Engineering Network (DREN)), and with the university-led Internet2 Abilene network at exchange points in Chicago and on the east and west coasts. International high-performance testbeds peer with NREN via the Chicago exchange point. NREN also peers with the NASA Integrated Services Network (NISN), the operational network that supports NASA scientists. These peering arrangements enable NASA to pursue meaningful research projects with partners throughout government and academia, both domestic and international.

The Ground Truthing field experiment required access to NASA ARC, NASA GRC, and the Earth Resources Observation Systems (EROS) Data Center in South Dakota. The two NASA centers are on the NREN testbed, and the EROS Data Center (EDC) is accessible to NREN via USGS networks.

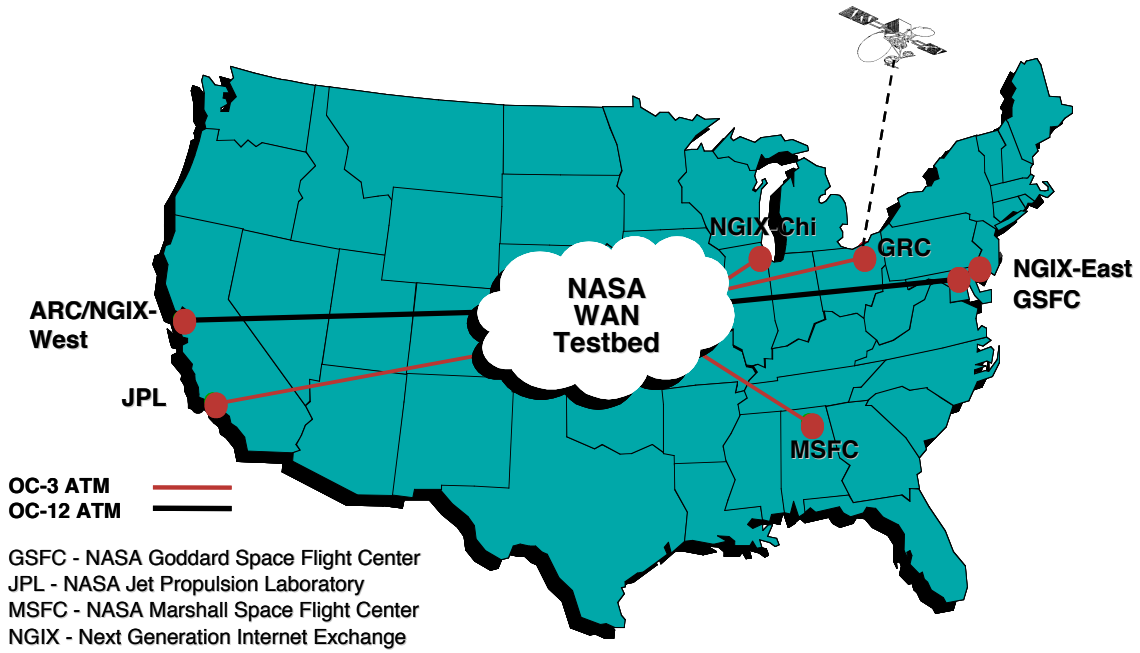

Figure 2. NREN testbed

3.2.2 Portable Satellite Dish

The Ground Truthing experiment typifies the many NASA missions that require access to people or equipment in remote locations. The experiment was conducted in the desert near Vernal, Utah, on government land managed by the US Bureau of Land Management. This site, selected because of its interesting geological features, is located several miles from the nearest community. Because of its remoteness, the only feasible network access to and from the site is via satellite.

The first time that the NREN project prototyped an application in a remote location we rented a satellite dish and installed it on the roof of a building. After that experience, recognizing the importance to NASA of being able to support scientific experiments in the field, we developed our own mobile satellite ground station facility. This facility, called the Transportable Earth Station (TES), consists of a trailer equipped with a twelve-foot satellite antenna and supporting electronics, along with a van to pull the trailer. The TES, pictured in Figure 3, can be driven to a site, parked, the antenna deployed, and the system used for satellite access to provide temporary networking facilities at that site. The Earth station is a completely self-contained Ku-band system, able to simultaneously send and receive up to 50 Mbps data streams. Hence, it is capable of supporting high data rate networking experiments.

