USING NEW TECHNOLOGIES IN SUPPORT OF FUTURE SPACE MISSIONS

Adrian J. Hooke[1]
NASA Jet Propulsion Laboratory, California Institute of Technology
Pasadena, California USA
David C. Welch
AlliedSignal Technical Services Corporation
Lanham, MD USA

Abstract

What will Mission Operations be like in the future? How will future space missions benefit from new technologies being developed today? Is it possible to operate an entire spacecraft, or even a constellation or family of spacecraft, from your desktop PC?

This paper explores these topics, forming a perspective of how new technologies such as onboard autonomy and Internet-like protocols will change the look and feel of operations. It analyzes the concept of a "lights-out" mission operations control center and it's role in future mission support and it describes likely scenarios for evolving from current concepts. It contemplates the concept of smart satellites which monitor their own well-being (and perhaps the well-being of other satellites within a local constellation) and plan their own operational activities, both to perform the mission objectives and also to recover from detected problems. Alternative methods for space to ground communications are explored, such as the use of private sector communications satellite providers to provide a "Phone-Home" service whereby spacecraft **in Earth-orbit may be given commercial telephone numbers.**

0 INTRODUCTION

A decade ago it would have been almost impossible to foresee today's Internet-linked world, with home users having cheap and routine dial-up connection to the Web and access to then-unimaginable troves of multimedia information. The three enablers of the ground Internet revolution - fully-standardized communications protocols, cheap and powerful processors and intelligent software - are now rapidly emerging as feasible technologies for application to space mission operations. As spacecraft become vastly more capable and accessible during the coming decade, the way that we interact with them will also change rapidly. In this paper we will review some of the expected dimensions of that change. We begin by tabling three propositions:

- ***Proposition 1:*** *communicating with a remote spacecraft should be no more difficult than communicating with another computer across the Internet.*
- ***Proposition 2:*** *integrating a spacecraft with this networked mission operations system should be no more difficult than integrating a desktop PC with its local network services.*
- ***Proposition 3:*** *just as "smart agents" are emerging to search the Web for the information that we need, smart spacecraft will emerge which perform a significant fraction of their mission for us in an autonomous and unsupervised mode.*

1 SPACECRAFT AS "NODES ON THE INTERNET"

1.1 Standards for Space Communications

Similar to the way in which the Internet has been shepherded by the Internet Engineering Task Force (IETF) from its early days as the ARPANET to its current status as the backbone for global connectivity, the development of interoperable space networks has been steered by the international Consultative Committee for Space Data Systems for the past 15 years. Over thirty space agencies from around the world are now part of CCSDS, working together to develop the standards which will

[1] **A portion of the work described in this paper was performed at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.**

allow interoperability across the networks which interconnect spacecraft and their ground systems. The CCSDS technical work (Figure 1) is structured into three main thrusts, each of which is allocated to a panel of experts who develop the standards that can enable a set of flexible mission support services to be emplaced across the agencies:

1. *Space Data Transfer Services,* which provide the hi-directional communication of information between the spacecraft and the ground.
2. *Space Data Interchange Services,* covering the processing, exchange and archival storage of space mission information products within the user community.
3. *Space Data Cross Support Services,* involving the mechanisms whereby the ground infrastructure owned by each agency can expose its services to other agencies.

