THE ART OF INTERNATIONAL SPACE STATION TELEMETRY BANDWIDTH MANAGEMENT

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ABSTRACT

The technicalities of sharing telemetry bandwidth have been addressed in design and specification for the builders of the International Space Station.

But success in sharing bandwidth comes from building relationships, documenting guidelines, negotiating, understanding human nature, peer review and willingness to participate in an evolving process.

The station, 240 miles above Earth, moves through space at 17,000 mph, has its mass added to by humans and machines, regularly docks with visiting spacecraft, has year-round residents, and communicates with space agencies around the globe.

Each new module -- with associated computers, multiplexers, and communications buses -- creates additional telemetry demands.

KEY WORDS

documented guidelines, format over-subscription, multiple users, sharing bandwidth

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How data flows from the International Space Station to ground. Fully assembled, the international Space Station will house thousands of sensors and mechanical devices that feed telemetry data to hundreds of multiplexing computers. The computers transmit the data to the resident crew and to ground control in Houston. Vehicle operation is a coalition of humans, software and machines.

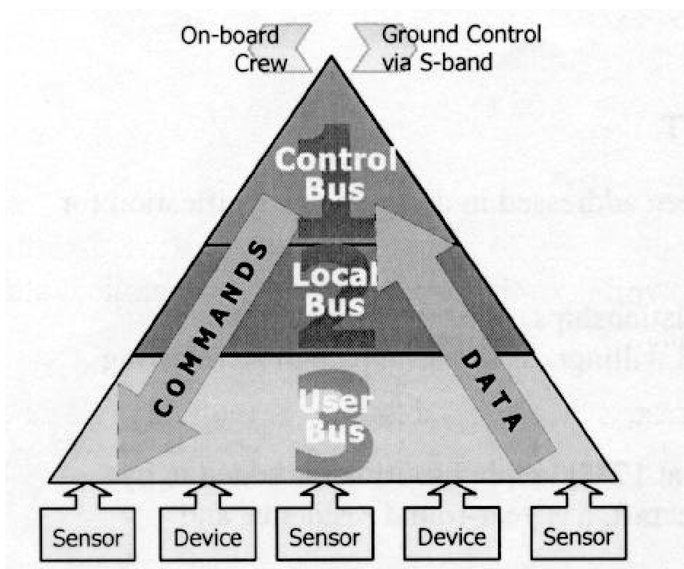
Before assembly is complete, the act of constructing the station requires systematic reconfiguration of telemetry assets to meet the objectives of each flight. Each new module -- with associated computers, multiplexers/demultiplexers (MDMs), and communications buses -- creates additional telemetry demands.

This paper covers ted telemetry requirements associated with the various subsystems, such as electrical power and environmental systems, that oversee the health and well being of the station. Data that supports robotics activities is included, but payload data and audio/video downlinks are not.

A hierarchical architecture, shown at left, insures that data flows up from Tier 3, through Tier 2, and finally to the Tier 1 communications and control processor. The architecture is based on Mil-Std-1553B protocols. When data reaches the top tier, it is transmitted to the crew's portable computer system and to the ground in recurring cycles via satellite network.

The 1553B protocol dictates that only one processor on a bus is the controller; other processors are treated as remote terminals. Bus controllers can simultaneously serve as remote terminals on a second bus.