During the past two years the TES has been used to successfully support several NASA mission application demonstrations. For example, the TES is being used to support a series of field experiments at the Mars Desert Research Station near Hanksville, Utah to develop and test technologies for future planetary exploration [8].

When the TES is used to support a field activity, satellite time is purchased through a commercial vendor. Because satellite time is expensive, the amount of bandwidth purchased to support the Ground Truthing experiment was approximately 5 Mbps in each direction.

3.2.3 Wireless On-site LAN

An on-site 802.11b wireless LAN provided local communications at the field site. There were three access points. One access point was located inside the TES van, one on the RV, and one on the science trailer that carried various instruments into the field. Theoretical capacity of 802.11b wireless is 11 Mbps; approximately 6 Mbps was the maximum capacity achieved in throughput tests at the field site.

This wireless LAN enabled remote control of the science laptops by the scientists, as well as connectivity between the instruments at the field site and the TES so that the data could be transferred back to the NASA centers.

Figure 3. NREN Transportable Earth Station

3.2.4 Network Monitoring and Measurement

One of the NREN team's objectives during the Ground Truthing experiment was to collect data to enable us to evaluate data flow, both during and after the experiment. For this purpose we used a general network measurement and monitoring tool that was designed and developed by NREN researchers for use on the NREN testbed. This tool, called PCMon, enables detailed analysis of individual traffic flows, identified by source and destination IP addresses and port numbers. Passive PCMon meters are placed at strategic locations across a network to collect data according to user-supplied specifications. A prototype wireless monitoring capability was added to the PCMon system just prior to the Ground Truthing experiment, enabling us to monitor all types of traffic during the experiment. This was the first time we attempted to monitor wireless data flows; we have not yet determined whether we were able to record all the wireless traffic.

Figure 1 identifies four PCMon monitoring points, where PCMon meters were placed to collect data from each packet header that traversed the metered interfaces during the Ground Truthing experiment. These meters recorded statistics for the following types of data:

- ARC meter (ARCMon): all traffic destined to NASA Grid facilities located at ARC
- GRC meter (GRCMon): all data between ARC and GRC
- Utah meter (UtahMon): Hyperion instrument data downloaded from EDC to the field site, Web interactions with Grid computer facilities at GRC, *ftp* of data from ground instruments to backup storage on ARC Grid storage, Voice over IP data, and administrative traffic
- Portable wireless meter (WirelessMon): data transmitted from field instruments to the on-site scientists, and file transfers from the field to mass storage facilities on the NASA Grid

3.3 Data Collection and Data Flow

The one-week experiment was timed to provide two EO-1 satellite passes over the field site, which was chosen because of its geological interest. The satellite was directly overhead during the first pass, but at about a 65-degree angle for the second pass. During the first pass there was 100 % cloud cover, which prevented the Hyperion instrument from obtaining any useful data. However, the experiment team stayed busy testing equipment capabilities, e.g., wireless signal strength, and collecting test data from the ground spectroradiometer.

The weather was clear on the day of the second satellite pass. The spectroradiometer was mounted on the science trailer as it was driven over a predetermined route, collecting data from the area at the same time as the Hyperion hyperspectrometer. Since the EO-1 orbital period is approximately 90 minutes, the field site was in view of the satellite for only ten to fifteen minutes. The geologists were also interested in a nearby hillside that was in the direct field of view of the Hyperion instrument, due to the angle of the satellite during the pass. So, after they were finished with the science trailer, they mounted the spectroradiometer on a backpack and climbed the hill with the instrument, collecting data as they climbed. They stopped a few times to transfer the data back to an ftp server at the University of Cincinnati, experiencing a fairly consistent 880 Kbps data transfer rate over the 802.11b path, which included one wireless repeater between them and the field camp. Later on during the day, when the geologists were back at the field camp, they also transferred the spectroradiometer data to *lou*, the Grid mass storage facility at NASA ARC.

