Spacecraft/Ground Architectures using Internet Protocols to Facilitate Autonomous Mission Operations[1]

Jeffrey L. Hayden
Spacecraft/Instrument System Engineer - Retired
4982 S. Ulster Parkway #412
Denver, CO 80237-2814
303-779-6179
jlhayden@earthlink.net

Abstract–This paper describes utilizing Internet Protocols (IP) in the overall spacecraft/ground communications architecture for operating and receiving data from future low cost, highly capable, self-sufficient spacecraft.

It describes integrated and distributed architectures for those spacecraft, architectures for the ground stations, and concepts for operating the spacecraft, communications, and ground systems. Included is a discussion of how a spacecraft's communication to the ground can be initiated on demand by the spacecraft itself, or by a spacecraft instrument or subsystem user.

These concepts are extensions of those described for the future in the Consolidated Space Operations Contract (CSOC) Architecture Baseline document.

TABLE OF CONTENTS

1. INTRODUCTION

In the fall of 1998, NASA let the Consolidated Space Operations Contract (CSOC) to an aerospace industry team comprising Lockheed Martin (prime), AlliedSignal, Computer Sciences Corporation, Booze-Allen & Hamilton, General Telephone and Electronics, and others. The purpose of the contract is to perform consolidations and implement efficiency improvements across NASA's data distribution and mission operations activities and facilities.

As NASA developed over time, many new missions were added to the organization in a vertical fashion. That is, the implementation of a new mission resulted in the development of new infrastructure to support it. This form of infrastructure development was appropriate in the past as existing facilities usually couldn't support new missions. The resulting infrastructure has become quite expensive, as it requires considerable human support. It is now somewhat dated, both in facility capability and use of standards, such that it cannot be easily shared among different missions.

The CSOC program will conduct major efforts toward consolidating operations facilities and personnel, utilizing products and standards from the commercial sector, applying automation and autonomy into operations where appropriate, and utilizing modern networks for handling and moving NASA's mission data. Rather than starting anew, the CSOC program intends to modify much of the existing NASA infrastructure to make it function more horizontally – that is, unify and standardize operations, the networks, spacecraft, and science instruments across the NASA and CSOC enterprises.

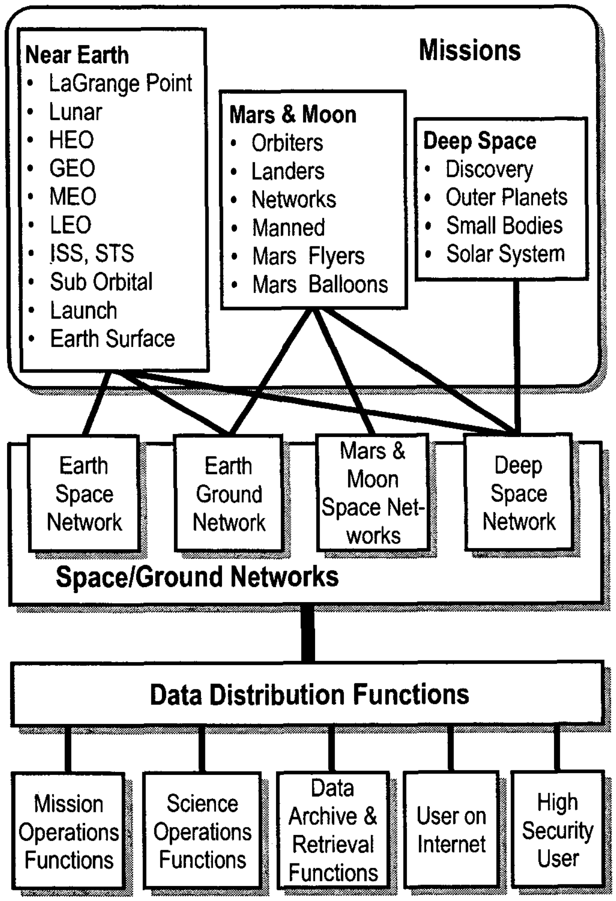

Figure 1 CSOC functional structure

The CSOC program is implementing the functional structure shown in Figure 1. All pieces of this structure are joined by the standardized data distribution functions. CSOC utilizes standard Internet Protocols (IP's) for data movement throughout the system. The space/ground networks include the following:

1. The Space Network (SN) – this is the Tracking and Data Relay Satellite System (TDRSS) that is controlled by ground stations at White Sands Complex (WSC) and Guam.

[1] 0-7803-5846-5/00/$10.00 © 2000 IEEE

2. The Ground Network (GN) - These are ground stations placed at various sites around the world.
3. The Mars and Moon Space Networks – These networks are not presently implemented and are not part of CSOC's purview, however they would likely consist of communications satellite constellations around the Mars and Moon and would relay data between local sites as well as to and from the Earth.
4. The Deep Space Network (DSN) – The DSN includes facilities with large antennas at Goldstone, Canberra, and Madrid, and the ground and satellite network connections from JPL to the rest of NASA.

The CSOC program will coordinate modifications to these networks to implement IP for moving data throughout the system; and will direct activity towards achieving autonomous operations of the ground station assets.

Similarly, the CSOC program will assist and coordinate the design and development of new spacecraft architectures that utilize on-board, autonomous operations and IP standards. These features bridge the connection between the ground-based user and the on-board instrument. New architectures will implement IP compliant, on-board, Local Area Networks (LAN's) to route data and commands between subsystems and science instruments, thus allowing the use of powerful Internet applications (e-mail, ftp) and languages (Java, Java script, html, xml, etc.) for operations.

Further efficiencies are obtained by raising the data transfer rates between spacecraft and ground. The higher the bandwidth of the data transfers, the shorter the time that is required from the space/ground network to provide the transfer service, thus providing more efficient use of the ground assets. The CSOC program will encourage the use of Ka-band (20GHz-30GHz) receivers and transmitters. In the case of Low Earth Orbiting (LEO) spacecraft, data transfer rates in the range of 100 to 1,000 megabits per second (Mbps) can be achieved with low power, light weight antenna and RF systems.

The concept of obtaining access to the space/ground network facilities on the demand of the user or the spacecraft is discussed. This important autonomous concept enables the user to control his/her spacecraft (or instrument) or the spacecraft to download its data without explicit scheduling, thereby reducing overall mission operations costs. Studies performed during phase 1 of the CSOC program indicated that over 400 man years could be saved over the later 6 years of the program by implementing access to the networks on demand rather than by scheduling that access.

This paper is concerned with describing some of the early modifications to ground assets and a few concepts for ground and spacecraft architectures that would enable the CSOC program's strategy in the future. It does not discuss consolidation except to note here that most consolidation will be implemented by standardizing the disparate mission operations facilities into Integrated Mission Operations Centers (IMOC's) that use as much Commercial Off-The Shelf (COTS) software and hardware as possible. The CSOC program will strive to make these IMOC's generically functional across programs. This paper does consider some implementations of automation and autonomy essential to reducing the manning levels needed for future mission operations.

2. SPACECRAFT AND GROUND ARCHITECTURES

Early Modifications to Existing Ground Stations

Modifications for connecting ground stations to the IP compliant networks are shown in Figure 2. These conversions are done early in the CSOC program to enable all of the ground assets to pass data over commercial networks rather than over lines dedicated to the infrastructure. Competition between commercial networks and the addition of capacity over time will enable future cost reductions. Data movement between the ground station and mission operations and/or the user is greatly simplified by use of IP address routing.

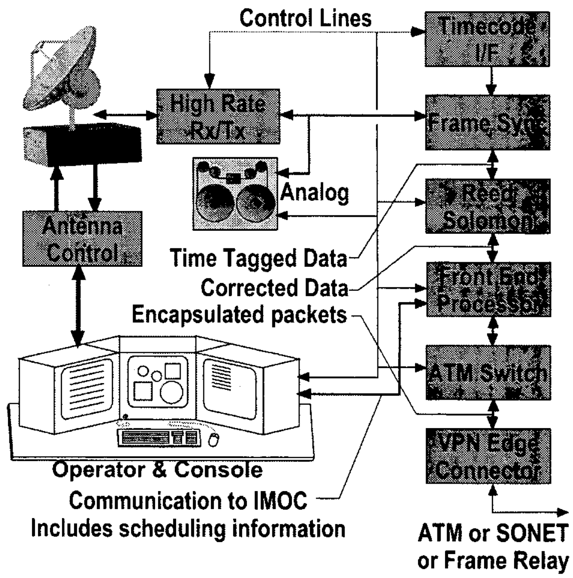

Figure 2 Early Modifications for Connecting Existing Ground Stations to IP

The early ground station modifications, shown in Figure 2, will retain the existing antenna, antenna control, console (and operator), RF subsystems, analog recorders, frame synchronization, timecode interface marking, and encapsulation/decapsulation (Reed Solomon, Viterbi) hardware. Changes are made at the Front-End Processor (FEP) and to the connections to the external networks. The FEP's are data conversion units that are specialized to handle the format for a particular mission. After modification, the FEP's will be reconfigurable to enable the handling of data from different missions.

In the near term concept, the FEP's are moved from the mission operations sites (e.g., Goddard Space Flight Center, GSFC) to the antenna sites. The purpose of the move is to enable the use of Internet Protocols for routing data to and from the antenna site. It is intended that the data that is moved to and from the antenna site be normal computer file compatible; i.e., the data is decommutated and contains no data formatting artifacts needed for the space to ground connections. By making this basic change, the CSOC program expects to reduce the data processing required of the user and mission operations center. The modification further enables the use of generic personal computers and COTS programs for higher level data processing.