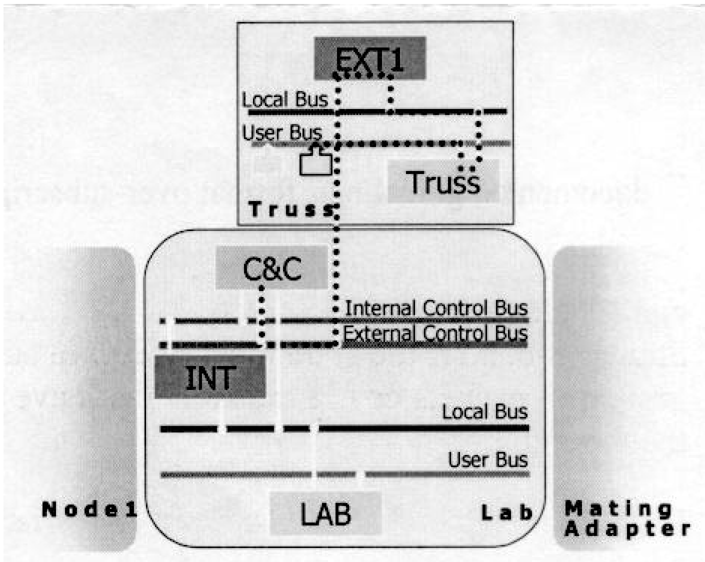
Bus controllers request data from remote terminals and maintain timing by broadcasting synchronization signals 10 times a second. Data for downlink is collected from remote terminals at 0.1 Hz, 1.0 Hz or 10 Hz, depending on the nature of the data.