Data collected from the Hyperion instrument during the satellite pass was downlinked to the EROS Data Center, where the raw data was formatted into Hierarchical Data Format (HDF), a common format for storing scientific data. The following day it was transmitted via *ftp* both to the field site and to NASA GRC for processing and storage on the NASA Grid. The data was initially stored on gm*ass* at NASA GRC. Data processing was done on the *aeroshark* cluster, also located at NASA GRC; the resultant data was stored both on *gmass* and on *lou* at NASA ARC. The processed data from *aeroshark,* both images and band-ratio data, was available to the geologists in Utah via a Web interface. Geologists in the field were able to interact with Grid resources in real-time, selecting additional band ratio calculations from *aeroshark* to enhance the satellite image. By

comparing the processed data with data collected on the ground, they were able to validate and calibrate the Hyperion satellite data while they were still at the field site.

4. Experiment Results

Real-time network connectivity between the remote site and NASA supercomputer facilities was the key to the success of the Ground Truthing experiment. Access to computer facilities from the field enabled the team to conduct near-real-time interactive data collection and analysis. The network allowed the scientists to combine the remotely sensed data and the ground-truthing data in near real time with extraordinary success and speed. This hybrid network allowed scientists to download 1.46 gigabytes of instrument data from the EO-1 satellite, apply atmospheric corrections, and validate the data with ground truth spectra within 90 minutes of satellite data availability. In a subsequent phase of the experiment, ground truth spectra were transmitted to remote servers while new spectra were being collected in the field. From the perspective of the geologists, this real-time science capability provided them an exciting opportunity. It allowed them to evaluate multiple hypotheses while still in the field, yielding more confident conclusions in just a matter of hours.

Bandwidth requirements to support the experiment were relatively modest. As indicated in the previous section, the bandwidth capacity of the three components of the hybrid network ranged from 5 Mbps to OC-3 (the capacity of the NREN link between NASA GRC and NASA ARC). The bottleneck link was clearly the 5 Mbps satellite link. The performance degradation caused by using standard transport layer protocols over networks with a large bandwidth-delay product, a problem that is well documented in the literature [9, 10], was clearly also a limiting factor.

The majority of network traffic during the experiment was simple file transfer. Specific files that were transmitted to and from the field site included the Hyperion instrument data that was downloaded from the EROS Data Center to the field site, file transfer from the ground spectroradiometer to storage facilities on the NASA Grid and to the University of Cincinnati, and images and band-ratio data that were retrieved via the Web. The size of the file transfers varied. The HDF data file from the Hyperion instrument was approximately 700 MegaBytes, compressed. This data was divided into two files, each about 350 MegaBytes in size. The transfer time for both files was about 30 minutes, giving a transfer rate that was measured at a sustained rate of 3 to 3.5 Megabits per second. We were able to achieve this relatively high utilization of the satellite link because the EROS Data Center server supported large TCP windows and the receiver was adjusted accordingly. Individual records from the handheld spectroradiometer were approximately 1 KiloByte in size. Although there were no stringent delay requirements associated with these transfers, large amounts of data were transmitted across the satellite link. Web data transfers are discussed below, since they represented real-time interactions.

Both *ftp* and *scp* (Secure Copy) (a protocol that encrypts data for added security) were used for file transfer of the data collected in the field. *ftp* was used for transfer of files to

the University of Cincinnati, which is the home university of one of the geologists, while a Grid-enabled variant of *scp* was used for transfer of files to *lou*, the mass storage facility on the NASA Grid at ARC. Figures 4 and 5 present the same *ftp* data flows in two different ways. Figure 4 graphs throughput for each individual flow, while Figure 5 graphs the combined throughput. The multiple *ftp* flows that occurred around 6:10 p.m. represent the parallel transfer of multiple files, a technique called striping. A comparison of Figures 4 and 5 shows that the use of striping significantly increases throughput. Figure 6 graphs *scp* data flow. *scp* was significantly slower than *ftp*, indicating the extra overhead required for encrypting the data. The observed throughput rates for all the file transfers originating at the field site were low compared to the link capacity.