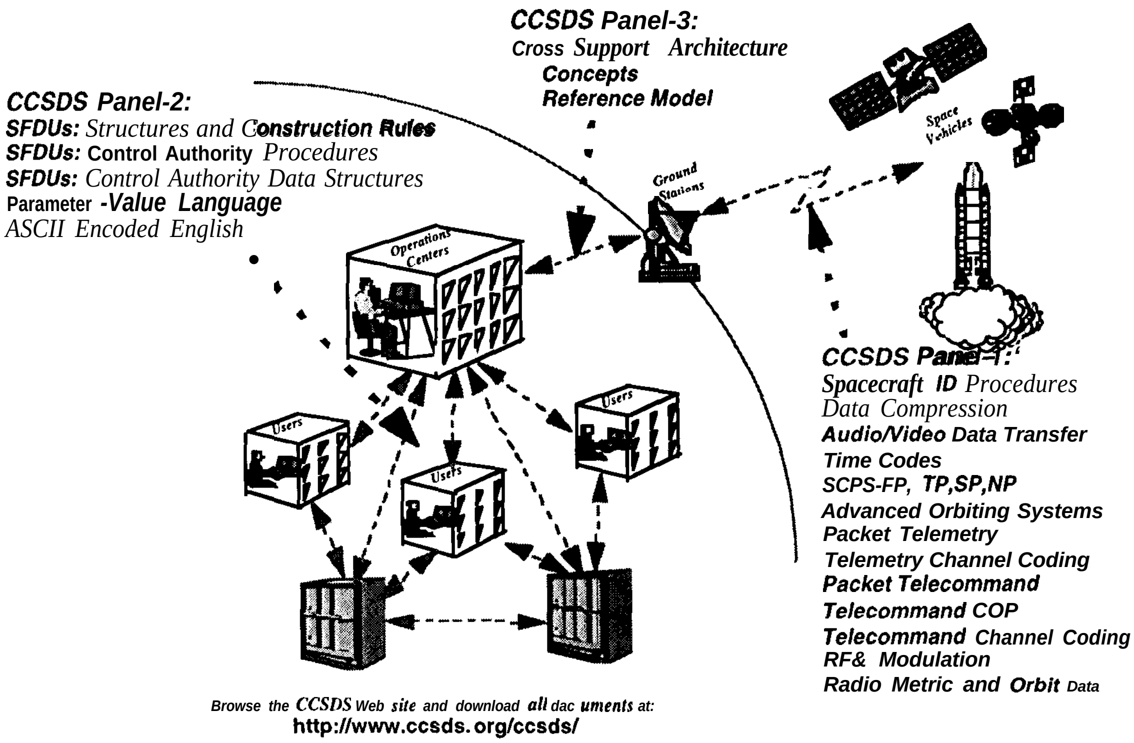

Figure 1: Scope of CCSDS Work

The current suite of CCSDS standards are in widespread use across the world space community. The CCSDS specifications can be electronically downloaded from the CCSDS Web site or are all available on a single CD-ROM.

1.2 Extending the Internet into Space

The current set of CCSDS standards for Space Data Transfer mainly focus on the techniques required to establish the physical channels which interconnect the spacecraft and the ground (e. g., radio frequencies and modulation mechanisms) and the protocols used to flow data hi-directionally over the space-ground link (e.g., packetized telemetry and telecommand). With the exception of the "advanced orbiting systems" standards that were targeted towards the international Space Station, the CCSDS work has not so far embraced the kind of Internet services that are in widespread use on the ground in the form of FTP, TCP and 1P. This void is currently being filled by the new "Space Communications Protocol Standards" (SCPS) which are mapping the Internet services into the space mission environment. Sitting on top of the current CCSDS packetized telemetry and telecommand protocols, the first wave of the SCPS will provide the stack of standardized capabilities that is shown in Figure 2.