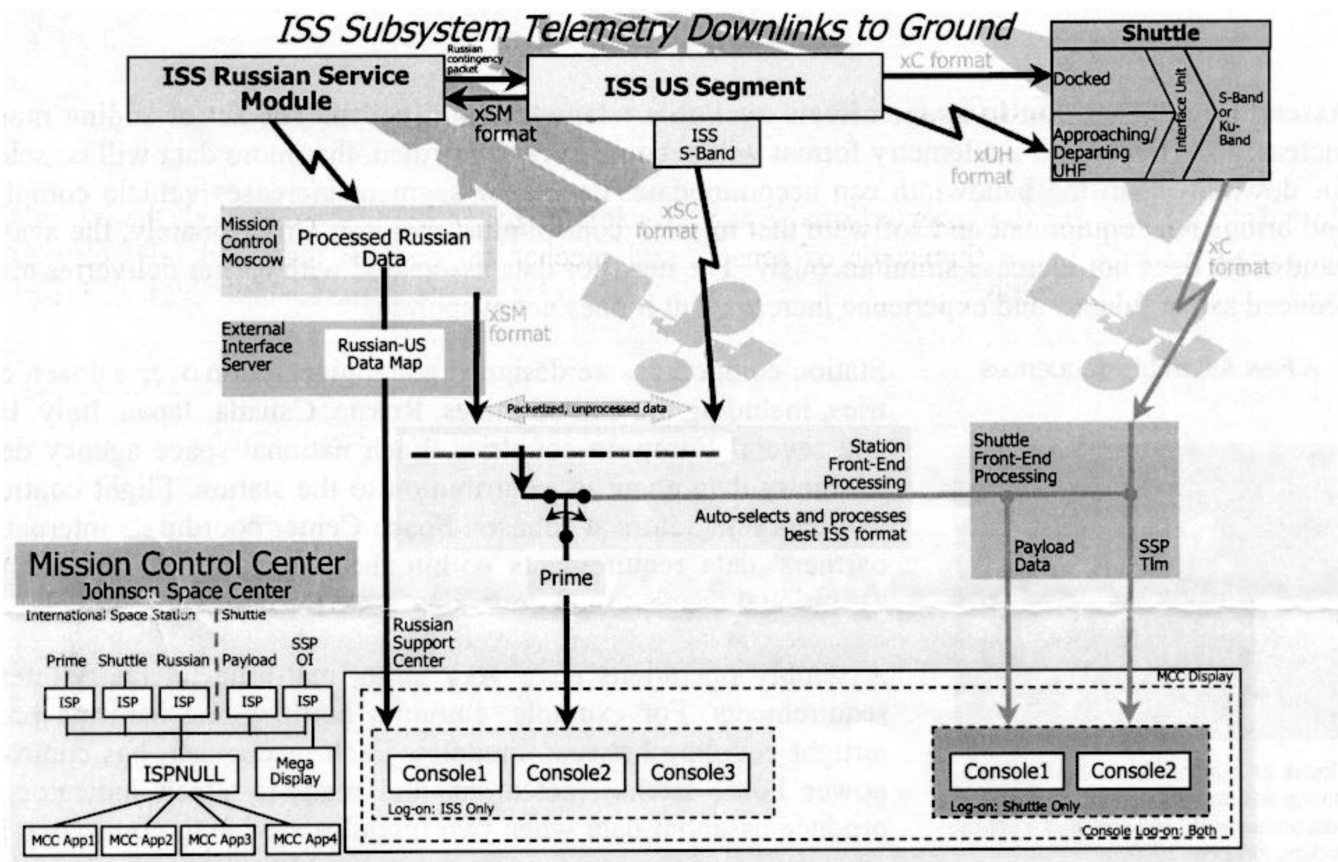


Tiered Architecture All computers in the tiered architecture are multiplexers; they can receive and send multiple streams of data. The computers on Tier 1, the Control Bus, provide both crew and ground control a single point of interface to the on-board network. Tier 2, the Local Bus, handles subsystem applications. Tier 3. the User Bus, provides processing for thousands of sensors and device interfaces.

Physical layout. When computers are connected to more than one 15 53B bus, (which can serve one or more modules of the space station), the tiered architecture is not obvious. The abbreviated example at right shows data collected, via a *user bus*, from a sensor by a computer located in the initial truss, which acts as a junction for 11 other trusses. Processor *Truss* transmits the data to processor *EXT1* via a *local bus*, which then transmits it to the Tier I processor *C&C* (command and control) in the Lab module via a *control bus*. Processors *INT* and *LAB* do not participate in this transaction.

Downlink options. Flight controllers, who are specialists in specific subsystems, choose the data that the ground control will be able to view. The following downlink options and their varied technical attributes help clarify both expected and contingency operations.





Station-to-ground via S-band, called the *SC* telemetry format, is the preferred format for recurring data that is closely monitored. It is utilized when the station has line of sight to TDRSS satellites, approximately 60-70 minutes, of every 90-minute revolution. This format has three packets; each designated to carry different types of operational data.

Additional formats, designated for other downlinks, are populated with data appropriate for each format's operational concept. These formats carry smaller amounts of data than the *SC* formats and may have slower transmission rates; consequently, flight controllers must use operational discretion in selecting data.

For example, the **station-through-shuttle-communications-systems-to-ground** (*C* format) downlink can be used when the station's S-band is not available but the shuttle is docked to the station. A **station-to-ground via the Russian service module** (*SM* format) link can be implemented when specific, pre-defined conditions are encountered. The **station-to-approaching/ departing/ docking shuttle** (*UH* format) downlink carries data for close operations of the two vehicles. Mighty Mouse, a format associated with an earlier communications computer, is available if the multiple redundancies of its successor controllers fail. *Mighty Mouse* can be carried on a bus reconnected to Station S-band or jumpered to Shuttle S-band if the shuttle is present. In addition, data stored in on-board computers can be dumped to ground in packets or file transfers that have pre-emption relationships with the other packets that utilize the S-band link.

Flight controllers and data integration teams must work together to get appropriate data into each format for each assembly flight.

Assembling the station in space affects available telemetry bandwidth. The act of adding modules increases the likelihood a telemetry format will become over-subscribed, that more data will be selected for downlink than the bandwidth can accommodate. Each new segment increases vehicle complexity and brings new equipment and software that mission control must monitor. Unfortunately, the available bandwidth does not increase simultaneously. The need for data associated with earlier deliveries may be reduced as confidence and experience increase, but it does not evaporate.

Station components are designed and engineered in over a dozen countries, including the United States, Russia, Canada, Japan, Italy, Brazil and several European countries. Each national space agency desires telemetry data about its contribution to the station. Flight controllers and data integrators at Johnson Space Center coordinate international partners' data requirements within the boundaries of the telemetry operational concepts and governing State Department protocols.