Network hardware is added to the ground station. That hardware is shown as an Asynchronous Transfer Mode (ATM) switch and a Virtual Private Network (VPN) edge connector. This hardware will likely change depending on the commercial service provider's normal network connection. Likely network connections include ATM, Synchronous Optical NETwork (SONET), frame relay, various Digital Subscriber Line (xDSL) options, and etc.

Architecture of Today's Typical Spacecraft

The ground stations described above provide scheduled service to spacecraft with architectures similar to that shown in Figure 3. The CSOC program must continue to support these "legacy" spacecraft throughout most of the contract period. To be sure, there are many variations of spacecraft architecture in use today. The one shown in the figure does not include every possible subsystem in use today, but it includes functions needed by most spacecraft.

Most spacecraft employ telemetry systems with two or more RF subsystems. One is usually a low-rate system that listens and radiates over a wide angle. This subsystem, normally S-band RF, is used for receiving short command strings and for sending down status telemetry. It is also used in emergencies wherein the spacecraft may send SOS messages or the ground may attempt to regain command control of a tumbling spacecraft. It is not typically used for sending down science data. A second, higher rate subsystem is commonly used for moving science data to the ground and for uploading lengthy software changes.

The Command and Data Handling (C&DH) subsystem (the term may vary), is a control unit of some kind that is used in every spacecraft; and it is usually an interface box that is computer controlled. The attempt has been made to use standards, commercial (VME) and military (ASCM), for the backplane of the card chassis. However, modifications to add card redundancy and reduce power have usually resulted in non-standard implementations of the backplane. Several of the cards are often duplicated for redundancy.

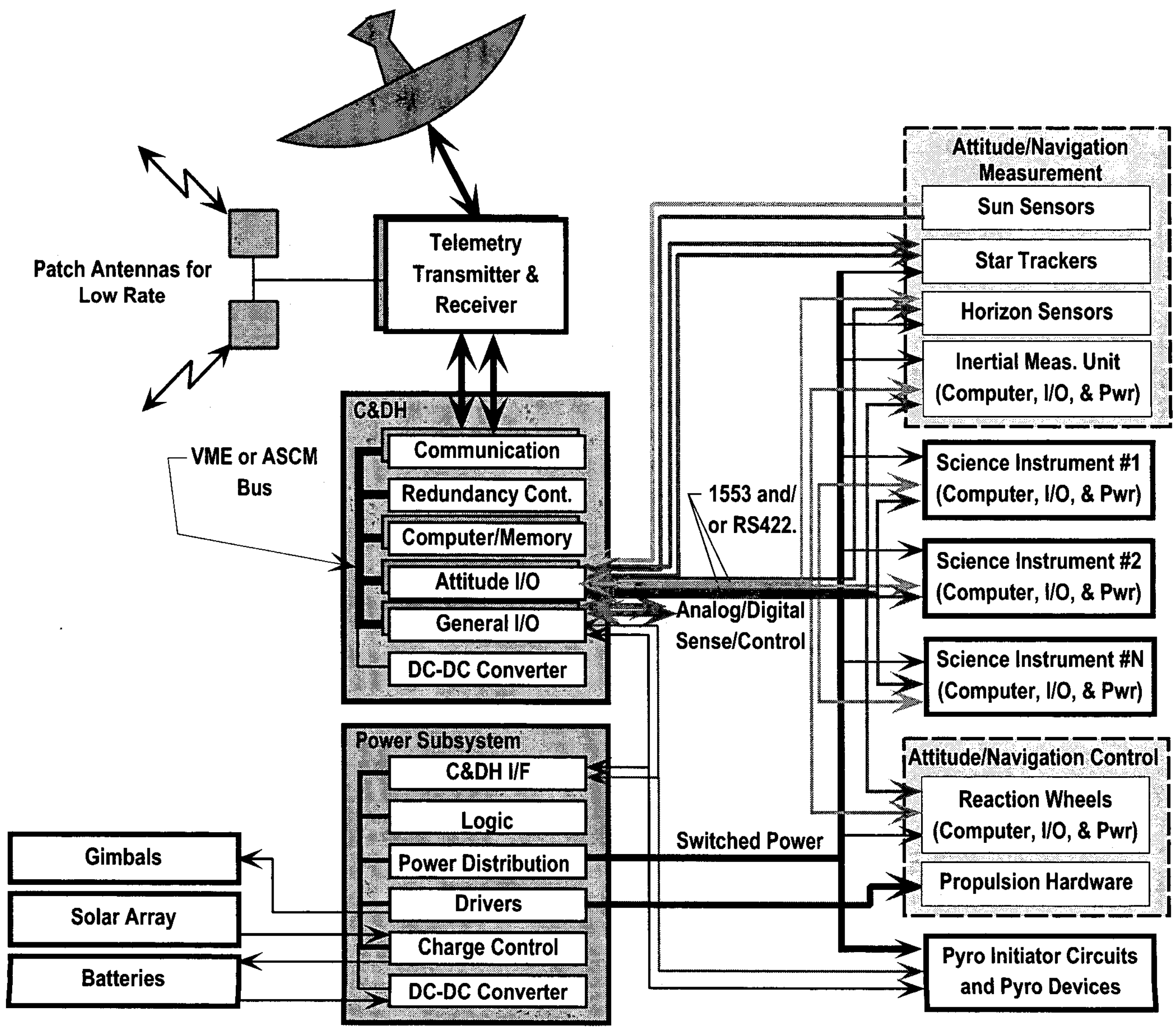

Figure 3 Today's Typical Spacecraft

However, only one of a pair is used at a time. The unused card is usually off.

The C&DH box contains a communications card that processes the digital data that is sent to or received from the transmitter and receiver. The digital data is specific to the format adopted by the mission. Of late, many missions have adopted the standard formats defined by the Consultative Committee for Space Data Systems (CCSDS). However, there are still many non-standard "commutated bit stream" spacecraft in use. The encoding and decoding that occurs on the communications card of these legacy spacecraft are matched by the FEP in the modified ground station described above. The ground station's FEP is reconfigured on command from mission operations to handle each mission's data just prior to rendering the scheduled service.

Other cards in the C&DH include a redundancy control card, redundant sets of computer, memory, and input/output (I/O) cards and a power conversion module for operating the cards. The redundancy control card is often connected directly to the communications card so that special uplinked commands can bypass interpretation by software. This is to enable ground control of the power and data bus redundancy switches and to enable computer reset on command. The commands are captured with hardware on the communications card, which controls the appropriate switches on the redundancy control card. The computer and memory card controls the spacecraft. Typical processors in-flight today include RAD6000, R3000, 386, and others. The amount of memory varies from 10's to 100's of megabytes. If more memory is required, it is added as a separate solid state subsystem and controlled similar to a tape recorder. The computer communicates with other cards in the chassis via the backplane. It communicates with other spacecraft subsystems through interface circuits on the I/O cards in the chassis. Serial digital circuits on the I/O cards are used for controlling and reading data from the spacecraft subsystems and science instruments. Most of these serial circuits conform to IEEE1553, IEEE1773, RS422, and RS232 hardware standards. Other buses may follow a proprietary standard defined by the spacecraft manufacturer. However these buses are slow by today's commercial standards; and the protocols for passing data and commands along these buses are usually peculiar to each spacecraft. While some spacecraft buses move data and commands using protocols that conform to CCSDS standards, these standards allow considerable design variance such that subsystems and instruments designed for one spacecraft's protocols usually need to be reprogrammed to work on another. Analog and digital level circuits are included for sensing the spacecraft's general health and status and controlling simple functions. The power conversion module changes the spacecraft's power bus voltage (usually 28VDC) to regulated voltages needed to power the circuits on the cards (typically +5V and± 15V).

The power subsystem includes control and status data interfaces to the C&DH, power distribution circuits and logic, motor and valve driver circuits, battery charge control circuits, and a power conversion unit. These functions may or may not be included in one chassis. If not, a function may be supplied as a separate subsystem chassis with its own control logic and interface circuits.

The power subsystem normally provides switched power (usually 28VDC) to each of the other subsystems and instruments. Many legacy spacecraft routed this power through fuses. The newer spacecraft use switches that act like circuit breakers that can be reset if they were to trip with an overcurrent, overvoltage, or undervoltage. The power switches are controlled by the logic circuits which respond to commands from the C&DH computer.

The drivers operate the spacecraft's motors and propulsion valves. Motors are often used in gimbals to steer a high-rate antenna dish and to point the solar arrays at the sun. Other drivers provide power to operate propulsion valves and various spacecraft heaters.

The charge control circuits usually operate autonomously and either switch solar array segments in and out or use shunt regulators to control the battery charge current.

Most spacecraft use one-shot pyrotechnic devices to perform one-time deployments of items such as unlatching the solar array foldout panels. These circuits receive power from the power subsystem and are controlled by the computer. These circuits use logic to prevent accidental actuation of the pyrotechnic devices. The circuits may stand alone with their own interfaces or be incorporated into the power subsystem.

The navigation and attitude measurement subsystems include sun sensors, star trackers, gyros and accelerometers (Inertial Measurement Unit – IMU), and other specialized hardware such as horizon sensors. The navigation and attitude control subsystems include reaction wheels, small spacecraft thrusters, magnetic torquers, and the main spacecraft engines. The sun sensors are simple devices that present either a digital pattern or an analog signal to one of the I/O cards. The star tracker, IMU, and reaction wheels typically have their own control logic. These devices generate data for the C&DH computer to process with the navigation and attitude control software. In some spacecraft, the software resides in a separate computer in another chassis dedicated to attitude and navigation control. Most of the subsystems include their own control, sensing, and power conditioning hardware and are interconnected to the central computer with the serial digital buses.

