SpaceOps-2021,8,x1393

An Augmented Ground Station Architecture for Spacecraft-Initiated Communication Service Requests

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Abstract

Spacecraft performing science and exploration missions have increasingly complex and event-driven objectives, making communication needs difficult to predict in advance. Additional flexibility is required in space communication provider networks to effectively meet time-varying demand. We envision a framework for automated resource allocation in which requests for communications service are initiated by spacecraft based on current mission needs. We propose an augmented ground station configuration featuring a wide field-of-view antenna to receive transmissions from spacecraft requesting high-rate communications. A software suite to automate the service fulfillment process, including interfacing with external scheduling systems such as NASA's Near Space Network, is described. Experimental results characterizing the physical-layer link between the wide field-of-view antenna and a software-defined radio testbed on the International Space Station are presented. We also discuss long-duration software testing on a ground-based testbed. Taken together, these proof-of-concept results demonstrate the feasibility of the concept to improve the responsiveness of space communications.

1. Introduction

Modern space communications networks are tasked with supporting scientific and exploration missions with increasingly demanding and dynamic communications needs. As both the number of active spacecraft and the resolution of their instruments increase, improved efficiency is required to meet additional demands for network capacity. Intricate science objectives impart event-driven and low-latency service requirements including adjusting spacecraft trajectory or instrument operations in response to changing circumstances. To give one specific example, consider the observation campaign which commenced after a neutron star merger was detected by the LIGO and Virgo gravitational wave interferometers [1]. Numerous orbiting observatories were retasked to produce follow-up observations in the hours to days after detection. Campaigns such as these involved in transient science (observations of phenomena whose occurrence can be difficult or impossible to predict in advance) must transfer large volumes of unanticipated data to scientists on Earth [2–4].

Presently, many requests for communications service are initiated by a human mission operator who must anticipate future data transfer needs of their spacecraft. Operators submit highly explicit service requests, typically specifying a time and particular communications resource (a specific ground station or relay satellite). For very high-performance links, including many of those operated by the National Aeronautics and Space Administration (NASA), access is generally managed in a batch scheduling process overseen by human operators beginning weeks to months in advance of the communications service [5–7]. This imperfect process can drive inefficient utilization of communications resources. First, operators may request more services in the planning phase than are ultimately revealed to be necessary in the execution phase due to uncertainty in the true quantity of their future service needs and the likelihood that some requests will be blocked by higher priority users. This results in opportunity costs for other users.

Additionally, highly specific requests limit the network's flexibility to achieve globally efficient communications resource allocations. The manual nature of the traditional request process limits the network's ability to rapidly renegotiate schedules when unanticipated demand arises, such as in the transient astronomy case described above. Furthermore, in a future where large numbers of less-expensive small spacecraft are increasingly performing Decadal-class science [8], this level of human attention increases operations costs. Evolving space communications architecture envisions future high-bandwidth networks in operation around inter-solar system bodies such as

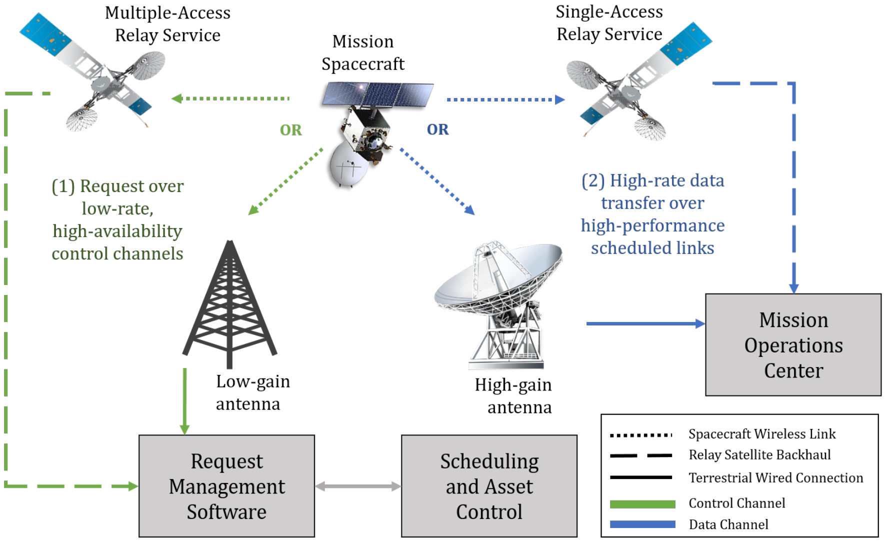


Fig. 1 Overview of generic request and service fulfillment process initiated by an Earth-orbiting satellite. A request to schedule service (1) is sent over a control channel. Scheduled high-performance service over a data channel (2) is used for operational communications. Several options exist for both control channels and data channels.

the Moon and Mars to support dozens of surface and orbiting spacecraft accomplishing complex objectives [9]. Increased latency to Earth makes human-in-the-loop scheduling of links among a regional network elsewhere in the solar system infeasible. As network traffic increases to include communications with destinations local to the regional network (e.g. a remote sensing stations providing info to a lunar exploration outpost), fully autonomous solutions to manage links in a responsive manner are required.

The ideal network infrastructure can autonomously allocate resources to meet each spacecraft's immediate demand. User-initiated service (UIS) aims to enable more responsive access to network services such as high-performance space communications links [10–12]. In the concept, a network user (i.e. the spacecraft itself) originates a request for communications service based on current needs. The event-driven scheduling process employs machine-to-machine communications over a low-rate, high-availability control channel. Essentially, we aim to use high-availability links as a mechanism over which high-performance links are autonomously scheduled. This mechanism of automation progresses towards a "Space Mobile Network" with a scheduling and resource allocation process analogous from the user's perspective to that of a terrestrial mobile network [11, 13].

This work proposes augmenting traditional ground stations with low-cost, omnidirectional antenna systems to establish a dedicated control channel for receiving service requests. Results from a demonstration using an experimental payload on the International Space Station (ISS) are presented to verify the feasibility of that concept. We discuss the design of automation software allowing the same ground station sites to be scheduled for high-rate data transfer, even during the same pass (dependent upon availability). This operations concept expands the flexibility of UIS, including support of less-capable small satellites. Future work to further mature the software suite and infuse automated service management into users of operational networks is planned. Additionally, applications are anticipated in the communications infrastructure enabling NASA's Artemis lunar exploration program [14].