Assembly operations have very large, real-time telemetry-intensive requirements. For example, common berthing mechanisms provide airtight coupling between modules. Each mechanism has controllers, power bolts, latches, actuators, and ready-to-attach indicators that produce essential data when two modules are being connected. Even after the berthing operation is complete and the demand for real-time data is lessened for these devices, ground controllers periodically need telemetry data that reflects the status of the connection devices.

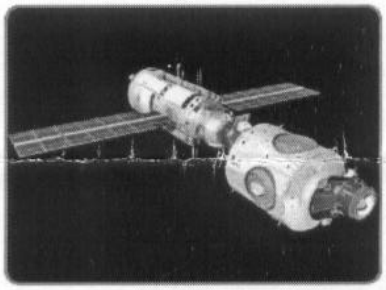
Robotic construction devices, such as the Mobile Transporter that provides mobility between work sites on the trusses and moves payloads across the station, produce large amounts of data for on-boardoperators and mission control. They are monitored even when not in operation to make sure there is no unplanned, inadvertent motion.

New on-orbit equipment residing within a module, such as a battery or an assembly of valves, is accompanied by a demand for data about it. Activation and checkout data confirms that a device works as expected in all the situations it may encounter. As operational confidence and experience build, the demand for data about the device during typical subsequent operations is reduced but not eliminated.

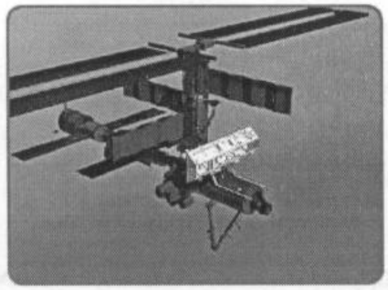
The flight controller specialists who manage and monitor each subsystem need data unique to their particular disciplines. No subsystem has the luxury of owning a format for its exclusive use. With experience, the amount of data about previously installed equipment can be re-examined and perhaps reduced.

But the continuing reality is that downlinked bandwidth is shared by multiple users.

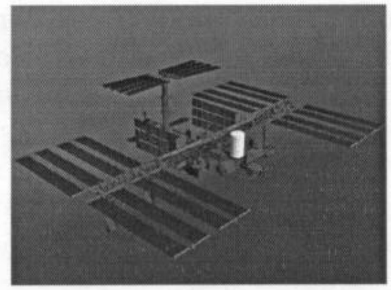
A Few Assembly Sequences



Flight 2A launched Node 1 (Unity) with mating adapters that connect US and Russian elements and provided a Shuttle docking location; 2000.



Flight 8A delivers the center segment of the 300-foot truss that will be attached to the U.S. Lab; 2001.



Flight UF7 shows the Centrifuge Accommodation Module, a facility to control gravity for research activities; 2006.

Pre-flight data production. Data integration occurs in pre-flight production cycles. The developers of new products for the station - which could be hardware, software or firmware -- provide computer files that identify all potential telemetry data that could be collected about their products. From that universe of potential telemetry, flight controllers select the data they need to accomplish their part of each assembly flight. The engineering community reviews the selections and recommends appropriate changes.

One example is the application software that controls the thermal control system, which maintains Space Station equipment and payloads within their required temperature ranges. The thermal control system has components inside and outside the vehicle.

To monitor external equipment, which includes motorized valve assemblies, flight controllers may choose to include the switch status of external valve modules in the telemetry downlink. In contrast, they could choose to rely on temperature data from the same area of the vehicle and *infer* the switch status of the assemblies. When necessary, they can command a specific assembly switch to a specific state.

Data production cycles. From the point of view of operations personnel, a typical production cycle runs about four weeks. The work to be accomplished during the cycle is defined by the software maturity levels of key computer software and the objectives of the assembly sequences.