The science instruments also connect to the C&DH via the serial digital bus lines. Most of these contain their own computer, control, sensing and power conversion hardware. Command strings usually pass from the RF receiver, through the C&DH to temporary memory and then to the instrument. The instrument then executes them immediately or later on a schedule. Science data is passed back to the C&DH to be held in the memory until the next scheduled ground connection. When connection is made, the data is often encapsulated using Reed Solomon and Viterbi coding techniques by the communications card and then passed to the ground station. The encapsulation enables the data stream to be reconstructed in the event noise causes some data bits to be lost.

Ground Station Modifications for Access On-Demand

Modifications to the ground stations and spacecraft later in the CSOC program will enable autonomous connection setup and tear-down between the spacecraft and the ground station.

The concept of obtaining access to the ground network on the demand of the spacecraft is shown in Figure 4. For this figure, we assume the spacecraft's data storage is near full. That is, in the case of a low earth orbiter (LEO), there is enough space available in storage to handle another orbit or two of science data, but after that, the storage would be full. So the spacecraft begins soliciting service from the ground stations by announcing over the area in front of its ground path with a low-rate, wide-angle RF pattern. Each message requests service from any available ground station by reporting the identification and position of the spacecraft and the amount and type of service needed by the spacecraft.

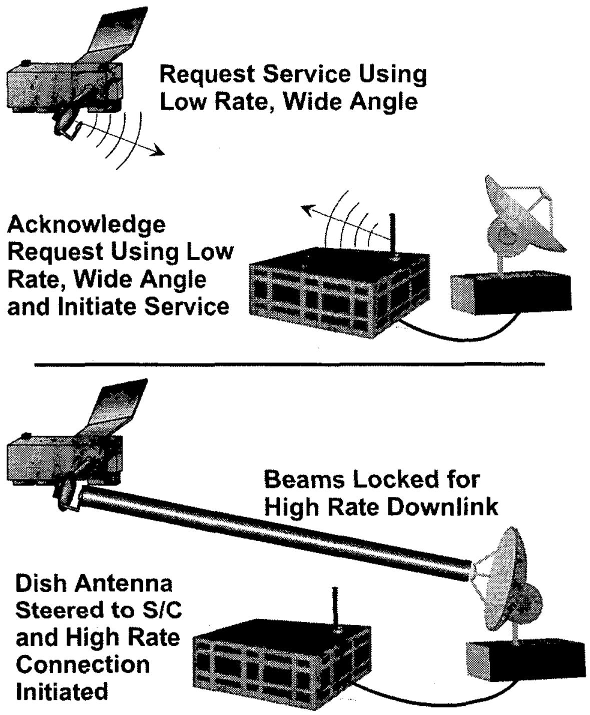

Figure 4 Network Access Rendered On-Demand With Ground Station Modifications

These ground stations will have been further modified to provide uniform, standard services to any spacecraft whose mission has permission to use the network and has been paying its communications bills. Ground stations listen for low-rate requests for service with an omnidirectional antenna. If a request is received, but the ground station is busy with another spacecraft, it ignores the message. If, on the other hand, the ground station is available, it transmits a low-rate message back with the omnidirectional antenna that it will provide service and immediately begins to point the high-rate antenna toward the spacecraft's reported coordinates.

Once connection is made between the spacecraft's and ground station's high-rate antennas, autonomous software agents at both ends optimize the connection by using the autotrack and fine focus features of the antennas to sharpen the beams. The agents also adjust data transmission rates to accommodate adverse weather conditions. If the spacecraft employs an antenna array, that too is optimized for the connection using a control loop on the received signal strength to point the receive and transmit antenna patterns.

The modified ground station is shown in Figure 5. The RF equipment will be modified to also handle Ka-band for faster downloads. The low-rate, omnidirectional RF will likely migrate to the Ka-band as NASA's future spectrum allocation moves to the higher frequencies.

The console and human operator(s) are replaced with autonomous agent software running in a personal computer that operates all the ground station's hardware. When requests for service come from the spacecraft or user side, the autonomous agent handles the operations to provide the service. In the case shown in Figure 4, the agent hears the spacecraft's request, points the large antenna, and optimizes the connection. For the case when the user wishes to contact his/her spacecraft or instrument, the agent hears the request and begins sending messages skyward for the spacecraft. Once the spacecraft hears the message, it replies and the connection handshake is made for high-rate data, if that service is requested. Otherwise the messages from the user to the spacecraft may be entirely handled through the low-rate systems.

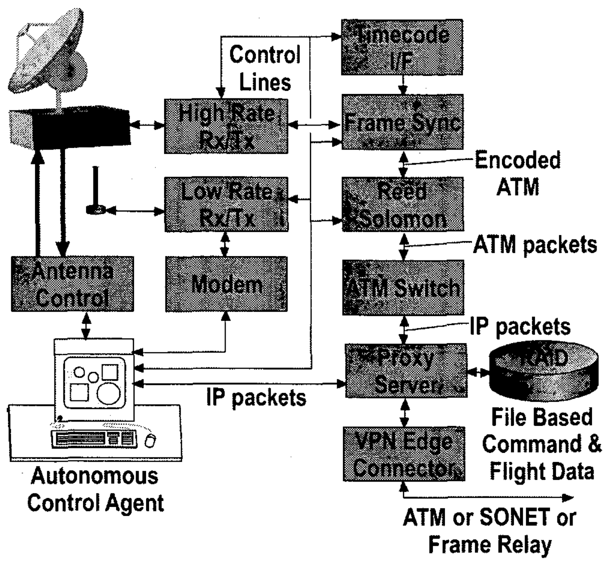

Figure 5 Ground Station Modified for Autonomous Demand Access Operation

Other modifications include the conversion of the space/ground communications to IP compliance and the implementation of a proxy server with a high-speed, temporary, digital storage. The proxy server enables the ground station to be treated more like a node on the CSOC Intranet. It provides a level of security protection and routes IP data to/from appropriate addresses at the ground site and to/from appropriate spacecraft addresses. This unit works with other CSOC servers to keep track of spacecraft and instrument data addressing and routing. The temporary storage will likely be a Random Array of Inexpensive Disks (RAID). The RAID is provided to prevent loss of data, it is not used as an archive. Data in the RAID is over-written after the data is forwarded safely to the correct address.

The ATM switch shown in Figure 5 is used to send and receive ATM packets for those spacecraft that implement an ATM edge connector on-board. Such a service is likely needed for the larger spacecraft that have many varied instruments, all sending data down at the same time. ATM is also useful for communications with shuttle and the International Space Station (ISS). Those spacecraft will likely be sending isochronous voice and video data that shouldn't be disrupted. That is, that data requires a high quality of service (QoS) to eliminate video or voice tearing. The actual implementation of IP into space is undergoing review.

Near Term Spacecraft Architecture

Near term spacecraft refer to those that could be launched in the 2003-2004 time period as it is expected that new hardware would be available by then. The architecture in Figure 6 shows the minor modifications needed to existing designs to enable the use of IP in space and the ability to implement demand access communication services from the ground or to hear requests from the ground.

Most of this spacecraft is similar to today's spacecraft architecture discussed above. Differences arise in the RF subsystems and the communications card. These will likely still use the present S- and X-band hardware, however it is possible the first Ka-band hardware may be available.

The most significant change is in the design and use of a network card in the C&DH. This card will be reconfigurable and will act as the network edge connector for the spacecraft. The card, in conjunction with the spacecraft's computer, becomes a single node on the network. The spacecraft is assigned a network address and the computer translates messages from the net side to commands on the spacecraft, subsystem, and instrument side. Data to be moved from the spacecraft side to the net side are retrieved from memory and packaged in IP packets and, perhaps, ATM packets by the network card. The network card then sends this data to the modulator in the transmitter.

This near term spacecraft will use the older style data buses on-board that will likely not handle IP packets. The purpose of having this interim design stage is to get IP into space as early as possible and to get experience with using it. Though it would certainly be desirable, this spacecraft may or may not be able to achieve access to the space/ground network on-demand.