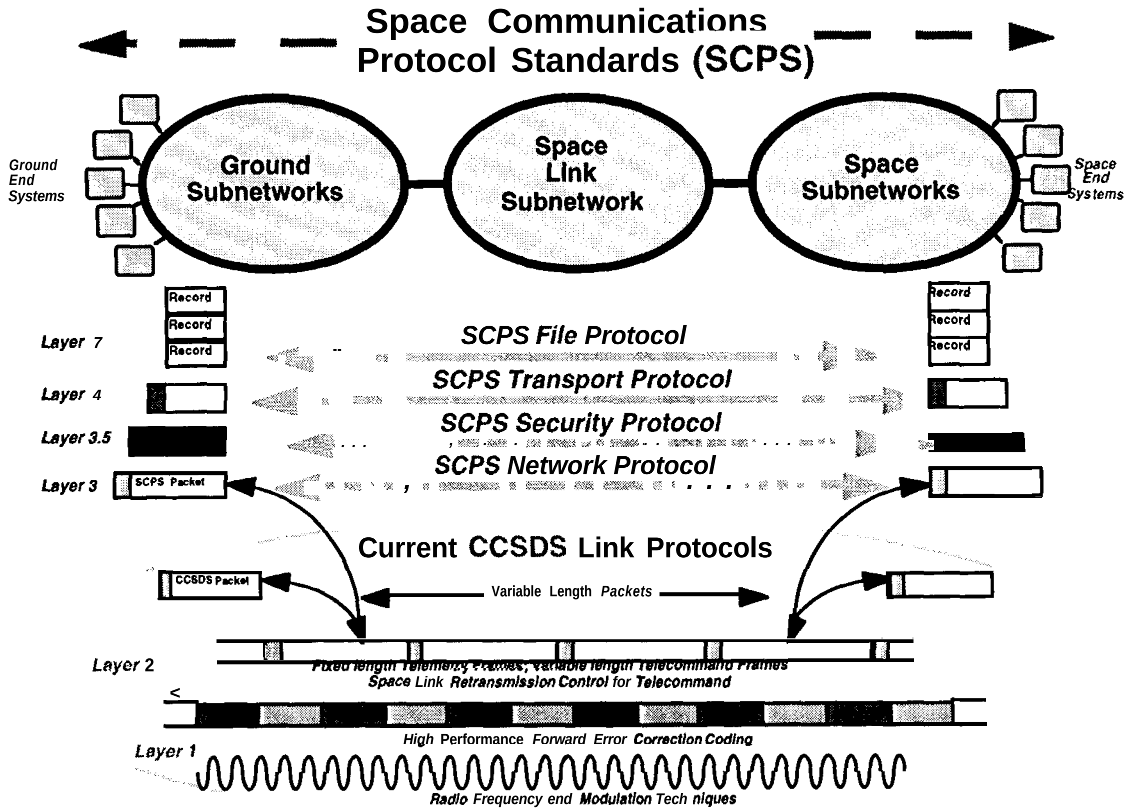

Figure 2: SCPS-era Space Communications Stack

The SCPS provide a set of specifications for standardized end-to-end space data transfer covering the following technical areas:

1. An efficient file handling protocol (the SCPS File Protocol, or SCPS-FP), which is fully based on the Internet File Transfer Protocol (FTP), with key adaptations as required to meet the unique requirements of space.
2. An underlying retransmission control protocol (the SCPS Transport Protocol, or SCPS-TP), which is fully based on the Internet Transmission Control Protocol (TCP) with extensions and modifications required for its efficient operation over the asymmetric, delay and error-prone space communication channels.
3. A data protection mechanism (the SCPS Security Protocol, or SCPS-SP) which assures the end-to-end security and integrity of such message exchange, ranging from simple command authentication all the way through full military-quality message encryption. The SCPS-SP is based on several other open protocol developments, but for reasons of communications efficiency it has been tailored to the space mission environment.
4. A scaleable networking protocol (the SCPS Network Protocol, or SCPS-NP) that supports both connectionless and connection oriented routing of these messages through networks containing multiple space data links. While providing the same kind of service as the familiar ground Internet Protocol (1P), the SCPS-NP has been customized to meet unique space needs, including communications efficiency, new constellation routing capabilities and the feature of being able to minimize and tailor the communications overhead to suit the mission application.

When the SCPS are available for widespread operational mission deployment - by the late summer of 1997- they will fill-in some of the missing components of the current CCSDS standards suite and will provide the "feel and flavor" of Internet communications to space mission users who wish to communicate with remote spacecraft. Subsequent variants of the SCPS will extend the reach of the protocols into missions which do not naturally follow the conventional Internet model of "on-line connectivity", such as those with half-duplex communications links and the need to operate in a store-and-forward mode.