In addition to the file transfer there was a modest amount of real-time traffic associated with the Ground Truthing experiment. The web interactions were real time, though delay tolerant. Types of files available via the web included 4.5 MegaByte band-ratio binary data files, 1 to 2 MegaByte image files, and thumbnail images that were tens of KiloBytes in size. Approximately 170 MegaBytes were transferred from the *aeroshark* cluster to the field site via Web requests for images and band ratio data. Over a 5 and 1/2-hour interactive work session, this translates to an average throughput of approximately 70 Kilobits per second. Note that this number is not indicative of achievable link capacity, since the interactive work session included time spent computing and analyzing results, as well as time spent transferring data.

Another type of real-time activity was the remote control and viewing of the laptop display that was connected to the ground spectroradiometer. Figure 7 is a graph of wireless data flow between the science trailer laptops and various team members in the RV on the day of the second EO-1 pass. This is data that was transmitted over the on-site wireless LAN.

Finally, another real-time application that provided valuable support for the Ground Truthing experiment was Voice over IP (VoIP), bringing the telephone to the field site. These IP phones were used for troubleshooting a DNS problem at one of the NASA centers, for adjusting field plans with experiment partners due to the cloud cover on the day of the first EO-1 pass, and for teleconferencing with management back home. Although the volume of traffic attributable to VoIP was relatively low, this was real-time traffic that required low delay. Figure 8 shows some of the VoIP conversations during the field outing.

Figure 9 is a graph of data flow over the satellite link while instrument files were being downloaded from the field to offsite facilities, representing a time when there was always data waiting to be transmitted. The relatively low throughput illustrates inefficient use of the satellite link. Table 10 compares typical data transfer rates that were observed for different types of traffic going off-site over the satellite link. The relatively low throughput rates listed in this table, in addition to the low throughput illustrated in Figure 9, indicate that not all the end sites had been tuned to optimize the performance of TCP.