2. System Overview

Advances in software-defined radios, reconfigurable wideband front-ends, and a diverse landscape of government, commercial, and non-profit space communications infrastructure offer a variety of potential paths for data transfer. Though generalizations are difficult, we can broadly classify wireless links based on their prioritization of availability versus performance [13]. *High-availability* links maximize the number of simultaneous users, generally by employing a multiple access scheme. However, dividing available resources (e.g across the frequency or code domains) places a limit on achievable per-user data rates. *High-performance* links employ large apertures and

Byte	Description	Byte	Description
0	Protocol Version	13	Service Urgency
1 - 2	Destination Identifier	14 - 17	Size of Data to Transfer
3 - 4	Source Identifier	18 - 21	Suggested Minimum Event Duration
5	Service & Transaction Type	22 - 25	Suggested Maximum Event Duration
6	Message Type	26 - 29	Required Minimum Event Duration
7	Flags	30 - 49	Suggested Asset Identifier (e.g. TDRS-10, WS1)
8	Service Identifier	50 - 53	Suggested Radio Settings Identifier
9	Message Sequence Number	54 - 57	Time the Event is Required Before (UNIX Date/Time)
10 - 11	Message Length	58 - 61	Checksum of Spacecraft's Current Schedule Data
12	Header Checksum	62	Multiple Event Flag
		63	Immediate Access Flag
		64	Message Checksum

Table 1 Format of the UIS request message. A common header (left column) begins all UIS messages. The UIS data transfer request message (right column) includes information, both suggestions and requirements, which aids the scheduling process.

specialized electronics to maximize instantaneous link capacity. However, this performance is generally only available to one spacecraft at a time with a scheduling process to balance demand across potential users.

The high-level concept of an Earth-orbiting satellite initiating a request for communications service is shown in Fig. 1. The process takes place in two parts: (i) a request to schedule service is sent over a high-availability control channel and (ii) scheduled service is used for operational communications over a high-performance data channel. In this work we will consider the service requested by the spacecraft to be a high-rate data downlink (though requests for additional network services such as navigation support can also be supported by extensions of the protocol). The automated process is aided by software for request management and control of assets (i.e. relay satellites and ground stations).

2.1 Request Process

Consider a near-Earth spacecraft performing the complex science or exploration objectives alluded to in Section 1 which make its communication needs difficult to anticipate in advance. Onboard software determines when the spacecraft requires communication service. This can be triggered by instruments generating time-sensitive science observations, health monitoring systems reporting anomalous sensor readings, or simply data handling software observing that onboard data storage is nearly full. The spacecraft forms a UIS data transfer request message (Table 1) which must be transmitted to request management software on the ground. The request management software must then send a response informing the spacecraft if its requested service has been successfully scheduled. Both these messages, request and response, are transmitted over a low-rate, high-availability *control channel*. As indicated in Fig. 1, two options exist for control channels in the near-Earth environment:

A) **Multiple-Access Relay Satellite Service.** Previous UIS flight experiments [15] used the multiple-access service of a NASA relay satellite as a control channel. Commercial relay constellations could also offer additional channels with high availability to Earth-orbiting satellites [16].
B) **Wide Field-of-View Ground Station Antenna.** Alternatively, a dedicated control channel antenna colocated at a ground station can be used. The feasibility of this approach will be discussed in this work.

2.2 Service Process

In response to a spacecraft's request, service is scheduled on one of several high-performance assets. Based on asset availability, service may take place sometime in the near future or even during the same pass. At the start of its access the spacecraft begins exchanging data over the high-rate *data channel*. Two classes of data channels exist for transferring data between a spacecraft and its mission operations center (MOC) on Earth:

1) **Single-Access Relay Satellite Service.** Prior UIS experiments demonstrated the ability to autonomously schedule the single-access service of a NASA relay satellite in response to a spacecraft request [15]. Future work may also interface with commercial relay satellite systems.
2) **High-Gain Ground Station.** Automation software developments discussed in this work also allow high-performance ground stations to be scheduled and controlled in an automated fashion. Additionally, the system could interface with commercial ground station providers via their scheduling application programming interfaces (APIs) [17, 18].

These systems typically use highly directional mechanically steered antennas which make them ideal high-rate data channels. However, aside from certain special cases (a cluster of small Earth-orbiting satellites [19] or several space vehicles in the vicinity of Mars [20]) these assets can track only one spacecraft at a time making them inherently single access.

3. NASA's Space Communication Networks

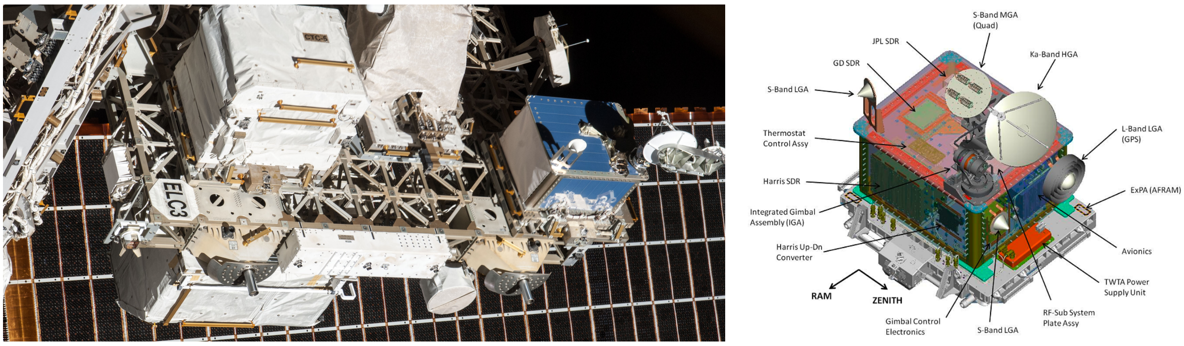
To provide context for the developments presented in this work, the following section will discuss specific control and data channels available within NASA's Near Space Network.

3.1 Relay Satellites

NASA's Tracking and Data Relay Satellite System (TDRSS) is a constellation of relay satellites located in geosynchronous orbit. Two mechanically-steered 4.6 m antenna reflectors each provide a high-performance link to generally one Earth-orbiting spacecraft at a time (i.e. single-access service). Additionally, each relay is equipped with a grid of S-band antenna elements which provide multiple-access service to several spacecraft simultaneously. Beamforming using a spacecraft's orbital state vector allows the service to track the vehicle through electronic steering while spreading codes unique to each radio provide a multiple-access scheme.