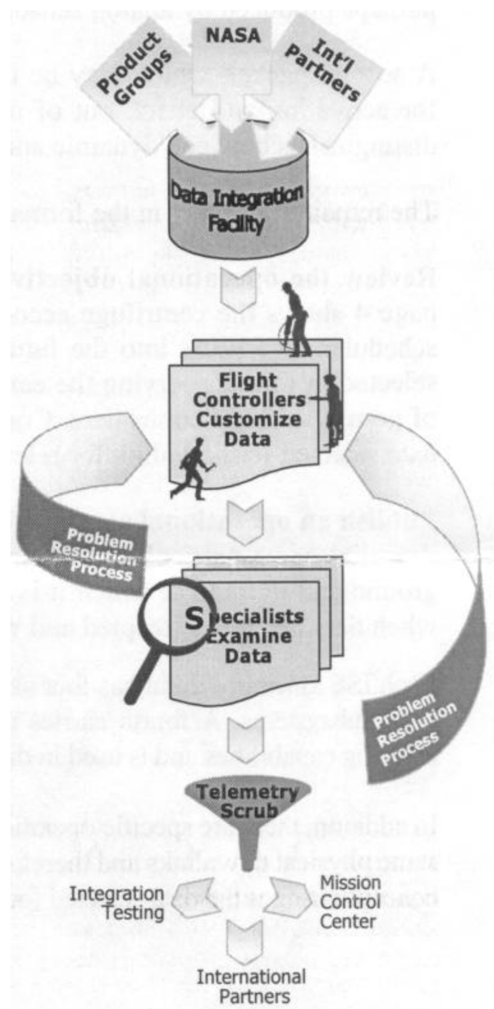
During the cycle, station flight controllers customize telemetry data for use in mission control, based on their understanding of the product, the station and operational objectives.

Reducing data in the downlink. When telemetry formats are oversubscribed, a scrub goes into effect to reduce the data selected for cyclic downlink. This process involves both methodology and face -to-face negotiation with flight controllers; details are in the final section of this paper.

Data integration. Teams of specialists examine the results of the flight controllers' production cycle work to identify and correct any problems. Data specialists examine the data from a pure database point of view: "Does each field have the correct number of characters?" "Are they in the correct order?"

Assembly sequence specialists look at the work from a specific flight point of view: "Does the data support pre-flight hardware, software and integration testing?" "During flight, can the operational objectives be met?"

Data Integration Production Cycle



Any problems uncovered are documented, researched and submitted to a succession of boards, who determine if the problem should be corrected immediately or if a workaround is appropriate.

The data files are then available to testing organizations, international partners, and mission control.

Start the scrub before the telemetry data is selected. Downlinking only the data that flight controllers need, and no more, can cause hard feelings and product rework if data is reduced at a point in flight preparation when reconsideration cannot be accommodated. To avoid that scenario, several pre-data integration steps are taken.

Develop generic guidelines. Independent of specific flight objectives, generic guidelines based on link-to-ground, preemption relationships and word rates tell flight controllers where broad categories of data should be placed for downlink. These guidelines apply to all flights.

The preferred format (*SC*) consists of three packets, each with 1.0 Hz and 0.1 Hz word rate capabilities. Based on the packets' pre-emptive relationship with each other as well as other contingency packets, generic guidelines define the general characteristics of the data designated for each packet. After the appropriate packet is selected, a second guideline defines the characteristics of data selected for specific word rates.

Following the generic guidelines produces these results: essential health-of-the-station data is placed in a packet that cannot be preempted by any other packet. Within that essential packet, dynamic status information about the on-board processors is downlinked at 1.0 Hz. Data that is relatively more static, perhaps produced by analog sensors, has a specified 0.1 Hz rate.

A second packet, which may be temporarily preempted in specific situations, is the designated packet for activation and check out of new equipment, a planned event. The same word rate guideline that distinguishes between dynamic and static data applies to this packet.

The remaining packet in the format has yet a third set of operational guidelines.