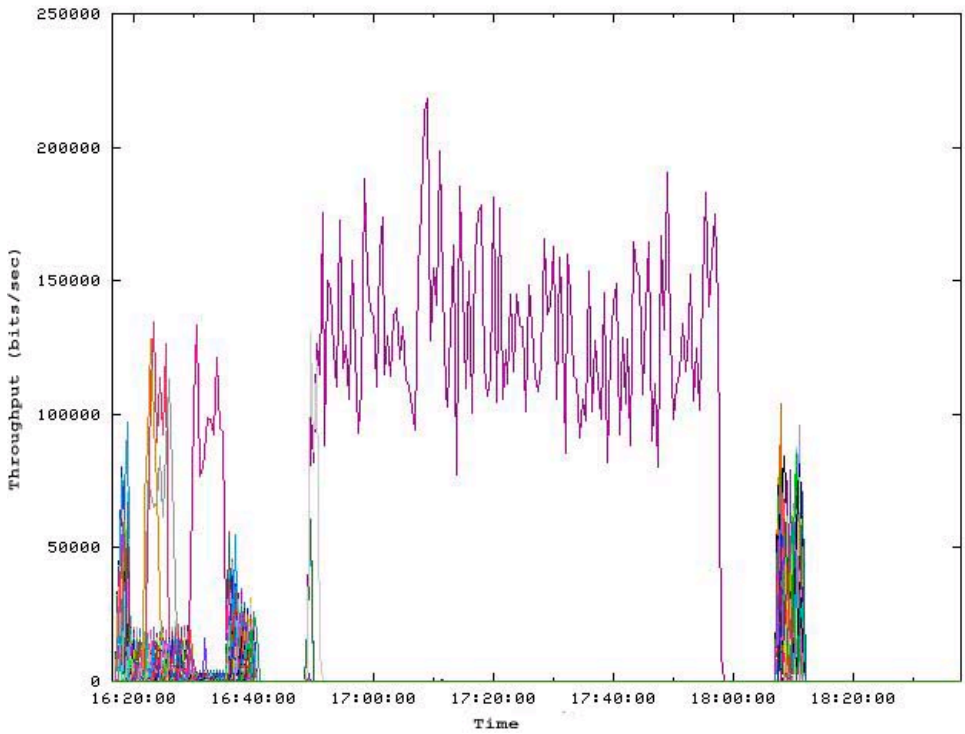

Figure 4. ftp data flows to University of Cincinnati

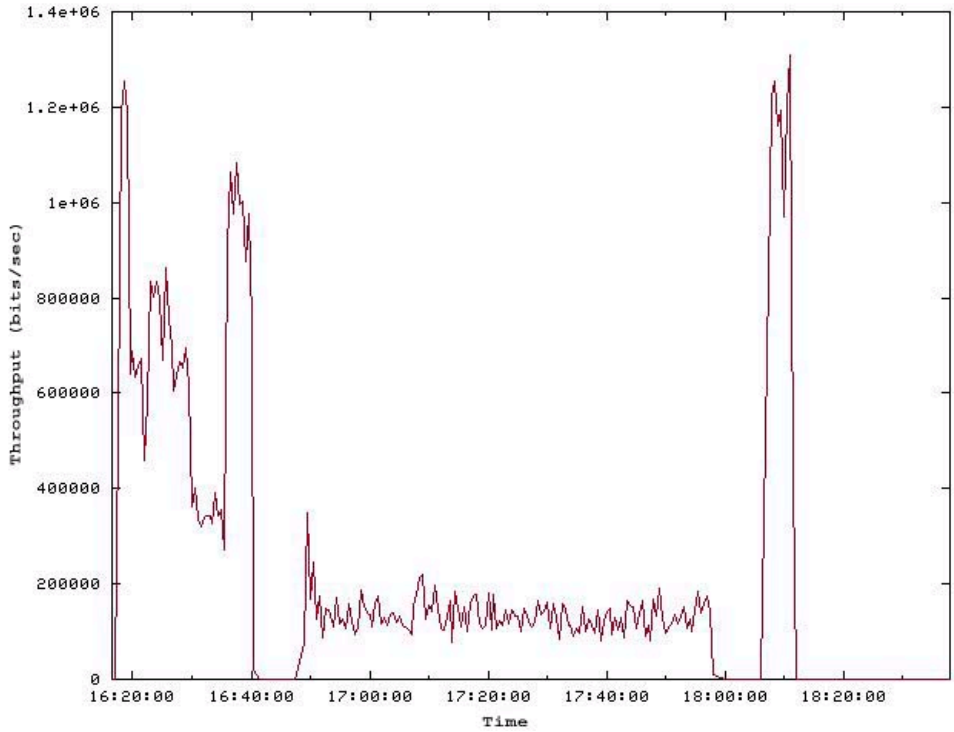

Figure 5. Combined ftp throughput to University of Cincinnati

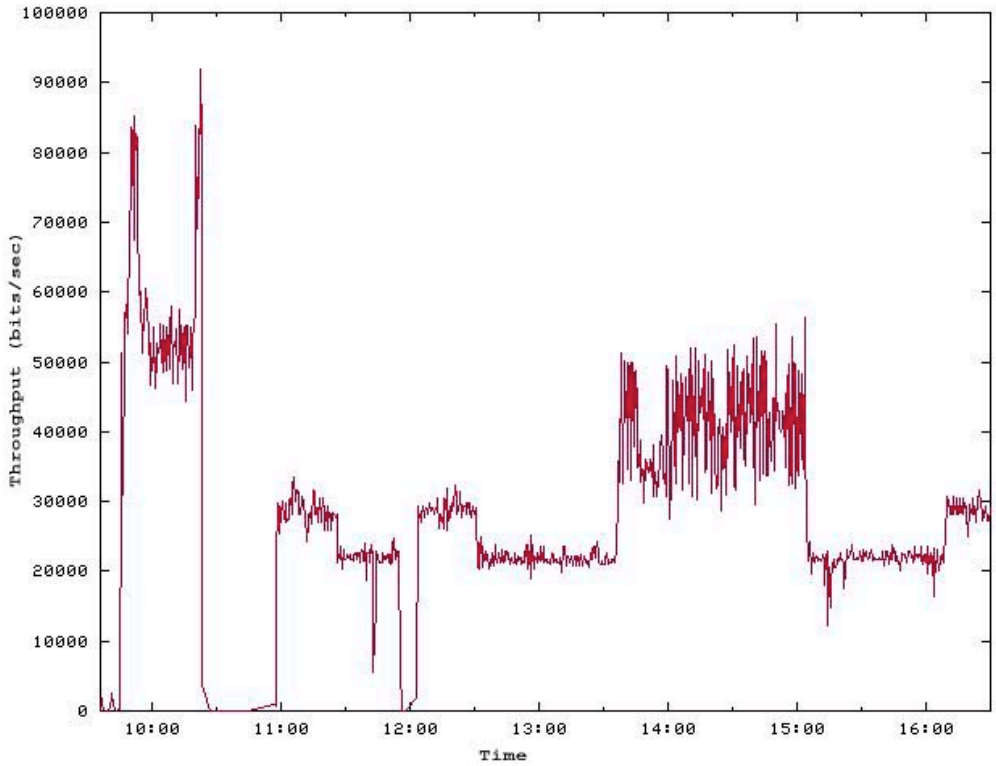

Figure 6. scp data flows to NASA Grid

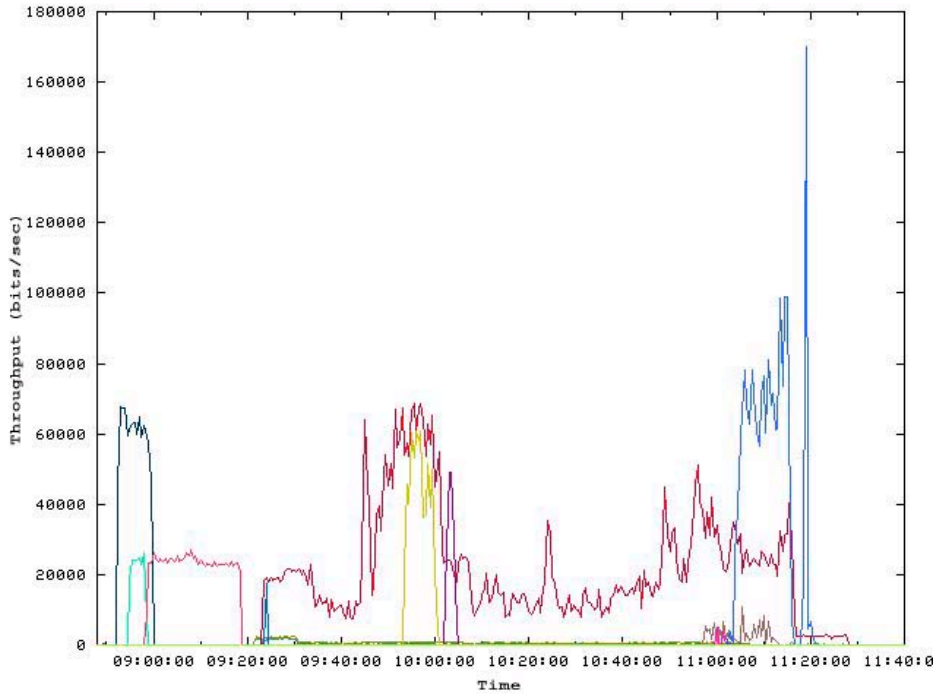