1.3 The “Plug-’n-Play” Spacecraft

Even with afull-suite of Internet-like communications protocols inplace, integrating a payload with a spacecraft is still a complex and costly proposition. On the other hand, “plug-’n-play” interfaces are commonplace in the commercial market, so why shotddn’ t they be developed for spacecraft?

The next wave of standardization will certainly focus on the interfaces which enable distributed systems to be almost automatically integrated. One of the applications of interest and where there is considerable commercial heritage isthatof space mission monitor andcontrol, i.e., the transmission of commands to remote spacecraft and payloads in order to configure them to conduct an operation, and the verification of correct command execution and system response. In recent years, NASA has been working within a “Space Project Mission Operations Control Architecture” (SuperMOCA) research project to study the potential application of factory automation and process control technologies to space missions. In automated factories, the Manufacturing Messaging Specification (MMS) protocol is now in widespread use, for example in automobile plants, where it permits a central shop-floor computer to orchestrate the operations of complex robots and programmable logic controllers as a car body progresses down the line. A derivative of MMS - the Fieldbus Messaging System or FMS - is now gaining fast pickup in chemical plants and refineries where fast-response process control loops must be operated in hazardous environments where power consumption must be minimized in order to avoid explosion. The possibility of using both MMS and FMS for space mission control is tantalizing - perhaps the full-blown MMS for monitor and control of ground systems (such as remote tracking stations) and the skinny FMS version on the spacecraft, thus permitting a single, unified approach to the command and control of complex, highly-distributed systems. It is interesting to note that the FMS architecture (a powerful application protocol running directly over a thin, efficient local link layer protocol) came directly out of early activities in the 1990s when attempts were made to use the MMS protocol over the CCSDS packetized link layer for Space Station control. That early export of space technology into industry may now possibly be re-imported to help lower the cost of space operations.

Eventually, it is hoped to standardized virtually all aspects of routine operations associated with integrating, testing and operating the distributed systems which make up a space mission. Just as no current ground user would seriously contemplate custom-designing the interconnection of computers to perform a business operation, so the future space scientists will be able to focus on the things that **matter - the sensing technology and the science - while being able to ignore** the more pedestrian parts of mission operations.

1.4 “Phone Home” Operations

However, even with plug-n-play interfaces and fully standardized Internet-like communications services such as SCPS running over the current CCSDS packetized telemetry and telecommand capabilities, there is still a need to utilize costly networks of globally-distributed ground data acquisition stations to actually connect to the spacecraft. Even with the new CCSDS cross support services coming into use, communicating with a remote payload is still considerably more complex than just logging onto the Net via a PPP phone call to a local Internet Service Provider.

Fortuitously, the new constellations of satellites which are being deployed to offer mobile personal communications services on a world-wide basis to ground users may also possibly be extended so that they are accessible by other Earth-orbiting spacecraft. A scientific satellite in low, medium or geosynchronous Earth orbit could therefore theoretically be assigned a commercial phone number, and a ground user could place a call to the satellite using regular telephone service - and vice versa. One recent study has proposed flying such a commercial telephone package on the early-1999 launch of a British “Space Technology Research Vehicle” (STRV). This “Phone Home Link for Autonomous Spacecraft Handling” (PHLASH) experiment would equip the STRV (Figure 3) with a transmitter/receiver package that is capable of communicating with the geosynchronous INMARSAT system, allowing hi-directional communications at data rates of approximately 600 bits/second.