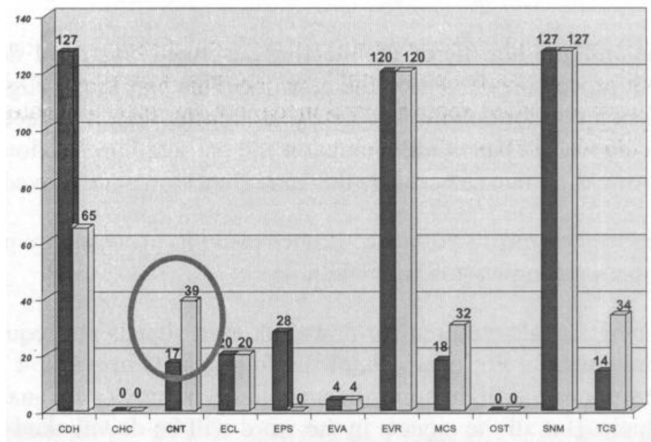
Review the operational objectives of each relevant ISS assembly sequence. The right-hand image on the previous page shows the centrifuge accommodation module added to the vehicle in assembly sequence UF7, scheduled five years into the future from the time this paper was written. If data for the module was selected in formats serving the earlier flight 8A, it would take up valuable room in the downlink but be of no use to flight controllers. Consequently, analysts assigned to each assembly sequence examine the data selected for downlink for relevance to the goals of each flight. Irrelevant data is deleted.

Publish an operational concept for each telemetry format. The act of selecting ISS subsystem data for downlink via a particular telemetry format determines the communications path that carries the data to ground and the rate at which it is transmitted. It also determines when data is available in the MCC-H, when data can be interrupted and when it can interrupt.

Each ISS assembly flight has four assigned telemetry formats. Three provide information about the health of on-orbit subsystems. A fourth carries data between the station and the shuttle. Each format has different data-carrying capabilities and is used in different operational scenarios.

In addition, there are specific operational scenarios that initiate the use of contingency packets that may use the same physical downlinks and therefore have an effect on the assigned formats. Clarifying a format's operational concept changes the data selected for downlink.

For example, the chart to the right shows how the number of words selected by flight controllers responsible for vehicle communications and tracking (CNT) changed. The dark bar shows the number of data words they selected when the format was characterized as a general back-up format. The lighter bar shows the number selected when the format was designated for use as an S-band recovery format.



Coordinate with International Partners. NASA meets regularly with international partners to develop telemetry format strategies for their data. Station modules provided by Nippon Aeronautical and Space Development Agency (NASDA) have their own computer network that interfaces to the 1553 bus network to downlink telemetry data. Using documented generic guidelines and operational concepts, NASDA data specialists were able to appropriately assign thousands of individual signals to specific packets and word rates two years before their modules will be added to the station.

Analyze the bandwidth. Bandwidth is managed in 16-bit words. The carrying capacity of a downlink determines the number of words that can be placed in a format. Reviewing the number of data words in each format takes place in multiple steps. First, a bandwidth analysis report calculates the percentage utilization of each packet in each format. The excerpt below shows the percentage utilization of 1.0 Hz words in the Essential Packet in the fonnat called 10SC. This report identifies packets that are over-subscribed; the packet shown is 89% full. More data could be downlinked in this packet if necessary.

Telemetry Bandwith Analysis
Wed Jan 24 12:31:07 2001
Cycle 21 Pass 1
Format 10SC Essential Packet 1.0 Hz Words

Flight Controller Discipline	Words Available	Words Selected	Bits Selected	Utilization % Words
CDH		440	6888	19.30
CHC		0	0	0
CNT		153	2013	6.71
ECL		76	940	3.33
EPS		88	1198	3.28
EVA		4	64	.18
EVR		824	11240	30.81
MCS		230	3551	9.73
OST		0	16	.04
SNM		1	1844	5.05
TCS		126	1327	4.52
Total	**2280**	**2045**	**29081**	**89.69**

For oversubscribed formats, a more detailed report, showing every data word selected for downlink, accompanied by its ops name, is produced. The sample below shows four signals that are part of a single data word with their operations names. The signals shown belong to the data handling discipline and are downlinked to ground when flight controllers are setting up a memory dump of the multiplexing computer in the airlock. Analysts use this report, which may contain more than 60,000 line items, to identify data words that are candidates for a lower transmission rate or perhaps deletion.