Figure 7. Wireless data flow between science trailer and RV

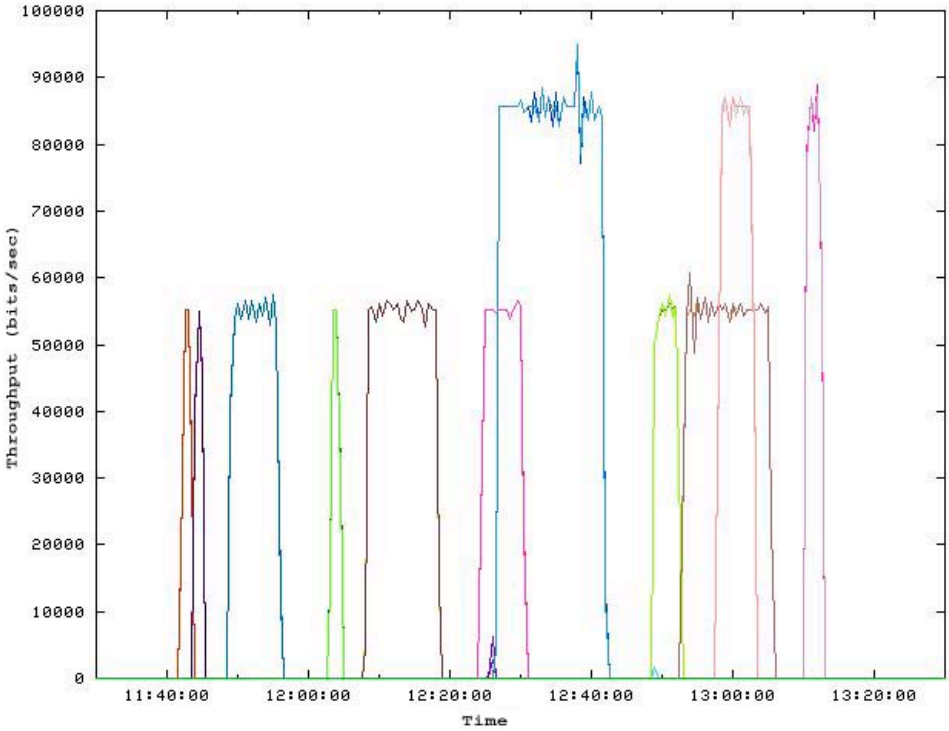

Figure 8. VoiP

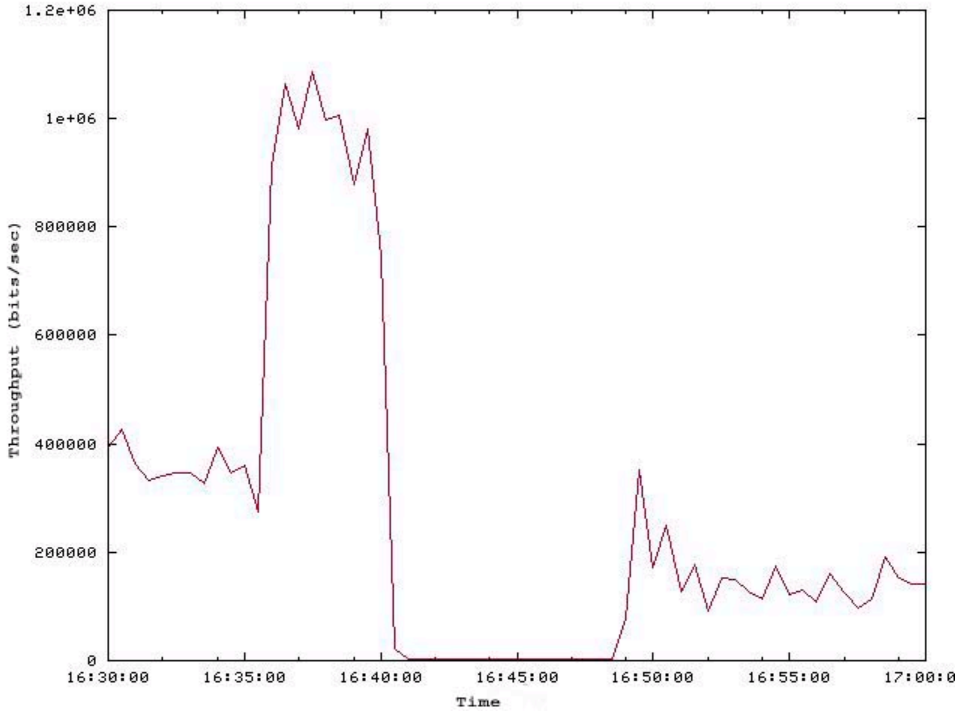

Figure 9. Off-site traffic over satellite link

Table 10. Observed data throughput

Type of data	Observed Throughput
ftp of field data to Univ. of Cincinnati	180 Kilobits/second
scp of field data to NASA Grid	30 – 60 Kilobits/second
Web data access	70 Kilobits/second
VoIP	60 Kilobits/second

5. Future Enhancements

This experiment provided a proof of concept of a new paradigm for Earth scientists working in the field. The extension of NASA Grid resources to remote teams via NREN's hybrid networks promises to enhance future Earth and space exploration missions.