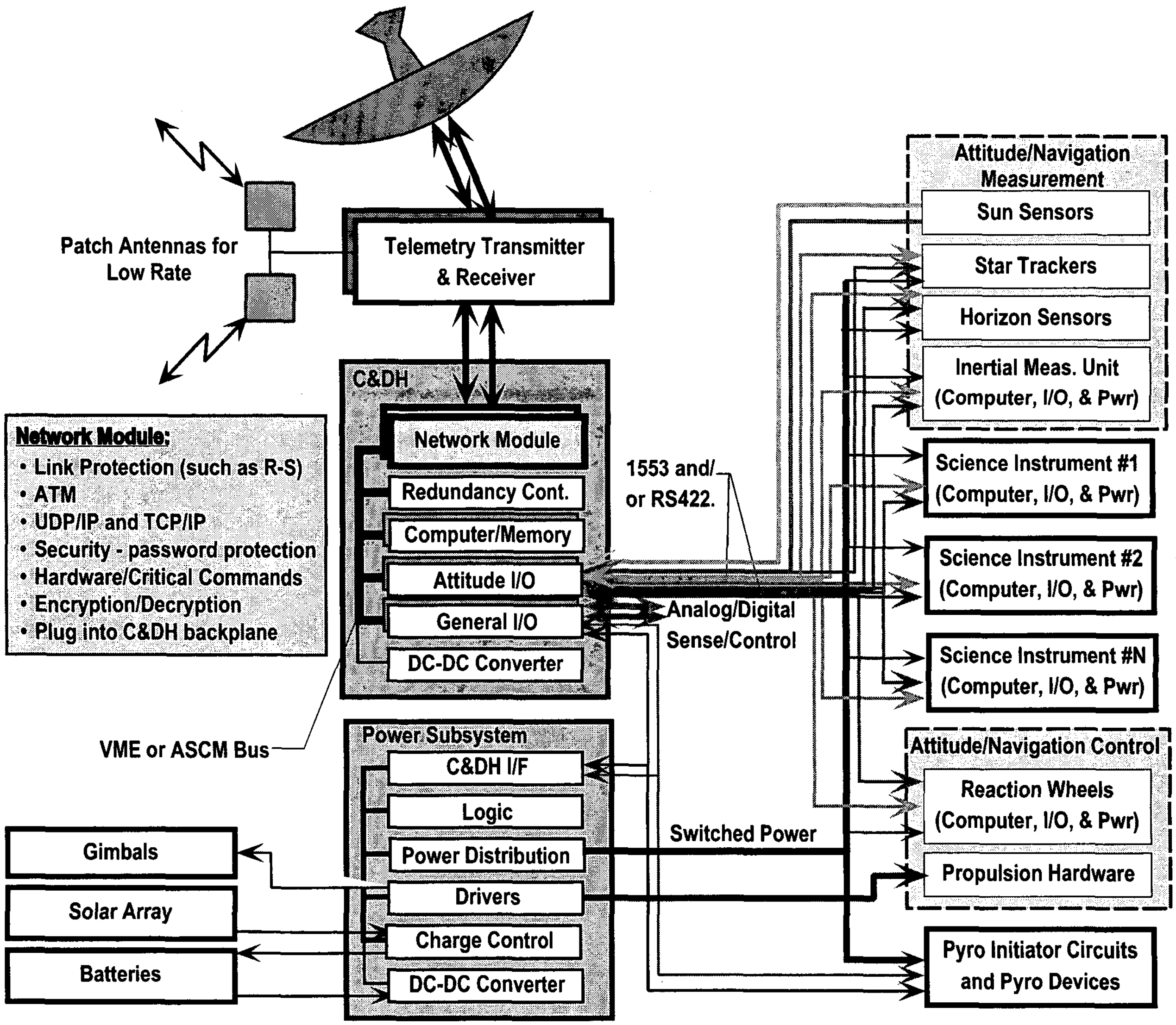

Figure 6 Near Term Spacecraft Architecture

Near Term Network Module

The hardware for the early network module is blocked out in Figure 7. The digital data between the RF hardware and the network module is IP packets or IP packets segmented into ATM packets, depending on the mission requirements. In either case, the data may be encapsulated with Reed Solomon and Viterbi, again dependent on mission requirements. LEO missions may not require encapsulation if the signal strength is sufficient.

The edge connector block has the logic to remove the ATM layer, if used, and the IP from the received data. The computer then directs the data to memory. There are only two IP addresses used in this module: one to the spacecraft and one to the spacecraft clock. The edge connector also directs the clock set data to the module's spacecraft clock.

Alternatively the spacecraft computer could handle the IP address resolution for instruments and subsystems by simulation. If so, the computer will sort data streams by received IP addresses and pass the data, not the IP, on to the affected units. When data is to be passed to the ground, the Edge Connector can packetize older, commutated data all with the same source and destination addresses; or, it can packetize individual file data from each subsystem and instrument with unique source addresses and unique destination addresses. Of course the computer software handles the logic for this.

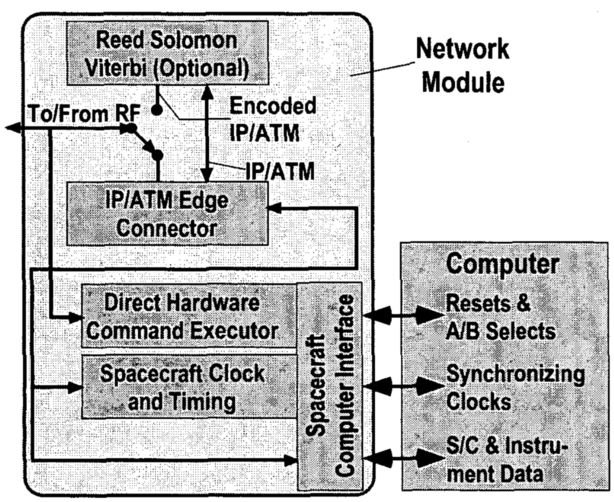

Figure 7 Near Term Network Module

The network module also employs direct hardware command executor circuitry that monitors the input data stream for special codes. Upon receipt of a special code, the following data are captured in registers that immediately and directly control hardware. These circuits are used in an emergency, when ground personnel feel the spacecraft is out of control. These circuits can be used to reset the computer, switch from A to B bus redundancy, and switch from A to B power redundancy – if those redundancies are implemented.

Miniature Autonomous Ground Station (MAGS)

When high-rate, Ka-band RF systems, IP networking, and on-demand access to the networks becomes available to the space mission community, a new form of inexpensive, generic ground station becomes possible for earth orbiting missions. The Miniature Autonomous Ground Station (MAGS) is envisioned to be a small stand-alone unit that can be placed almost anywhere that has power and network connections.

The block diagram of the MAGS is shown in Figure 8. The system utilizes a 0.6 m to 1.0 m dia. steerable dish with the Ka-band transmit and receive module likely attached directly to the back. The design could also be implemented with an array antenna rather than a dish, however, a dish is shown here. Since the MAGS design is a ground implementation and is thus repairable, the mechanical steering assembly can be quite inexpensive. The dish, in this case, uses an adjustable secondary mirror to change the beam spread from wide to narrow angle. This feature, in conjunction with the use of autotrack, makes it easier to find and focus on the spacecraft's signal. This small dish will support 100's of megabits per second data transfer rates to and from LEO spacecraft and near 100 Mbps transfers to GEO spacecraft, depending on the GEO spacecraft's RF subsystem capability. During a 6-minute pass at an average of 300 Mbps, over 13 gigabytes (GB) can be transferred.

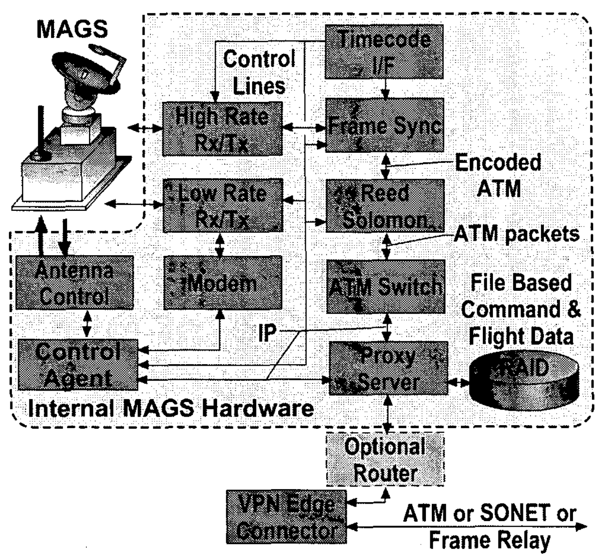

Figure 8 Block Diagram of Miniature Autonomous Ground Station

The MAGS also employs a low-rate, omnidirectional antenna to listen for a spacecraft's request for service, or to radiate a user's request for contact upward.

In the MAGS implementation, the functionality of a ground station is reduced to autonomous agent software, a few cards in a chassis and a RAID, which are all contained in the base of the unit. Most ground station functions are preserved. Even console control by a human can be performed via the network connection. In this case, the MAGS would report its status to the external console by the use of web pages. Request messages from the user and commands from mission operations personnel would likely be sent to the MAGS by e-mail using simple mail transfer protocol (smtp) or by a file transfer protocol (ftp) put operation. A user's upload to his/her spacecraft or instrument would be an e-mail attachment or an ftp put operation that is temporarily held by the MAGS and then passed on to the spacecraft when the connection is made.

Each station would be able to service any compatible spacecraft. It would serve as a temporary buffer for uploads and downloads such that requests from the user or the spacecraft do not need to be supported in real time. For example: a user would send a software upload to an instrument as an e-mail message with instructions to load the software that is included in the attachment. The e-mail passes through a CSOC server that routes it to one or more MAGS units and/or ground stations. The message and attachment are then held on each station's RAID until one of the stations makes contact with the correct spacecraft. Once contact is made, the e-mail message and attachment is passed on to the spacecraft and a message is passed back to the CSOC server to indicate the e-mail transfer has been serviced. The CSOC server then informs all other ground stations to clear the message from their RAID's.

Messages to and from a MAGS are in the clear. That is: anyone can receive the messages; the encapsulation (Reed Solomon, Viterbi) to protect against noise dropouts is not secret; and, the IP/ATM packet headers are not scrambled. Thus if secure communications is desired, encoding and decoding must be done at the end points; at the spacecraft or instrument and at the user site.

Operation of the MAGS is shown in Figure 9 and it is similar to the way the ground stations, described above, operate. Again, the MAGS low-rate omnidirectional antenna picks up the spacecraft's request to access the ground. Once contact is made, the higher rate dish antenna can be brought in to handle large data dumps.