Access to network services is shared among multiple missions which schedule service across two systems. Scheduling through the Network Control Center Data System (NCCDS) begins more than two weeks in advance. During this forecast period network operators fulfill requests from mission operators based on priority. After the forecast scheduling process is complete (at least one week in advance) the active scheduling period begins. During the active scheduling period mission operators can submit additional requests which are allocated on a first-come, first-served basis. Mission operators can interact with NCCDS through a network-provided graphical user interface, an NCCDS-compliant external processing system which is generally mission-specific software, or through person-to-person interactions (e.g phone calls, emails). The NCCDS handles single- and multiple-access services in both the forward (network to spacecraft) and return (spacecraft to network) directions.

The Demand Access System (DAS), the second of the two systems, allows multiple-access return service to be scheduled for extended duration. Each dedicated user is allocated an on-ground beamformer allowing for 24/7 reception of low-rate data [21]. While both single-access and multiple-access relay services can be provided by the



(a) (b)

Fig. 2 SCaN Testbed showing (a) the payload's former location on an ExPRESS Logistics Carrier (ELC-3) and (b) a detailed view of antennas and major components.

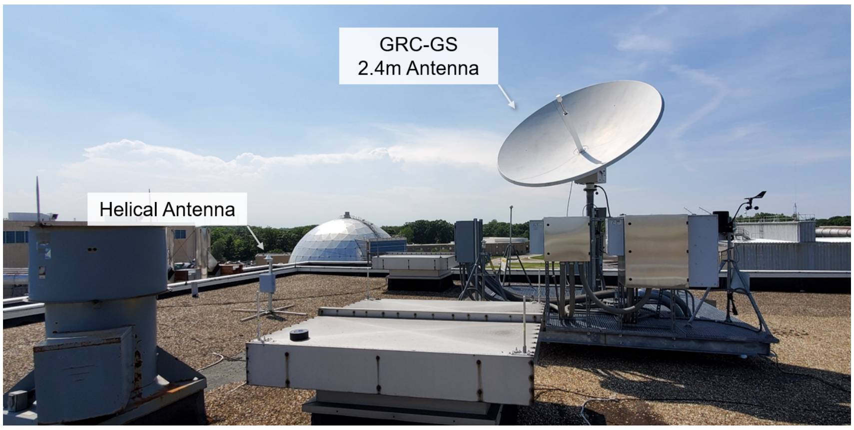


Fig. 3 Wide field-of-view helical antenna colocated with the 2.4 m S-band ground station dish at NASA Glenn Research Center.

same relay satellite, the performance difference is stark. Though the multiple-access system can support many simultaneous users, it is limited to a per-user data rate of 300 kbps. The single-access system, though only able to support one user per antenna (two per relay), can provide much higher performance. For example, the single-access return service can operate up to 1.5 Gbps at Ka-band, an increase greater than 3 orders of magnitude compared to multiple access.

3.2 Ground Stations

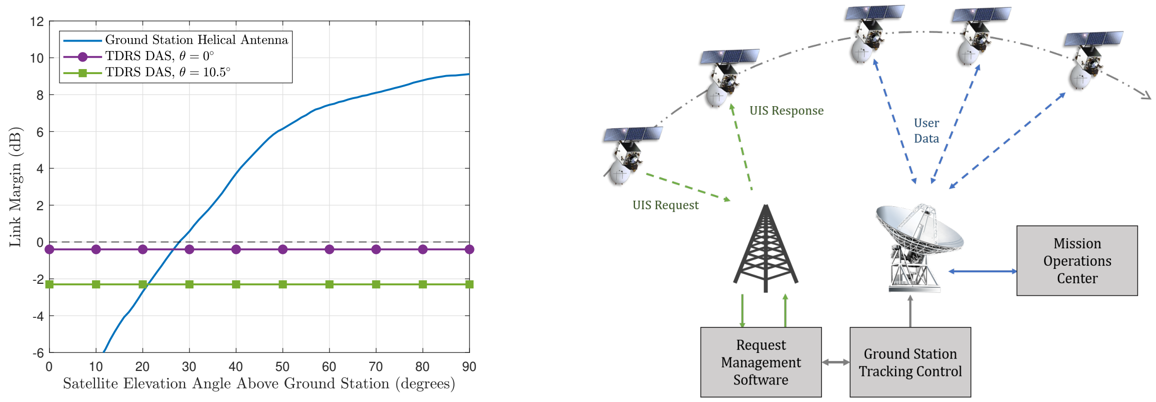
Spacecraft operating in Earth-orbit can also be served by a network of ground stations owned by NASA or partners (commercial entities or government agencies). Ground stations that comprise the Near Space Network span the globe with sites on every continent. Many ground stations use mechanically-steered parabolic dish antennas (up to 18.3 m in diameter) to provide high-performance links - generally to one spacecraft at a time. Spacecraft beyond the Earth-Moon system communicate through the Deep Space Network, comprised of three main complexes with dish antennas up to 70 m in diameter. Though this work will focus on the near-Earth domain, we note recent research has discussed user-initiated service for the Deep Space Network. In this concept, beacon tones send unacknowledged requests to overcome the severe round-trip delay from deep space [22, 23].

3.3 Experimental Assets

In addition to operating the networks above, NASA Space Communications and Navigation (SCaN) conducts experimental research in space communications. SCaN Testbed (Fig. 2) was a technology development platform flown as an external payload on ISS from 2012 - 2019 [24]. Experiments with SCaN Testbed investigated reprogrammable, adaptive, and intelligent wireless communications and networking using three software-defined radios (SDRs). Collectively, the SDRs were reprogrammed over 880 times during 4,000 hours of operation [25]. Results in this work were obtained using one of the three radios on SCaN Testbed: the S-band SDR built by NASA Jet Propulsion Laboratory (JPL) and L3 Cincinnati Electronics (hereafter the JPL SDR). To support the SCaN Testbed experiments program, NASA constructed a 2.4 m S-band ground station at NASA Glenn Research Center in Cleveland, Ohio, USA (hereafter the GRC-GS).

4. Motivation of Direct-to-Earth Requests

An initial UIS demonstration performed with SCaN Testbed used TDRSS multiple-access service as a control channel over which low-rate UIS request messages were sent [15]. This work will examine the feasibility of an alternative concept in which request messages are transmitted direct-to-Earth. In this concept, a wide field-of-view antenna colocated with a ground station provides a dedicated low-rate control channel available to any spacecraft within view. Figure 3 provides an example of such an arrangement. This approach offers several advantages.