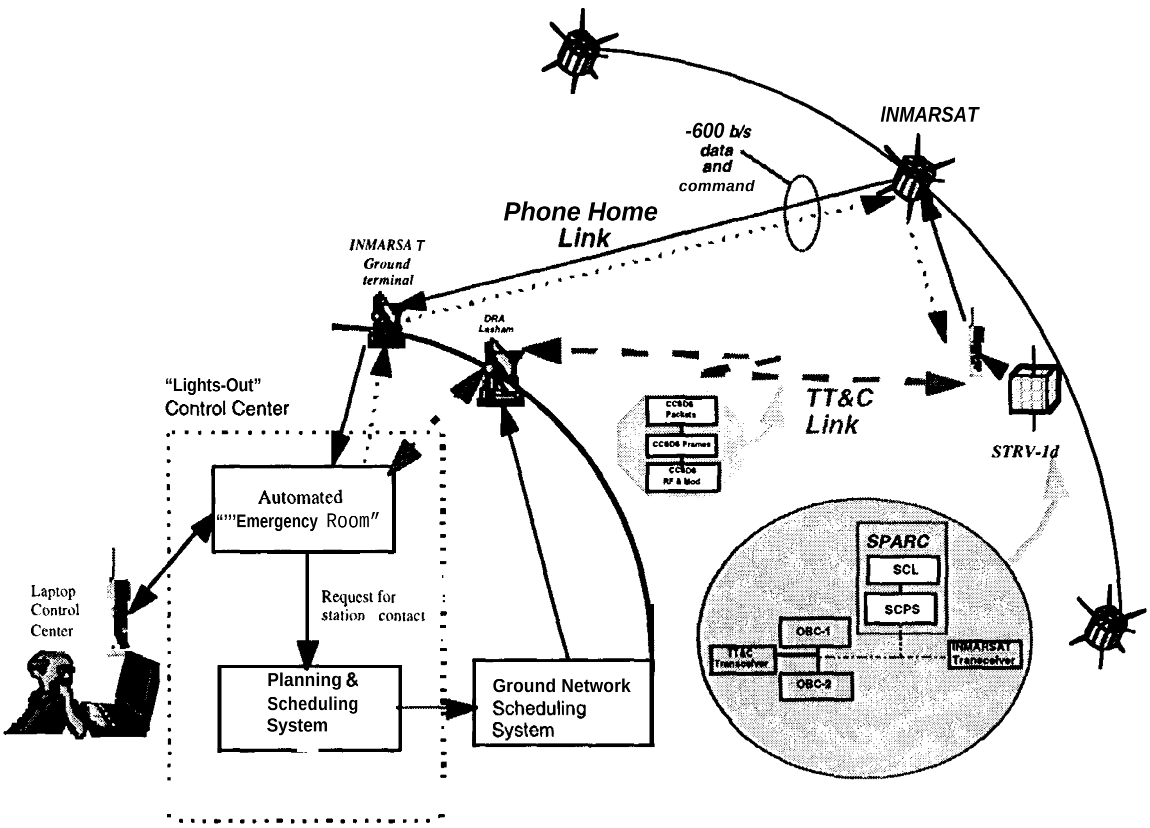

Figure 3: The PHLASH Concept

PHLASH is actually a highly integrated concept, since it consists of two parts: an onboard software autonomy experiment, coupled with the phone-call communications capability. Hosted in a powerful onboard processor, an onboard reasoning engine - such as the commercial Spacecraft Command Language (SCL) package that has been proposed for PHLASH - would have access to all key onboard housekeeping telemetry and would therefore be able to make autonomous local control decisions. The results of these decisions (files containing the onboard operations logs) **could then be sent to the ground two** ways over the SCPS stack: over the CCSDS Link protocols and then the S-band TT&C link; or over the INMARSAT telephone link. PHLASH is therefore a "spacecraft within a spacecraft". Future users of such a capability could have the opportunity to interact with the onboard payload outside of the normal constraints of formal ground station tracks, perhaps by tweaking some parameters in order to enhance an upcoming data-gathering pass, or reading-out key measurements to verify successful conduct of a recent session. In some cases it is feasible to think of spacecraft which have only an emergency TT&C link, with most routine operations being conducted over the telephone - just like a Web browsing session today.