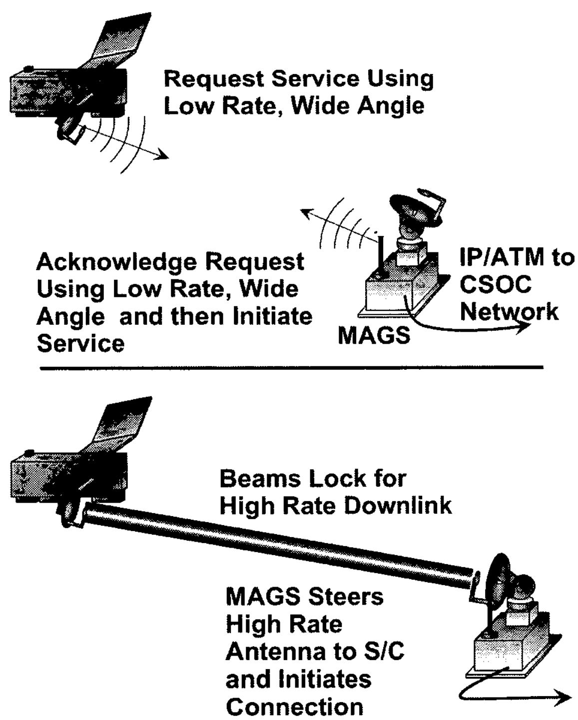

Figure 9 Network Access Rendered On-Demand By Miniature Autonomous Ground Station

Spacecraft of the Future

Spacecraft implementations will take advantage of the new functionality afforded by connection to the Internet and by the autonomous methods of operation of the ground network and of the spacecraft and instruments. Two architectures are described. One is a distributed architecture that uses mostly self-operating subsystems and instruments. The other is an integrated architecture that supports subsystems and instruments that rely on the spacecraft's computer for much of their operation and control. the distributed version is more appropriate to mid-sized and larger spacecraft, while the integrated version is well suited to small spacecraft.

The distributed spacecraft allows for independent development of the subsystems and instruments. However, this also tends toward making each subsystem and instrument more expensive. Each unit requires its own computer, memory, I/O, and power conversion subsystems, thus each subsystem requires more design, parts, assembly, and testing.

The integrated architecture shares much of the hardware between all the subsystems and instruments. The spacecraft's computer, memory, I/O and power conversion can all be shared with each subsystem's sensors and actuators thereby saving considerable time, effort and cost for design, parts, assembly, and testing. To be sure, the designs of all the subsystems and instruments have to be coordinated closely. The software for each of the closely integrated subsystems and instruments runs on the spacecraft computer. So this too must be carefully controlled

There are advantages and disadvantages to either architecture. It is likely most spacecraft will use features of each.

Distributed Architecture

This spacecraft type is shown in Figure 10. The RF systems include the low and high-rate Ka-band units needed to interface with the new ground stations. These will also interface with the Ka-band Tracking and Data Relay Satellite (TDRS) System (TDRSS) upgrade that comes with the launches of satellites H, I, and J.

The figure shows a pair of low-rate, patch antennas for requesting service and for listening for user requests. To work with a TDRS, this low-rate system will also need to operate in the S-band as the multiple access (MA) system of a TDRS operates there. The spacecraft will use the MA system to demand access from the TDRSS.

While two high-rate antenna types are shown, only one will likely be used. A steerable dish or a steerable beam phased array antenna will provide for high-rate transfers. For LEO spacecraft, either one would suffice to talk to ground stations or to the TDRSS at very high-rates. Again, the main purpose of the high-rate connection is to get the transfer done quickly so the ground or TDRS asset can be released as soon as possible and be made available to the next requestor. An additional advantage is obtained by enabling much larger quantities of data to be transferred during a single transaction.

The architecture in the figure indicates several changes. The C&DH can be split into smaller and simpler units called servers, with a network module in each. A modern commercial standard bus, such as IEEE1394, can be used with redundancy to interconnect the servers, subsystems, and instruments. And, if the spacecraft operates at LEO, a Global Positioning Satellite (GPS) receiver is included.

By splitting up the C&DH into smaller identical server units, redundancy can be achieved simply by adding units. The data to/from the RF is connected to both units and the active server operates on it. The figure shows, as an example, a redundant pair of the IEEE1394 buses in use. This bus has many advantages, not the least of which is that it is a commercial standard. It is very fast at 100–400 Mbps and the commercial world is working hard to increase its speed to the 800–3200 Mbps range. Integrated circuits exist now for the slower designs. This bus can be operated in an isochronous fashion that affords high QoS on video and voice data, similar to ATM. Another feature is that it can be operated in a mode that extends the memory of the processor using it. That is, the bus can extend memory addresses to remote devices so that they appear as memory locations to the controlling processor at the local end. This can be useful for simplifying the operation of remote devices. Items along an IEEE1394 bus tree can be turned off without affecting the bus operation, thus enabling additional redundancy without the complication of handling powered-off component interfaces.

Draft requests for comment (draft RFC's) have been submitted to the Internet Engineering Task Force IETF) that implement standards for interfacing the IEEE1394 bus to IP networks. Once the drafts acquire RFC status, implementations will become available to enable IP to pass over this

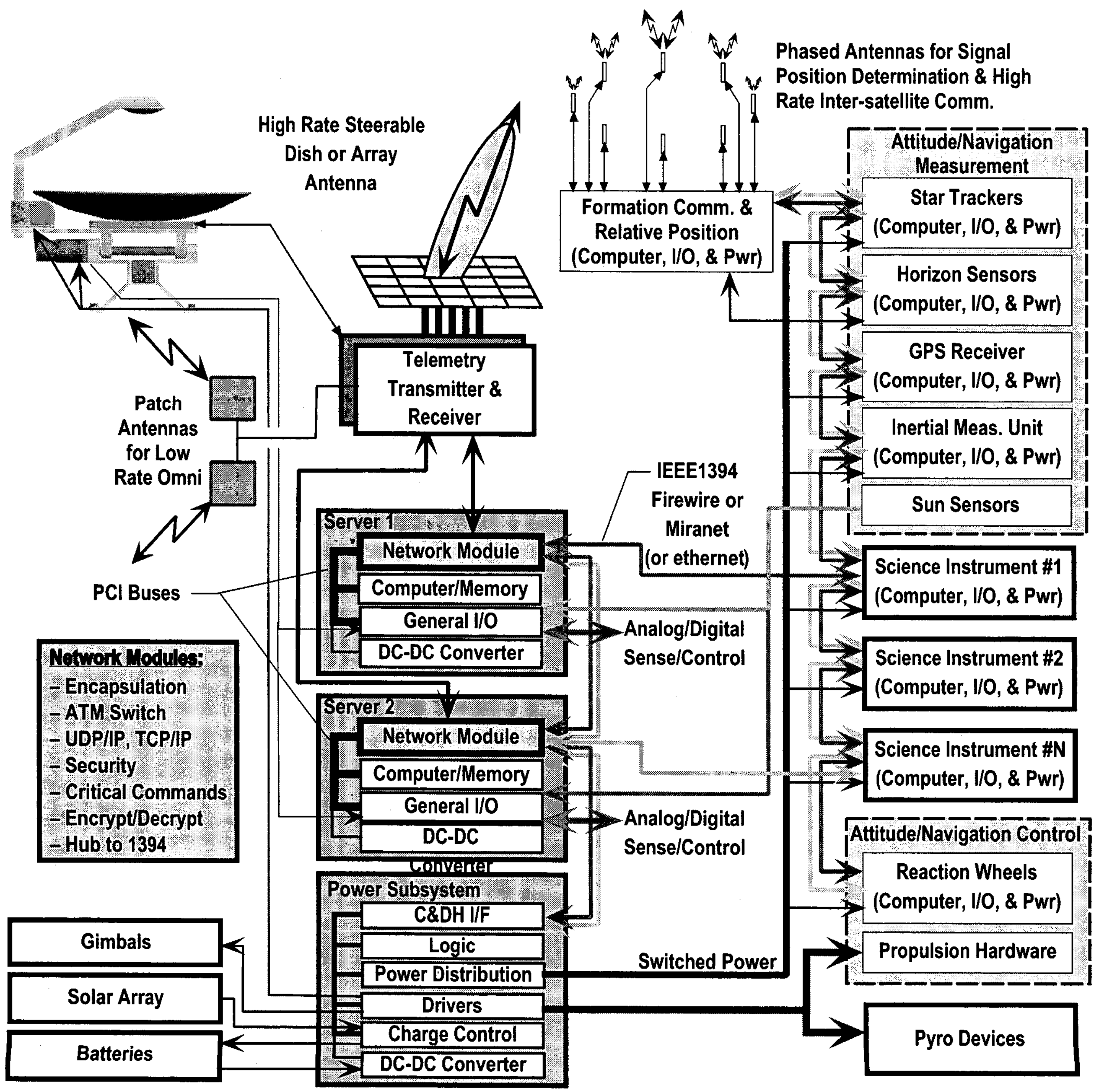

Figure 10 Spacecraft of the Future – *Distributed Architecture*

bus between the network module and the subsystems and instruments.

Other on-board local area networks (LAN's) can be implemented. The Miranet is a type of very high-speed network that uses parallel wires. It's possible that it could be used to handle IP data. Another possibility is to use Ethernet as the on-board LAN. Many commercial designs and chips exist for Ethernet, as it is the most common of network implementations. A ring architecture bus standard, IEEE1393, could be used. It implements a fast, redundant, fiber optic ring around the spacecraft and uses the ATM protocols.