(a) (b)

Fig. 4 (a) Link margin versus elevation angle when transmitting to a wide field-of-view antenna from a low-power spacecraft (ISS orbit). Additional traces show negative link margin both when the satellite is directly below a TDRSS relay and at the maximum angle (10.5°) of the relay field of view. (b) Concept of immediate requests during the same pass over a ground station site with both a dedicated control channel antenna and high-gain steered antenna.

4.1 Support less-capable spacecraft

Many spacecraft may opt for the near 100% orbital coverage of geosynchronous relays and use TDRSS or an equivalent commercial relay constellation as a low-rate control channel over which UIS requests are sent. In contrast, there will be times when an Earth-orbiting spacecraft is not within sight of a ground station. However, space mission users have diverse needs and the design of their spacecraft will reflect choices made about the inherent trade offs with which they are confronted. In particular, many missions based on small satellite platforms may tolerate the increased wait time to send direct-to-Earth service requests if they were able to save the size, weight, and power (SWaP) burden required to communicate over geosynchronous relays. Fig. 4a considers the case of a small satellite with a 0.5 W S-band transmitter, antenna with directivity of 0 dBi, and data rate of 1 kbps. While the spacecraft is unable to close a link to TDRSS even at low rate, it can easily transmit its request to a wide field-of-view antenna on the ground.

There are currently 14 ground station locations that are part of the Near Space Network. Table 2 analyzes the availability of a control channel link if each site is augmented with our proposed dedicated wide field-of-view antenna. We see that a spacecraft in polar sun-synchronous orbit (the orbit of the Soil Moisture Active Passive (SMAP) Earth-observation satellite [26] is used as an example) has an opportunity to transmit a service request approximately every 21 minutes. While not instantaneous, mission designers may prefer increased time between service requests if the choice results in the reduced SWaP of a direct-to-Earth communications subsystem. As the following sections will show, the hardware required for a dedicated control channel antenna is minimal. This could allow deployment at even more locations to increase coverage.

Example Spacecraft	ISS	SMAP
Orbital Inclination	51.6°	98.1°
Average altitude	400 km	685 km
Percent Coverage (1 year average)	12.5%	27.7%
Time between contacts (1 year average)	49.9 min.	21.0 min

Table 2 Line-of-sight coverage analysis between spacecraft in low-Earth orbit and NASA ground station sites.

4.2 Support immediate same pass requests

Locating a control channel antenna at a ground station site enables an advantageous concept of operations: requests for immediate service during the same pass (Fig. 4b). As the following section will show, a wide field-of-view antenna can receive a service request shortly after the transmitting spacecraft appears over the horizon. If an antenna at the site is idle, the request management software could schedule it for immediate access. Furthermore, if the requesting spacecraft is experiencing an emergency (as indicated by the Urgency field in Table 1) an antenna in active use could abandon its current service to instead handle the urgent communication needs.

4.3 Overcome current hardware limitations

Under the concept of operations discussed in [15], each spacecraft using a control channel link provided by TDRSS will be registered as a dedicated DAS user. The number of simultaneous DAS users is limited by available hardware such as beamformer and receiver units [21, 27]. While additional digital beamformers and software-defined receivers can be integrated into the network, a dedicated antenna provides an alternative path to increase the number of spacecraft that can be supported over a control channel.

5. Control Channel Link Design & Test

SCaN Testbed was used to verify the feasibility of using a direct-to-Earth control channel link. This section discusses the design of the RF hardware chain and software-defined modem used in the experiment.

5.1 Antenna Criteria

To define criteria for the dedicated control channel antenna, it is helpful to ask the question: why not use the existing parabolic reflector dish antennas to provide a control channel? This scenario presents two problems:

- High-performance antennas will generally already be heavily tasked with providing high-rate communications to spacecraft. Reducing their availability in order to provide a low-rate control channel is inefficient.
- In the UIS concept, requests can come from any spacecraft within view at any time. Steered directional antennas must track a spacecraft during a pass. It is impossible to perform this tracking if it is not known which of several spacecraft within view will send a request.

While it would be possible to use an electronically-steered multibeam antenna to simultaneously track each spacecraft within view using independent beams [13], this work will consider the simpler solution of using a helical antenna with a hemispherical pattern. A disadvantage of this choice is the greatly reduced directivity. We will compensate for this primarily by operating at very low data rates of 0.5 − 1 kbps. A helical antenna with a 3 dB beamwidth of 90° and maximum gain of 4 dBi was selected. The antenna was mounted adjacent to the GRC-GS with boresight directed at zenith. RF and modem design of the direct-to-Earth control channel link is discussed in detail in [28].

5.2 SDR Modem Design

Figure 5 shows the modem design optimized for low bit rates which was developed and deployed on the JPL SDR. Radios connected to the helical antenna on the ground employ a similar high-level structure. Link characterization was performed with SCaN Testbed and the helical antenna deployed as in Fig. 3. A preliminary link budget (Fig. 6) suggests it is possible to close a bidirectional 0.5 kbps link at the horizon (0°) and a 1.0 kbps link whenever ISS is at elevation angles greater than 8°.

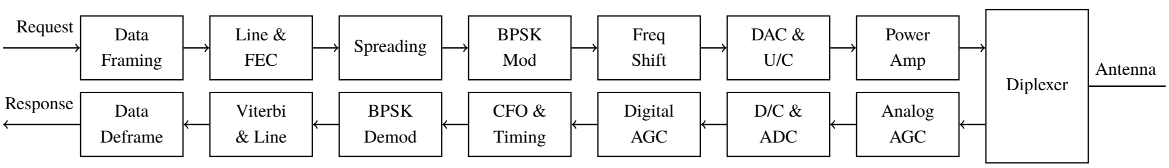
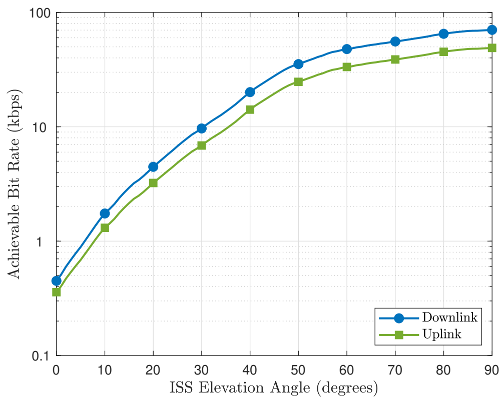


Fig. 5 Modem design implemented on the JPL SDR.