NREN is committed to furthering the development of networking technologies to provide communications support in areas that are not serviced by permanent terrestrial networking infrastructures. This Ground Truthing experiment was one of the first field outings supported by NREN. While this experiment focused on geology, NREN is also participating in a series of Mobile Agent field activities, which are focused on developing techniques to enable planetary exploration. Another activity at NASA ARC that NREN is pursuing is a disaster management activity called FiRE (First Response Experiment). This latter activity focuses on the use of an unmanned aerial vehicle (UAV) flying over a natural disaster, such as a forest fire, taking aerial pictures, and using a satellite to transmit images to the ground to assist the fire-fighting team. Currently the team is using commercial satellite facilities and the Internet for image distribution. NREN can offer higher performance capabilities to support the effort.

The most basic capability that NREN provides for these field activities is simply to provide IP connectivity between the field site and facilities back home. While this capability alone has proved extremely valuable, NREN seeks to infuse additional emerging networking capabilities with each new field activity, to further enhance the science that is being supported. Specific enhancements planned by NREN include

improving performance via TCP tuning, increasing the flexibility of the wireless on-site network configuration by incorporating ad hoc networking, providing a level of Quality of Service (QoS) over wireless, improving energy efficiency, and increasing the portability of satellite facilities.

5.1 TCP Tuning

The most straightforward enhancement for NREN to pursue is TCP tuning. Note from the graphs in the previous section, although the capacity of the satellite link was 5 Mbps, actual data transfer typically fell far short of this number. The only exception was the data transfer from EDC to the field site, where the TCP window sizes had been adjusted for the satellite link.

5.2 Ad Hoc Networking

The wireless configuration to support on-site communication for previous field activities has been relatively simple. Introducing ad hoc networking to support field activities would allow more flexibility in the scientific activities. In a planetary exploration scenario, sensors might be deployed either as an ATV is driven around or by a robotic assistant. In a forest-fire scenario sensors might be dropped from a UAV to collect temperature and wind information to assist the fire fighters. These sensors would then automatically configure themselves into an ad hoc network. This would considerably simplify the pre-experiment setup activities in the first scenario. Of course, in the fire-fighting scenario, manual configuration of a network to collect this type of data would be impossible.

5.3 QoS Provisioning

A further capability that NREN plans to pursue is QoS provisioning, both for the end-to-end data path over the satellite link and for the wireless LAN. QoS provisioning is necessary to enable multiple types of traffic with widely varying requirements to share the limited network bandwidth that will always be the case at remote field sites. Types of traffic that must share these facilities include command and control of instruments (including voice recognition for communication with robotic assistants), VoIP, file transfer, and video conferencing. A simplistic technique that has been used in the field to protect a critical data stream has been to inform team members in advance to stay off the network during a specified time period. QoS in the wireless environment is a fairly new research topic. Limited results have been produced thus far, e.g., [11].

5.4 Energy Efficiency

Limited battery lifetime is a serious issue out in the field. Failure of a battery has often caused plans to be cancelled, or at best, postponed. CPUs are now available that can be run at multiple power settings. Some interesting research projects are developing techniques for adjusting these power settings, based on application requirements. Early results are encouraging, indicating the ability to achieve a significant increase in battery

lifetime [12]. In addition multiple levels of transmit power are now available on some wireless network interfaces. The development of energy-efficient network protocols based on variable transmission power is another fruitful research area [13]. NREN is pursuing both these areas.

5.5 Satellite Dish Portability

A final enhancement would be to improve the portability of the satellite equipment. The TES has limited portability, because of its size. It would be desirable to be able to mount a satellite dish on an ATV, so that the satellite capabilities could accompany the ATV as it moved around the field site. The use of Ka-band, rather than Ku-band, would enable reduction of the size of the satellite dish because the wavelength characteristics of Ka-band permit the use of relatively small receiver antennas [14]. Ka-band is scheduled to be commercially available in 2004.

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