Figure 10 also indicates a means for inter-satellite communication and relative position determination. The isochronous features of ATM or IEEE1394 could be of use in coordinating constellation operations. Further discussion of communications within a constellation of satellites is beyond the scope of this paper.

Advanced Network Module

For the future spacecraft, the network module has the additional functionality of servicing the on-board LAN and an option is shown that could provide hardware encryption and decryption of all data passing through the module. A block diagram for the advanced network module is shown in Figure 11.

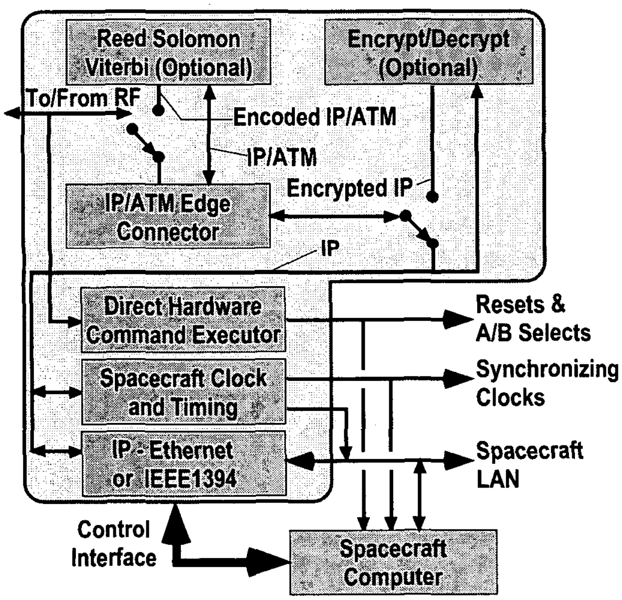

Figure 11 Advanced Network Module

Similar to the earlier described network module, the digital data between the RF hardware and the network module are in IP packets or in IP packets segmented into ATM packets, depending on the mission requirements. Again, the data may be encapsulated with Reed Solomon and Viterbi, dependent on mission requirements. LEO missions may not require encapsulation if the signal strength is sufficient.

The edge connector block has the logic to remove the ATM layer, if used. The IP layer is retained and used by the network module for on-board routing of the received data. There are only IP addresses used within the module: one to the spacecraft and one to the spacecraft clock, as before. The edge connector also directs the received clock setting data to the module's spacecraft clock. IP packets directed toward the subsystems and instruments are passed through the IP-Ethernet or IEEE1394 block that translates the IP to the correct format for the LAN. As the IP messages pass through the module, the server computer can redirect them to memory when the addressed instrument is not in use. When the instrument is turned on, the server passes the messages to the instrument after it logs-on.

Data movement from instrument to the ground is performed in a similar manner. The instrument sends a message to the user (or several users simultaneously) with the data tied to the message as an attachment. If the user is not immediately available (no connection is in-place to the ground) the message is captured by the on-board server and put into temporary storage until ground connection is made. Then the message is passed through the encryption hardware, if used, through the network card's edge connector circuitry, through the Reed Solomon circuitry, if used, and through the spacecraft's RF subsystem down to the ground station server's RAID. The message is passed on to the CSOC mail server. This unit sends duplicates of the message to the e-mail server of each addressed user's Internet Service Provider (ISP). The users can then capture the data at log-on, or have it automatically downloaded with autonomous software on the their computers.

Note that the spacecraft clock will be allocated an IP address on the LAN. That enables any instrument or subsystem to obtain accurate time of day for time tagging their data. More precise timing functions for synchronizing measurements and equipment can be obtained when using an IEEE1394 bus's timing signals. The network card will provide the IEEE1394 clock. This clock will also maintain time of day and will be adjustable by uplinks from the ground.

Similar to the previous network module, this one also employs the direct hardware command executor circuitry that monitors the input data stream for special codes. Upon receipt of a special code, the following data are captured in registers that immediately and directly control hardware. These circuits are used in an emergency, when ground personnel feel the spacecraft is out of control. The circuits can reset each computer, switch from server A to server B, data bus A to data bus B, and switch from power bus A to power bus B, if those redundancies are implemented.

Integrated Architecture

Smaller spacecraft may be implemented more like that shown in Figure 12. In this case, the spacecraft is small enough that mass, power, and cost are at very high premiums. Yet, since the cost expended on each spacecraft is low, redundancy can be obtained by flying several spacecraft. Small implementations enable redundant items to be removed from each spacecraft. In fact, one might argue that it is no great loss if a cheap spacecraft is lost due to not implementing redundancy on-board.

The integrated architecture spacecraft also uses the same advanced network module. This provides spacecraft LAN connectivity for any distributed instruments that are not integrated tightly to the server. Science modules have been added to the server to handle the operation of simpler science sensors and actuators. For example, the integrated instrument might be a light spectrum analyzer that uses

Charge Coupled Devices (CCD's) to measure the variation of light spread over a distance by an adjustable diffraction grating. Lenses, slits, grating, and CCD would make up the sensor. A grating motor would be the actuator. In the integrated architecture, the CCD readout circuits and local memory would reside on an instrument card in the server; and the motor drive circuits would reside on the driver module in the power portion of the server. All would be under the control of instrument software routines running on the server's computer.

Modifications that implement IP/ATM over the TDRSS

The active TDRSS constellation is shown in Figure 13. The present implementation has TDRS 1, 3, 4, 5, 6, and 7 in space. Three are active and the other three are held in reserve. Three more will be launched in the near future. These are TDRS H, I, and J. The nomenclature is changed to reflect different capabilities and a different manufacturer. The figure indicates that TDRSS provides full earth coverage to earth orbiters.

Each TDRS operates in a "bent pipe" fashion. That is, RF data sent to it is immediately turned around and sent down on a different frequency. A TDRS performs no detection, interpretation, or operation on the data as it passes through. Each TDRS has four RF systems that are important to providing communications services. One system is the Ku-band up and down links to the controlling ground station at White Sands Complex (WSC) and at Guam. The second is the Multiple Access (MA) system that operates in the S-band and provides moderate-rate communications service over several spacecraft simultaneously. The third are S-band receivers and transmitters in each of the 2 large steerable dishes. The steerable dishes are Single Access (SA) systems, as they can only talk to one spacecraft at a time.