Parameter	Value
TX Power into Helical Antenna	3.2 W
SCaN Testbed EIRP	7.5 dBW
SCaN Testbed G/T	−28.4 dB/K
ISS Altitude	400 km
Atmospheric & Rain Attenuation	0.5 dB
Modulation	BPSK
Convolutional Code Rate	1/2
Required E_s/N_0 for BER = 10^{-5}	6.5 dB
Link Margin	2 dB

(a)



(b)

Fig. 6 Link budget calculation. (a) Assumptions for SCaN Testbed and the helical antenna. (b) Achievable rate in the uplink and downlink as a function of ISS elevation angle.

5.2.1 Space-to-Ground Downlink (UIS Request)

The downlink carries the initial UIS request from the spacecraft to request management software on the ground. Data is packed into frames following the Advanced Orbiting Systems (AOS) Space Link Data Protocol [29]. Spreading is employed on the transmit side to meet power flux density (PFD) regulations [30] and provide a multiple access mechanism. Spreading codes unique to each user allow the ground to decode messages received simultaneously. A digital frequency shift module is used to compensate for tuning error in the radio's front-end. This module is also responsible for transmit-side Doppler pre-compensation. The baseband signal is converted to analog and passed to the JPL SDR's front-end which provides upconversion to S-band and amplification. The signal passes through a diplexer which separates transmit and receive chains connected to the common nadir-facing antenna.

5.2.2 Ground-to-Space Uplink (UIS Response)

The uplink is used to send a response (pre-compensated for Doppler) to the spacecraft in acknowledgment of its request. The signal received by the JPL SDR passes through an automatic gain control (AGC) circuit before downconversion to an intermediate frequency and digitization. The analog AGC and an additional digital AGC are used to keep the input signal at approximately the same level as the distance between ISS and the helical antenna varies throughout the pass. It is assumed that the ground will send a response to one spacecraft at a time. This, coupled with the absence of PFD restrictions in the uplink, removes the need for spreading. Frequency and timing recovery stages employ Costas and Gardner loops, respectively. The bandwidth of these loops is initially set wide for fast acquisition. Once synchronization has been achieved loop bandwidths are narrowed for more reliable tracking. After Viterbi decoding and AOS deframing, the UIS response message is recovered.

6. Automation Software Suite Design

Thus far, we have dealt with the physical layer control channel used to convey the UIS request message from the requesting spacecraft to the Earth. Several interconnected software components are required to automate the process of resource allocation (Fig. 7). Building on the framework introduced in [15] we have developed a suite of software that demonstrates the feasibility of handling direct-to-Earth requests. These software components, collectively the AutoCAT Suite, fulfill core functions of the UIS process:

- **Event Manager (EvM).** After receiving the UIS request message over the control channel, the Event Manager negotiates access to assets on behalf of the requesting user spacecraft. Once service has been scheduled, EvM responds to the user spacecraft with information about the scheduled access.
- **Tempus.** Tempus is an external processing system which provides an interface between EvM and the NCCDS, allowing spacecraft-initiated scheduling of TDRSS resources. Future work will develop Tempus-like interfaces between EvM and the scheduling systems of additional external service providers.

- **Flight Service Manager (FSM).** The Flight Service Manager, a software component which runs onboard the user spacecraft, handles UIS request and response processing. FSM provides the spacecraft's command and data handling (C&DH) software a simple user interface over the Core Flight Software Bus [31].

Some ground station sites may have existing scheduling and asset control systems which EvM can communicate with through Tempus-like interfaces. For other ground stations (such as the GRC-GS) that don't have an preexisting framework, additional components in AutoCAT Suite offer a solution for "lights off" operation which interfaces with the UIS automation architecture:

- **LynxCAT.** Designed to run locally at a ground station site and interface directly with an antenna pointing gimbal, LynxCAT enables automated ground station tracking control in response to instruction sets provided by EvM.
- **Network Service Manager (NSM).** The Network Service Manager handles the case where instances of LynxCAT are deployed across several sites within a provider network. NSM sorts instruction sets from the common Event Manager and distributes them to the correct instance of LynxCAT.

The software is designed to be modular with connections over terrestrial Internet, allowing each component to be hosted on separate machines at different locations. An additional design constraint is the small size of UIS response messages required to traverse low-rate control channel links in a timely fashion. Both the direct-to-Earth channel considered in this work and future plans for a TDRSS forward broadcast service allow for control channel rates of approximately 1 kbps [32]. This presents a challenge as the response must contain all the relevant information about the scheduled service: start time, stop time, allocated asset, and ideally a pointing solution also. This section will outline a series of architectural decisions that allows us to compress this information into very small data volumes, typically 100 bytes.

6.1 Access Computation

Solving for future line-of-sight access is critical to scheduling event-driven service. Spacecraft must know when the direct-to-Earth control channel is available (i.e. they are within view of a ground station augmented with a control channel antenna). EvM must determine when a spacecraft will be able to see an asset in order to properly schedule service. Finally, the spacecraft must determine how to orient its antenna throughout a pass. A common computation engine (Astro Engine) runs as part of several software components to predict the motion of satellites relative to ground stations.

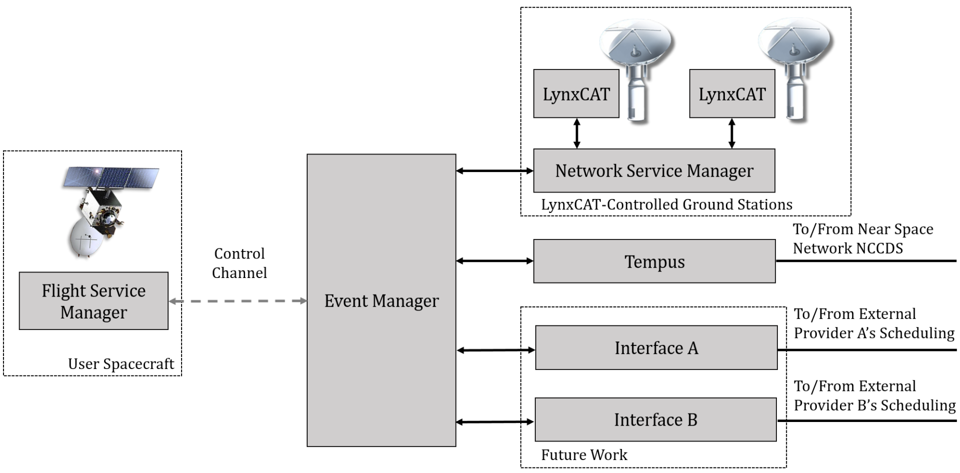


Fig. 7 Connections between major components of the automation software suite.