In practice, there are technical difficulties with communicating between two spacecraft in different orbits. The problems are tractable if the commercial satellites arc in highly elliptical or geosynchronous orbits, although in these case the communications power requirements on the user satellite increase to handle the path loss. If the commercial satellites and the user spacecraft are in low Earth orbit, Doppler shift may cause problems with signal acquisition and even if this is solved then the view-periods may be quite short - especially since the commercial operators tend to keep their beams tightly focused to conserve power and to avoid interference. Once these problems are solved, the era of "Phone Home" extraterrestrial may rapidly approach reality - in this case extraterrestrial smart autonomous spacecraft could simply place a call back to the control center when they have something to report. The "lights out control center" may therefore be close at hand, where operators are notified by beeper when they are needed - perhaps logging-in to the unattended control center over the Net in order to browse Web pages which have been automatically formatted with current spacecraft status. The supervision of these new space systems, with smart spacecraft appearing to be just "nodes on the Internet", raises interesting questions which will be addressed next.

2. MANAGING AUTOMATION AND AUTONOMY

2.1 Components of "Lights-out" Operations

Automation of a system means that routine decisions of a "reflex" nature are given over to machines, and humans are removed from the decision loops. As the decisions move away from simple reflexes and become more complex and judgmental, then the automated system transitions to an autonomous system which contains its own sophisticated machine reasoning. When thinking about automating a space system, not only must the level of autonomy be determined, but also the allocation of this autonomy between the space and the ground segment. We must also learn how to determine this allocation during the mission conception phase: waiting until the development phase will be to late as the retrofit of autonomy will then result in modifications, workarounds and added labor. Poor selection and allocation of autonomy can actually increase mission cost due to the use of inefficient or excessive automation, often with the result being that the automation is disabled by the operations team so that it doesn't get in the way. And waiting until after launch to deploy autonomy means only one thing - hire more people and develop custom solutions for a spacecraft which will be difficult to modify at best. To investigate these problems associated with moving towards more automated and autonomous systems we will first look at the three major functional areas of spacecraft operations separately, namely: Monitor and Control; Data Processing and Analysis; and Planning and Scheduling. We will then see how these three areas affect each other.

Monitor and Control

Since we have already introduced the PHLASH concept, we start with the mission Monitor and Control function. This function encompasses the transmission of commands, verification of their execution and monitoring of both the health and safety and the performance of the system. Historically, these activities are performed during real-time contacts bet ween the spacecraft and the ground system and are performed under the supervision of human controllers. But new technologies are now allowing computers, both on the ground and in the spacecraft, to assist, and ultimately replace, humans in these routine day-to-day operations. The first level of Monitor and Control is health and safety monitoring, which is a check of the instantaneous status of the system at any point in time. Capabilities such as limit checking of analog telemetry, state checking of discrete telemetry and configuration monitoring have been used for many years to assist human controllers in identifying problems. These have, in essence, enabled detection of errors to which responses are automated by the fact that front-line controllers identify the problem and look up and execute canned procedures to respond to those errors that have been previously identified and call for assistance from the experts when no response exists. This familiar "limit and state checking and manual response to errors" mode is still a viable option in many cases, such as satellite integration and testing and short duration missions. But there are currently a number of commercial tools available to assist operations and they provide a number of options for performing these capabilities. These new options include software packages that can suggest responses to take, or even respond themselves by sending commands or executing procedures in order to correct the problem or safe the spacecraft. Also, new products will now allow this function to reside on board the spacecraft, as well as on the ground, thereby minimizing the response time required to react to errors. Note, however, that in this scenario only known errors can be handled. Unknown errors for which canned responses do not exist still require contact with the ground in order to notify the spacecraft experts. This is where a spacecraft "phone home" paging capability could save hours or days of mission data by minimizing or preventing the amount of time spent in a non-nominal or safe-hold configuration without the expense of round-the-clock operational contact with the spacecraft.