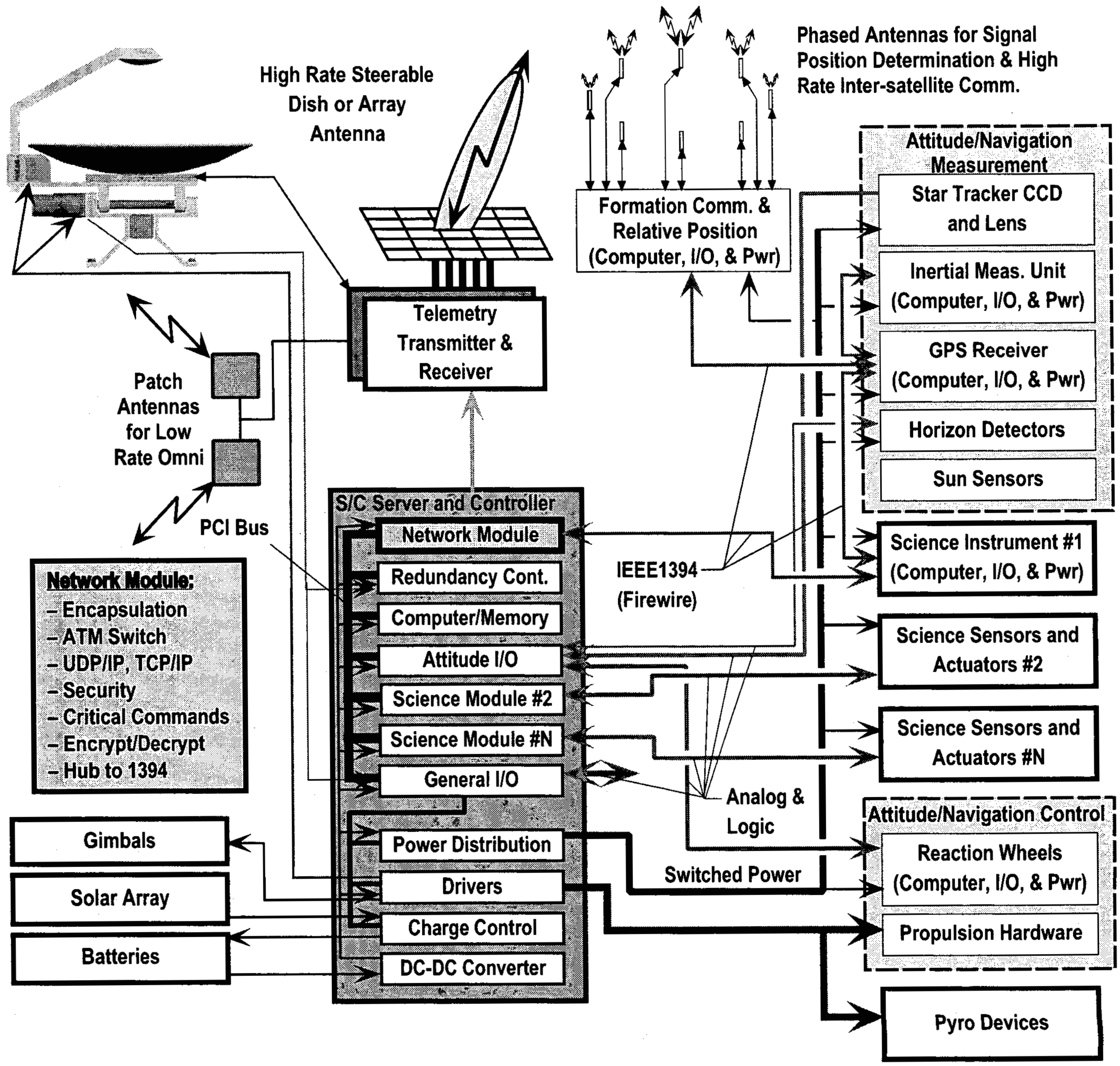

Figure 12 Spacecraft of the Future – *Integrated Architecture*

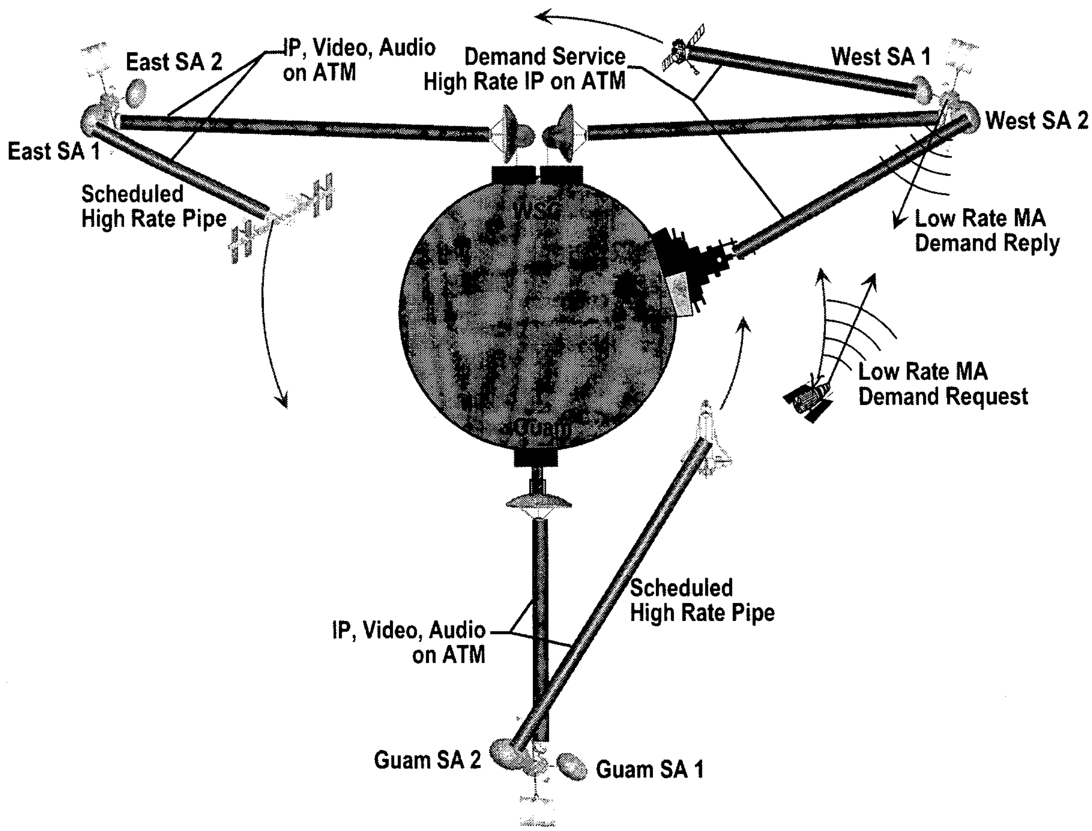

Figure 13 Tracking and Data Relay Satellite System (TDRSS) Active Constellation

The S-band Single Access systems are referred to as SSA systems. The fourth RF system includes the Ku-band transmitters and receivers that are also incorporated in the SA antennas. These are called the KSA systems. When TDRS H, I, and J come on-line, a Ka-band RF system is added to each of those new SA antennas. The older KSA system may then be referred to as KuSA, and the newer one as KaSA.

The figure implies how TDRSS would operate after modifications are implemented. A user spacecraft would hail in an upward direction in the MA system's S-band by sending identification, the rate of connection, and the quantity of data to be downlinked. The MA system sends the request directly to WSC. Hardware and software at WSC detect the request and determine the location of the spacecraft. The entire TDRSS schedule, see Figure 14, is inspected by software to determine the nearest time slot whereby the TDRSS could service the user spacecraft. When TDRSS is ready to service the spacecraft, it sends a message via the MA system and tells the spacecraft to begin pointing its high-rate antenna to a particular TDRS. The two RF systems then operate in the autotrack mode to ensure the highest-rate connection. The data is passed from the spacecraft to the TDRS, to WSC (or Guam), to the CSOC server, and thence to the user. ISS and shuttle would each get preferred service, that is, as near to 100% coverage as is reasonable. Other users might also get high priority service. Scheduled service will be maintained for these CSOC customers. The modifications will enable the considerable amount of unscheduled time to be used on the demand of any user or user spacecraft. Notice in Figure 13 that the TDRSS could service surface users as well as space users.

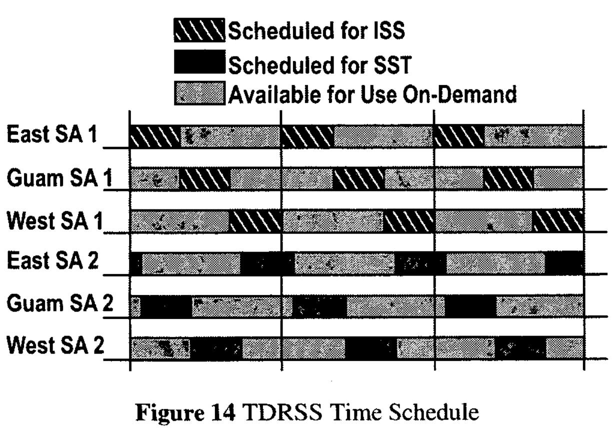

Figure 14 TDRSS Time Schedule

The TDRSS modifications will result in the architecture shown in Figure 15. A software agent that handles the Demand Access System (DAS) will control the TDRSS assets during unscheduled periods. The modifications being performed now will enable access to the MA system on the demand of a ground user. Other modifications are being studied to implement the hardware needed to pass IP/ATM traffic over the present TDRSS KSA system (Ku-band) for providing very high rate Internet service to ISS and shuttle.

Later, it is planned to integrate the control of the high-rate SA systems into the DAS. Other modification to the

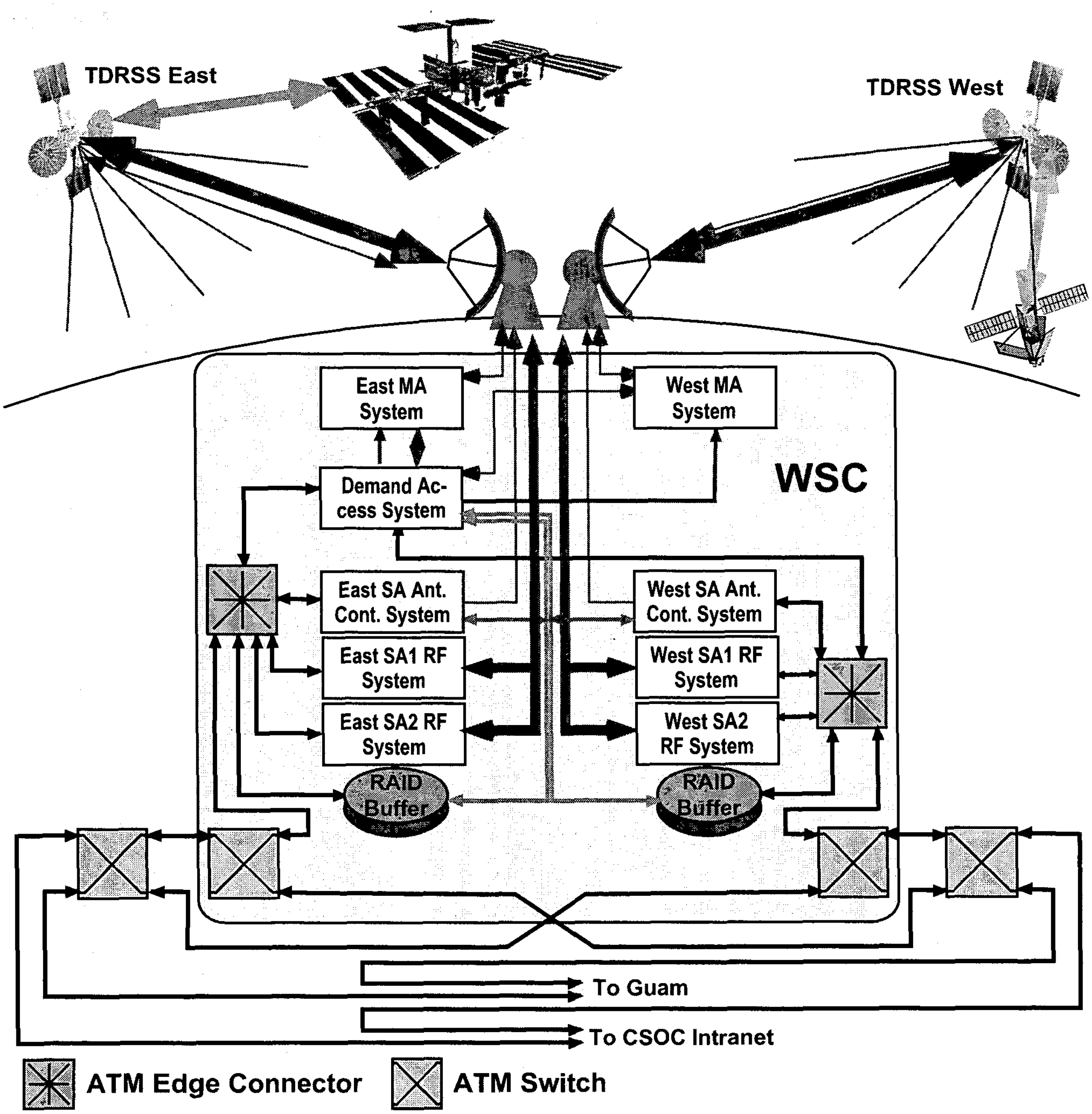

Figure 15 General TDRSS Modifications for IP/ATM and Demand Access

TDRSS include the addition of RAID disks and servers to temporarily store uplink or downlink data so as not to lose it before the contact to pass it on to the spacecraft or CSOC server is made.