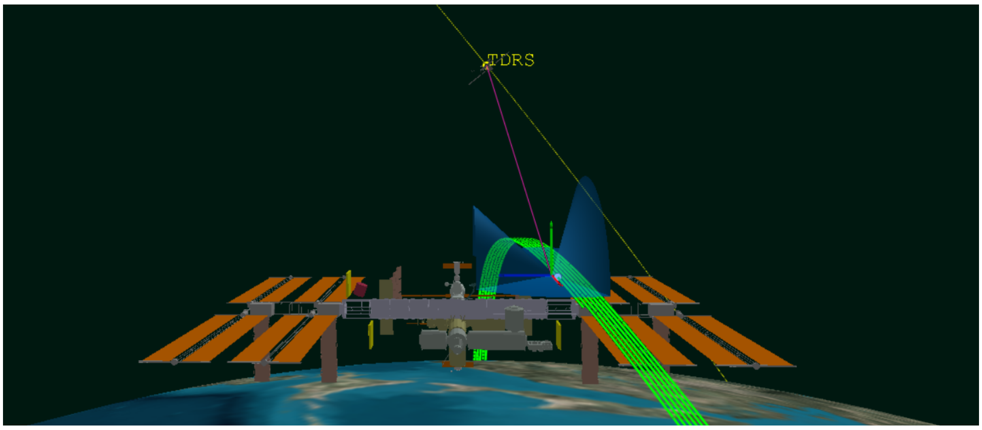


Fig. 8 Visualization of line of sight access between SCaN Testbed and a TDRSS relay computed in Astro Engine. Constraints taken into account include line of sight (purple line) and antenna field of view (blue cone).

6.1.1 Link Availability Calculation

Astro Engine will propagate the motion of each object in Earth-centered inertial (ECI) coordinates. This work will focus on satellites and ground stations as object types; though the software also supports planets, stars including the Sun, and space vehicle trajectories. Satellites are specified by their ephemerides which can be generated from two-line element (TLE) sets. Ground station locations are specified by latitude, longitude, and altitude. A spacecraft can be associated with multiple antennas (and more generally any instrument), each specified relative to the spacecraft's coordinate frame.

Segments indicate physically-possible links based on a set of constraints being satisfied. The primary constraint is line-of-sight. Additionally, Astro Engine can take other constraints into account such as antenna slew rate or field of view, Sun illumination or beta angle, the range between two objects, and more. Figure 8 visualizes a segment between SCaN Testbed and a TDRSS relay. The segment was calculated considering line of sight between the two satellites and the field of view of SCaN Testbed's high-gain antenna. Segments are categorized into various types, of which two are relevant to this work:

- *Request* segments keep track of when a spacecraft has a physically-possible control channel link (either through DAS or a wide field-of-view antenna on Earth). While most spacecraft in low-Earth orbit will continuously be within view of TDRSS, the intermittent connectivity to ground stations hosting control channel antennas necessitates a mechanism to track line-of-sight access.
- *Data* segments keep track of when a spacecraft can communicate with a high-performance asset (i.e. a single-access antenna on a relay satellite or at a ground station). In contrast to request segments which exist continuously, data segments are created once EvM has scheduled service to the high performance asset and are deleted after the access is completed. This reflects the concept that a spacecraft can always use a control channel to request service, but must be scheduled to use a high-performance asset.

6.1.2 The Minimal Instruction Set

We use the term *scenario* to denote the specific collection of spacecraft, relay satellites, ground stations, and segments relevant to a specific mission whose access is computed in Astro Engine. Lightweight execution of the UIS concept relies on synchronized copies of Astro Engine on the spacecraft and EvM running the same scenario. That is, both software instances propagate the same objects of interest and initially contain only request segments. After receiving a request and scheduling access on behalf of the spacecraft, EvM creates a data segment between the requesting spacecraft and the scheduled high-performance asset. This update must then be communicated back to the spacecraft. To do this, we transfer an instruction set which tells Astro Engine how to recreate the scenario. This includes simulation parameters, objects, and segments (both request and data). The instruction set can be loaded by a currently running instance of Astro Engine, allowing for real-time updates. The size of an instruction set depends on the number of objects the scenario contains.

As an example, the scenario shown in Table 3 considers a polar-orbiting satellite and 14 ground station sites. This scenario can be recreated in another Astro Engine instance with an instruction set of 64.1 kB. However, modifying this scenario to add one data segment only changes a small part. Since both the spacecraft and EvM begin with identical scenarios, we can simply transmit the difference between the two instruction sets. This allows data volumes to be very small and further reduced by compression. Table 3 shows the compressed instruction set update is only 110 B. From the updated scenario, Astro Engine can infer start time, stop time, scheduled asset, and a pointing solution. The advantage of onboard propagation becomes clear when we consider the resources required for keeping track of the direct-to-Earth request segments. Rather than requiring a list of access times which must be wirelessly transmitted and stored on the spacecraft, Astro Engine can propagate motion and determine access times indefinitely from the initial scenario (with periodic ephemeris updates to maintain accuracy). The savings become more dramatic if a pointing solution is required for antenna control during each access. From Table 3 we note transmitting each ground station access window and pointing solution for 1 year of operations would require 54.2 MB versus 64.1 kB for the equivalent instruction set.

6.2 Automation Process

In this section, we describe functions of the major software components during each step of event-based request handling. Figure 9 provides an outline of the process.

6.2.1 UIS Request

Onboard the spacecraft, mission-specific C&DH software determines when the spacecraft requires communications service. FSM was developed to be compliant with the open source Core Flight Software [31] to enhance mission adoption opportunities. The Core Flight Software Bus is used for data exchange between FSM and other spacecraft software, including the C&DH subsystem. Upon request, FSM will utilize its instance of Astro Engine to provide a list of times when the spacecraft will have line of sight to a control channel antenna. Once FSM receives a command to request service it will format a UIS request message according to Table 1. The message is passed to the spacecraft's radio and transmitted over the control channel. This process can be seen in Fig. 10a.

6.2.2 Event Handling

The control channel antenna receives the spacecraft's transmission and forwards the decoded UIS request message to EvM. EvM queries its local Astro Engine instance for a list of all potential data segments between the spacecraft and any compatible high-performance assets. Preference can be given to the asset suggested in the UIS request message (Table 1), and if the immediate access flag is set EvM will attempt to schedule service with the suggested ground station during the same pass. In most cases, we anticipate user spacecraft will not have strong preference over which ground station or relay satellite is used and the software has flexibility to optimize the schedule by allocating any available asset. This approach represents a shift towards service acquisition that is service-oriented rather than resource-specific [13].