The next level of Monitor and Control is performance monitoring. This is the measurement of how well the system is executing over time. In order to do performance monitoring, knowledge of the scheduled operations must bc known in advance. This has been one of the prime contributions that spacecraft controllers have made in the past. By knowing what should be happening (and when) human controllers can determine not only if the spacecraft is healthy, but also if it is doing what it is supposed to bc doing. They can also determine whether it is doing these things with the same results as it had last week, or last month, or last year. Performance monitoring therefore requires knowledge of the plan currently being executed, plus signatures and trends of the analog telemetry over time and under differing environmental factors (such as day versus night or summer versus winter). It also requires an expectation of how much data should be received so that an accounting of the transfer of this data from the spacecraft to the end user can bc made.

b .

Data Processing and Analysis

The Data Processing and Analysis functions have historically been considered to be performed off-line, i.e., out of the realm of a real-time contact. But both of these functions will benefit greatly from the new Internet-like protocols described earlier, even to the point of allowing an investigator direct interaction with his or her particular experiment. End-to-end file delivery can be assured and the retransmission of missing or corrupted data handled by the communications protocol, without involving human operators, These protocols will also allow files to be stored and forwarded by either the spacecraft or individual on-board instruments in a seamless fashion which will eliminate the need for the ground to perform level zero processing. The files that will be delivered to the end user will look exactly as they did when leaving the instrument or on-board data processing system. New computer technology will also allow more on-board processing and sorting of data so that valuable contact time and bandwidth will not be wasted on transmitting anything but the desired observations. For instance, land imaging satellites could throw away photos containing cloud cover, saving storage and downlink space for the next scheduled observation. Orbit and attitude data processing are other areas where new onboard capabilities are already saving operational expenses. GPS technology will allow instantaneous and precise ephemerides to be available for onboard attitude control and scheduling of activities, including event triggering, orbit maintenance and instrument pointing and observations. GPS technology also eliminates the need to perform tracking activities for the purpose of generating ephemeris for data processing and planning activities on the ground. Increasing capabilities in flight computers now allow trajectory or orbit propagation to be performed on-board, enabling closed loop attitude control and activity scheduling with only periodic ground maintenance.

Planning and Scheduling

The last major functional area to discuss is that of Planning and Scheduling. This function embraces: the determination and processing of payload inputs from the user community (including response to targets of opportunist y); the handling of engineering special requests, including maneuvers and the performance of anomaly isolation and resolution activities; the scheduling and configuration of event driven activities, such as reconfiguration necessitated by space environmental factors; schedule-driven activities such as communications support; and activities which must be performed on a periodic basis in either absolute or relative time, such as performing a calibration at noon everyday or swapping buffers every four hours until further notice. Work is currently ongoing in such areas as planning agent technology which will allow onboard decision making to be possible. Observational inputs could then conceivably just consist of uploading a file of observation requests, possibly using e-mail or Internet-like protocols. Anomalies and targets of opportunities could also be handled by these “smart” agents, which could factor in this need for replanning and rescheduling the mission observations. Requests for resources could be initiated by the spacecraft. These requests could consist of scheduling a ground contact for either data download or contingency support, or requesting that required data files residing on another platform (be it in space or on the ground) be forwarded to the spacecraft. These files could contain future observation lists for use once the current list has expired or could consist of flight software patches which are requested for automatic reload after an onboard computer reset. It is even conceivable that constellations of satellites could have master monitoring satellites which ensure the rest of the constellation continues to perform as expected.