Modifications to Provide Access On-Demand from the DSN

The JPL has been working on a method to conserve antenna assets as the numbers of deep space missions grow. This method is called beacon mode operation, see Figure 16. In it, sets of small DSN antennas listen on a schedule to different missions in the solar system. The mission spacecraft each report a tone back to earth. The frequency of the tone indicates whether the spacecraft is OK, needs to download data, has a problem, or has an emergency. This scheme will save time on the large antennas as they will not be brought to bear on a spacecraft until service is required.

Spacecraft do not have to be checked by the large antennas to get simple health data. It seems worthwhile to extend this concept to make it an even more robust demand access system. One addition would include using the small ground antennas to provide an earth position beacon for the spacecraft; and a second would be to modify the beacon tone to report a very few simple bits of information.

The effort to make spacecraft more autonomous would be aided by the implementation of earth "lighthouse" types of beacons. These beacons would serve to assist the spacecraft in performing autonomous navigation. If the light in the "lighthouse" is flashed (i.e., sends low-rate data), it could be used to inform the spacecraft as to what time it is on earth and it could be used to get a particular spacecraft's attention to inform it to begin downloading data. By the time the data gets to earth, a larger antenna would be ready to catch it.

One of the problems with the beacon mode, as described, is that it doesn't easily discriminate between several spacecraft within the same ground antenna pattern. If information could be sent to earth by simply flashing the tone during assigned time slots, the identity of the spacecraft could be determined and simple health data could be downloaded. The beacon mode is a worthwhile scheme and it deserves considerable study with an eye toward improving autonomous operations on the spacecraft and on the ground.

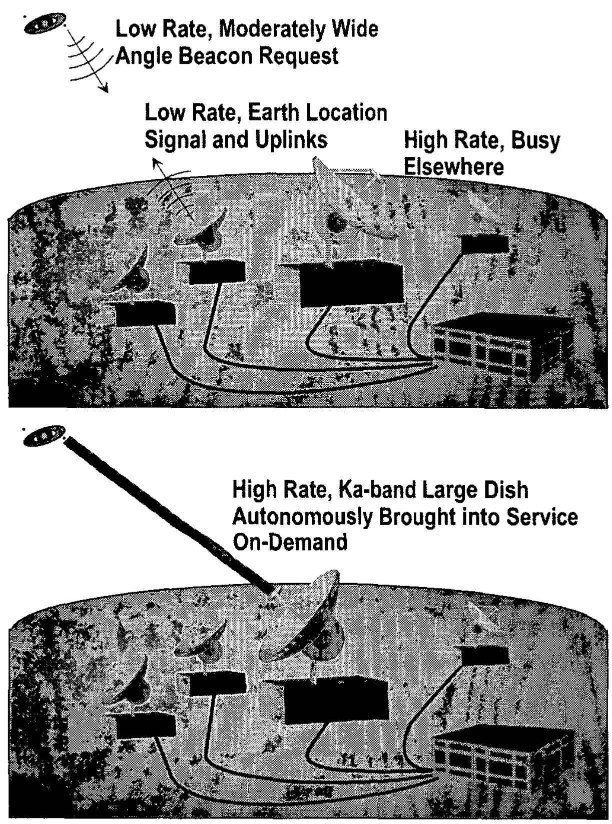

Figure 16 DSN Modified to Utilize Beacon Mode and Implement Demand Access

Other Architectures

There are many ways to design spacecraft and ground systems to get them to operate autonomously and to enable them to interface to the Internet. Only a few methods are covered here. It's worthwhile mentioning that JPL is pursuing the construction of a communications satellite constellation around Mars. This constellation would implement the Internet in the Mars heavens. Orbiting, landed, roving, flying, and manned missions would be able to communicate with each other through this constellation. For this constellation to work in an autonomous fashion, a means of providing access on-demand must be included. Similar constellations could be set-up around the earth's moon, around Jupiter's moons, and within the solar system, all depending on the amount of activity expected at those areas and on the cost of implementation.

3. Conclusions

Several architectures have been described for ground stations, spacecraft, the TDRSS, and the DSN. These modifications and new systems enable significant improvements in all aspects of communicating with in-space vehicles.

By enabling the communications system to be accessed autonomously by the spacecraft and user, and by providing the communications services in an autonomous fashion, the system becomes very inexpensive to operate and the services provided are increased. Services are provided when the user or spacecraft needs them, not on a schedule that is sometimes arbitrary. This autonomous access further enables efficient use of the Internet technologies in space. Without autonomous operation, the IP provides just another spacecraft busing system and communications packaging system. With autonomous access, IP provides essentially the same functionality that an earthbound user experiences - when the user logs-in to her e-mail server, her messages appear in a list. When a spacecraft logs-in to an earth-bound e-mail server, the spacecraft's messages are uploaded. The main difference is that the response time for the spacecraft may be longer because the spacecraft is not immediately connected to the ground. But, as soon as it autonomously obtains the ground connection, the mail is uploaded.

One of the most powerful features of this new set of architectures is that they can provide interspacecraft communication through the CSOC networks. This feature enables coordinated measurement science for observing in-space events such as solar flares or gamma-ray bursts. It also enables more team scientists to be plugged-into the spacecraft and instruments simultaneously.

Public outreach can be amplified by extending the Internet into space. The public can observe real time or near real time data by accessing mission web sites set up for that purpose. In some cases it will be possible for the public to safely operate equipment on-board a spacecraft. It would be an advantage to a mission to implement networking features that encourage the public to get involved in the mission's science.

The very high-rate RF subsystems discussed will enable the present assets to stay in service quite a bit longer. However, if the mission count really does increase – because we have greatly reduced the costs in implementing them – then adding to the ground network will be cheaper with concepts like the MAGS. Ka-band systems are expected to cost less due to the extensive design and production work done on them in the commercial sector.

4. Acknowledgements

I would like to thank the CSOC proposal and implementation teams for their support of the concepts for Internet in-space with IP to the space-borne instrument. In particular Scott Sawyer, Wendell Chun, Dave Beering, Martin Skudlarek, Rex Pendley, Frank Breshears, Charlie Lieder, Dave McGill, Bill Lynch, John Nelson, Fred Messing as well as others all helped in the formulation of the concepts,

often by playing the devil's advocate. I would also like to recognize the support given by management. Joel Porter and Rich Schell were the first to embrace the concepts and Ken Asbury helped tremendously by obtaining more outside expertise. Leroy Hall, while still somewhat skeptical, supported the concepts and activities completely.

5. REFERENCES

[1] "Section 4, Space/Ground Trades", *Consolidated Space Operations Contract Architecture Baseline,* CSOC document, December 1998.

[2] "Appendix C, Candidates For Spacecraft / Ground Tradeoffs By Functional Area", *Consolidated Space Operations Contract Architecture Baseline,* CSOC document, December 1998.

[3] Jeff Hayden, "Telecommunications for the CSOC, an Internet Interface to NASA Satellites", *1999 Second Annual International Symposium On Advanced Radio Technologies*, September 8-10, 1999

6. BIOGRAPHY

***Jeff Hayden** recently retired as an aerospace systems engineer for Lockheed Martin Astronautics in Denver. He recently worked on NASA's network design for the CSOC program. His concepts will be used to implementing Internet Protocols at the science instrument and on-board the spacecraft. He described new spacecraft architectures that would operate in an Internet environment. His Internet concepts are now baselined into the CSOC program's future infrastructure. Mr. Hayden has also performed initial spacecraft system designs for Stardust, Genesis, and Space Based Laser. Jeff's original expertise was as an instrument designer. He designed miniature mass spectrometers for Aerobee sounding rockets and for the Atmosphere Explorer C, D, and E satellites back in the sixties for the University of Minnesota. He designed the prototype for and leant extensive (2 years) consultation to the vendor for the Upper Atmosphere Mass Spectrometer for the Viking missions in the early '70's. He spent 2 years with a medical implantables company and designed a valve for an implantable artificial bladder sphincter in the mid '70's. While at Lockheed Martin, he designed the systems for Net Flux Radiometer for Galileo Probe and for the Gamma Ray Spectrometer for Mars Observer.*