EvM uses the list of potential accesses to put together a preliminary schedule. Beginning with the first segment, EvM attempts to find a suitable timeslot in the existing schedule then performs a series of checks to verify the

Number of passes over 14 ground stations containing control channel antennas during 1 calendar year	11,282
Data volume per pass to list start/stop times in UTC	8B
Average data volume per pass to list az/el pointing instructions in 32-bit floats with time step of 500ms	4.8kB
Total data volume to manage request segments without Astro Engine	54.2MB
Data volume of equivalent Astro Engine instruction set	64.1kB
Total data volume to manage one data segment without Astro Engine	4.808kB
Data volume of Astro Engine compressed patch for one data segment	110B

Table 3 Scenario containing polar-orbiting satellite and 14 ground station sites.

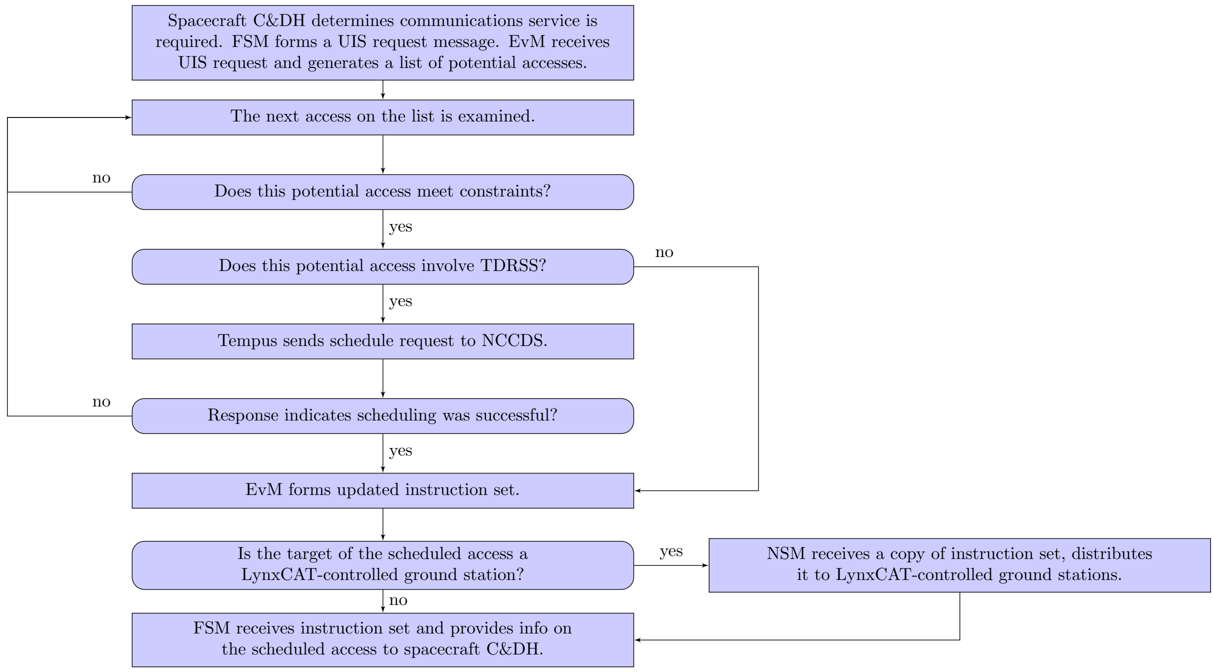


Fig. 9 High-level flow describing how the automation software presented in this work processes UIS requests.

segment meets requirements such as the minimum required event duration (Table 1). If a segment is not suitable, EvM begins the process again with the next segment returned by Astro Engine. Future work will discuss how this process can be augmented with calls to more sophisticated scheduling algorithms to optimize across multiple factors such as cost, latency, and performance. Machine learning techniques have shown great promise in handling these types of multi-objective optimization problems including in the space communications environment [33]. Research efforts underway at NASA aim to leverage cognitive optimization to improve performance of space communications over time [34].

6.2.3 Network Scheduling Interface

If access to the asset is controlled through an external scheduling system, EvM submits a scheduling request through a corresponding interface. Currently one interface, Tempus, is used to schedule TDRSS service through NCCDS though similar interfaces are being developed to interface with the APIs of additional service providers. Tempus formats segment parameters from EvM into the message format required by NCCDS. During the active scheduling period (in which requests are fulfilled on a first-come, first-served basis) NCCDS will either: accept the event as-is, reject it outright, or attempt to modify the start and stop times to fit within the existing schedule. Response messages from NCCDS are parsed and the results provided back to EvM. If the requested segment is rejected by NCCDS, EvM will begin the process again with the next segment on the list.

6.2.4 Update Astro Engine

With or without Tempus, the scheduling process ends with granted access to a high-performance asset during a period of time. EvM then creates a segment, connecting the spacecraft and asset during the scheduled time. The updated instruction set, containing the newly-created segment, is compared to the instruction set EvM knows is being used on FSM. EvM creates a patch containing the differences between the two and compresses it. This compressed patch is sent to the FSM over the control channel as part of the UIS response message (Fig. 10b).

FSM applies the patch to its instruction set currently running in Astro Engine. When prompted by C&DH software FSM responds with the start time, stop time, and identifier corresponding to the allocated asset. C&DH can also query FSM for a pointing solution to the asset. FSM responds with a list of azimuth/elevation commands

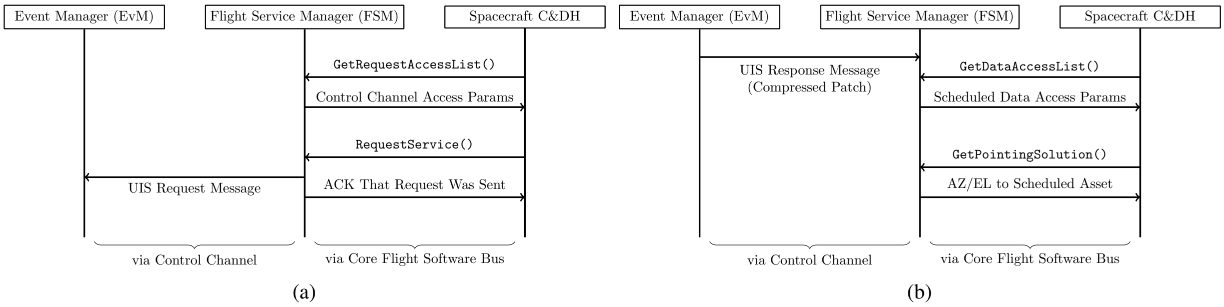


Fig. 10 Communication with the Flight Service Manager showing the process of (a) generating a UIS request message and transmitting it to the Event Manager (b) receiving a UIS response message from the Event Manager and providing access parameters to spacecraft command and data handling software.

to drive the gimbal controlling the antenna or the attitude control system pointing the spacecraft for body pointing. The spacecraft then simply waits for the scheduled event time to begin transmitting high-rate data.