2.2 Implications of the “Lights-out” Concept

“Lights-out operations” has been described as “the fully autonomous routine operation of unmanned satellites”. *But what is routine?* Should orbit and attitude maneuvers be considered routine? What about flight software maintenance activities? It becomes apparent that anything not planned for, and therefore not deemed routine, potentially could greatly increase the cost of keeping a mission flying. The most basic problem which will need to be tackled in moving to a lights-out mode is that of populating and maintaining the databases which support automated and autonomous operations. The more sophisticated the system becomes, the more information and interactions that will have to be monitored and controlled. A completely automated mission control center not only has to interact with the spacecraft, but also has to potentially interact with ground stations, communications networks and/or relay satellites which enable connection with the spacecraft. Troubleshooting these interfaces today remains a human function, with voice communication being the primary means of exchanging information. But a fully automated control center needs to be able to handle communication outages and a fully autonomous system must allow for communication between all elements, whether they be on the ground or in space. For instance, a spacecraft which decides it should turn off it’s own transmitter for awhile during a downlink because it is getting to hot, needs to have the ability to notify the receiving end of the transmission that it is temporarily terminating the link so that link recovery procedures are not initiated. It is also important to not overlook how a failure which necessitates reverting to manual operations will be handled once autonomy has been implemented. If the command and telemetry definitions are streamlined to optimize machine processing and execution of automated activities or control loops, they could be very cryptic and difficult to use in the event of a contingency which requires a lot of manual interaction to correct. It is necessary then, to assess the ability to rapidly revert the control system back to an integration and test like environment, where controllers operate the step by step activities of the space system.

Finally, we need to consider how to allocate automation amongst space and ground elements and how we then test that this automation actually works. Paramount to the decision of how to allocate automation is the amount of response time required to maintain spacecraft health and safety or to prevent an inordinate amount of lost data. If the spacecraft can remain in a “safe-hold” state indefinitely and the resulting data loss due to this abnormal configuration can be tolerated, then automation in the ground segment alone may be sufficient. This allows easy access to the system for configuration control and upgrades. However if such outages are not tolerable, such as on a deep space mission where response times are large and scientific opportunities are limited, then onboard autonomy may be required. Validating systems which include autonomous components is another problem; it will no longer be feasible to test the space and ground entities separately, bring them together for a couple of interface tests and then fly the mission. The automation and autonomy will have to become an integral part of the integration and test of space vehicles, and will have to be maintained and used during the environmental checkout of the spacecraft. Otherwise the mission operations will have to be specially staffed in order to perform on-orbit validation of the automated and autonomous components, which itself will become an expensive add-on to the mission system. It surely isn’t our goal to replace teams of flight controllers with armies of “automation support specialists”!

3. CONCLUSIONS

We are moving towards an era when integrating space systems will be analogous to today’s computing environment. We will purchase plug-’n-play components, build them rapidly into a custom configuration without the assistance of indentured craftsmen, allow them to communicate over an automated network, and allow them to seek information for us without our continuous supervision. Once these standard interfaces are established, generic subsystem maintenance becomes a real possibility. Standardized telemetry and commands as well as standard monitoring rule-bases and responses could be delivered along with the pertinent subsystem, eliminating the need to build custom databases for each new mission. If such things as power, thermal and data storage management and maintenance can be standardized, the need for revalidating command and telemetry databases, rule-bases, displays and procedures could conceivably be eliminated. Also, new technologies such as self-identifying instrumentation could allow these databases to be built on the fly. With this level of standardization, it will be possible to have a small generic team of spacecraft experts who can manage any anomalies which might occur across multiple satellites. However, for autonomous mission operations systems to work, they are going to have to be integrated and tested at a system level, both the spacecraft and the ground system together, utilizing the automation in order to perform testing. To accomplish this, it is highly likely that a conventional manual command and control system will still be needed to control the flow of integration and test activities. Such a ground test system should perform in the same manner as will be needed during on-orbit operations in the event that a manual override of the system is required. In other words, the test environment needs to simulate the flight environment as much as possible in order to validate that the system is truly autonomous. This will most likely require that a single team concept will be needed to support all of the space and ground segment integration and subsequent flight operations. The knowledge of this team will have to be progressively captured during the design, integration, test and flight phases by populating rule-bases which support the monitor and control of the system, i.e., the knowledge must be installed into the system - not in the head of a human being who probably won’t be around when the knowledge is urgently required.