6.2.5 Ground Station Control

LynxCAT is used to control real-time pointing of mechanically-steered ground station antennas. Each deployment of LynxCAT is paired with an instance of Astro Engine. When an updated instruction set is provided to LynxCAT it will solve for pointing solution, (from the ground station to the satellite) and start of the scheduled access. EvM provides the same instruction set to LynxCAT as it does to the FSM. Once a pass begins, LynxCAT will control the ground station to track the satellite in real-time.

It is anticipated that one common EvM will control scheduling for several ground stations, perhaps even at different geographical locations. The Network Service Manager provides a mechanism to distribute instruction sets generated by EvM to the scheduled ground station. NSM maintains a registration database which contains a numeric identifier for the ground station and the IP address at which the instance of LynxCAT associated with that ground station can be reached. This allows easy registration and relocation of ground stations. The EvM sends instruction set to the NSM where they are sorted and distributed.

7. Discussion

7.1 Link Characterization Results

Link characterization was performed with SCaN Testbed and the helical antenna deployed as in Fig. 3. Target data rates were set to 0.5 kbps in the downlink and 1.0 kbps in the uplink. Rather than operational data (UIS requests and response messages), a pseudorandom binary sequence (PRBS-11) was transmitted to enable calculation of bit error rate by comparing received bits to the known PRBS. The link was characterized during a typical pass over the GRC-GS. During the pass, a total of 2.1 kB of error-free data was exchanged in each direction. Considering a typical message size of 100 B, this data volume is equivalent to 21 UIS request and response messages. Or, stated equivalently, the spacecraft had 21 opportunities to send a request for high-rate service during a typical pass.

7.2 Software Testbed Deployment

SCaN Testbed was decommissioned before development of the automation software suite described in this work was completed. In its place, a ground-based testbed was used for development and verification testing. FSM software was deployed on the ARM processors of two Raspberry Pi 3B+ single-board computers to emulate the resource-constrained processing typical of spacecraft. Along with hardware emulation, an additional number of spacecraft were simulated in software. A long duration test was run with 20 spacecraft requesting access to 12 ground stations. Over 160 hours, 3,500 requests were fulfilled. The testbed also provided a capability for hardware-in-the-loop testing with a gimbal. A Moog QPT-500, the same model gimbal as used in the GRC-GS,

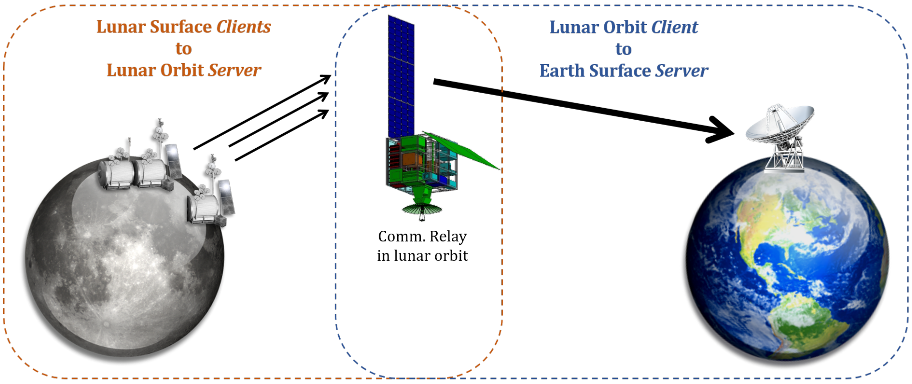


Fig. 11 Hierarchical view of spacecraft-initiated lunar communication services. A lunar relay satellite acts as a service provider for lunar surface users. The relay also acts as a user of the Earth communications network to request event-driven access of a ground station to downlink aggregated lunar data.

verified LynxCAT's ability to track a simulated spacecraft in real time. The AutoCAT automation software suite has been rigorously tested to NASA's Class C software engineering requirements and is transitioning focus towards integration into operations.

7.3 Support of Lunar Exploration

While this work has focused mainly on spacecraft in orbit around Earth, the UIS concept is extensible to missions beyond Earth orbit as well [13]. Dozens of planned missions in the coming decade, from small robotic platforms to human landing systems, will require communications support in the lunar vicinity [35]. International working groups planning lunar communications recommend spacecraft-initiated automated service acquisition for lunar spacecraft [9]. While some communications from the lunar surface will be direct-to-Earth, other links may be provided through relay spacecraft such as Gateway. Smaller lunar-orbiting satellites may also be used to fill in coverage gaps or add network capacity [14]. Relays can transfer data back to Earth or between data destinations on the Moon (enabling beyond line of sight communications, for example). In this hierarchical view local lunar communications form a subgroup of a wider network. This allows for a two-step process in which the same lunar relay satellite acts as both a UIS server and client (Fig. 11).

As a UIS *server* the relay satellite is a service provider which relays transmissions among lunar spacecraft and aggregates Earthbound data from individual spacecraft for transmission back to Earth. The relay satellite provides a low-rate control channel (e.g. via a low-gain patch antenna) over which surface craft can request service. The Event Manager, or similar request fulfillment software, is hosted onboard the relay satellite itself. In the UIS *client* role, the relay satellite requests on-demand service with an Earth ground station using the same process as an Earth-orbiting satellite. The Flight Service Manager, or similar software, also hosted onboard the relay satellite sends a UIS data transfer request message over a control channel (e.g. a medium-gain Earth ground station antenna with wide enough beamwidth to cover the entire Moon simultaneously). In this manner, routine and opportunistic service needs of the entire lunar network can be fulfilled autonomously.

7.4 Conclusion

The anticipated increase in the number of individual spacecraft and the complexity of their missions requires more efficient and adaptive methods of data transfer. The concept described in this work provisions high-performance space communications resources based on spacecraft needs measured in real-time, rather than predicted far in advance. Software discussed and demonstrated here automates the process of scheduling service in response to a spacecraft's request received over a low-rate control channel. Specifically, this work described a direct-to-Earth control channel over which a spacecraft can communicate request messages. An over-the-air experiment with SCaN Testbed demonstrated the feasibility of augmenting an existing ground station with a wide field-of-view antenna to provide this channel.

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