Format Name	RATE	Word Unique Identifier	Engineering Name	OWNER	Signal Unique Identifier	OPS Name
10C	1	ALDS15MD0001L	FMT STATUS/FRAME COUNT	CDH	ALDS15MD4347J	AL_MDM_Loss_Of_Sync
10C	1	ALDS15MD0001L	FMT STATUS/FRAME COUNT	CDH	ALDS15MD4353J	AL_MDM_Frame_Cnt
10C	1	ALDS15MD0001L	FMT STATUS/FRAME COUNT	CDH	ALDS15MD5100J	AL_MDM_Dump_Pipe_Open
10C	1	ALDS15MD0001L	FMT STATUS/FRAME COUNT	CDH	ALDS15MD5101J	AL_MDM_Source_File_Name_Set

The multiple-bus, tiered architecture described on page I determines the rate at which data is acquired from processors served by the network. This may cause flight controllers to inadvertently select a transmission rate for downlinked data that is faster than it collected. A third, computer-augmented step in reducing wasted bandwidth compares the on-board acquisition rate of each processor with the downlinked transmission rate selected by humans. Data words are moved to lower-rate packets as appropriate.

Reduce wasted bandwidth. Proper packing of words by product designers conserves bandwidth. Improper packing wastes bandwidth.

Placing signals required for downlink with signals not required for downlink in the same word is poor word packing. For example, of the four signals in a 16-bit word like the report example shown above, the responsible flight controllers could deem only one signal should be included in cyclic data about the vehicle. But all the signals in the word will be downlinked in order get the one required signal, even if all are not used.

Another form of improper word packing includes placing a single, one-bit signal in a 16-bit word, wasting 15 bits of bandwidth.

Word packing should be accomplished with an understanding of the end-user's operational objectives and constraints.

Use operational analysis to reveal inappropriately downlinked data. Some subsystems do not function in a manner that supports downlinking data about them in a recurring packet. For example, ground control can utilize data produced by accelerometers and strain gages for insight into the station's structural response during dynamic events, such as shuttle docking/ undocking. But, the data is only available via a data dump from the processor that controls the subsystem; it is impossible to gather the information in real-time, cyclic data.

Provide meaningful names. The meaning of data words should be self-evident. Thoughtful naming distinguishes one data item from a multitude of similar data items. An example is a bit called "multiplexer/ demultiplexer self-diagnostic bit." On the surface, it appears to be an item that could be scrubbed if its format were oversubscribed. Further investigation, however, revealed that the bit, when set, indicates that a processor is totally unavailable to do its assigned tasks because it is diagnosing its own processing problems, very important information for the crew and to mission control.

Communicate regularly. The constraints of bandwidth management may be technological, but the solutions lie in uniquely human endeavors. Clear communication of expectations is mandatory. Flight controllers and data specialists meet regularly on telemetry issues, including production cycle kick-off meetings, weekly update meetings, and special scrub meetings about oversubscribed formats.

Stakeholder participation in operational concept development and implementation encourages ownership of the of the bandwidth management problem. When all parties participate, the chances of success are increased and the quality of long-term solutions is improved.

For partners not co-located, regular technical exchange meetings and teleconferences are both necessary to maintain good communication. Cultural differences, which can exist within a single organization as well as separate countries, are barriers to clear communication. National languages, time zones, multi-partner coordination complicate working relationships. To overcome differences in language and expectations, the goal should be solid working relationships at the lowest practical organizational level.

Establish a checklist. Flight controllers are the acknowledged experts in their disciplines. But data specialists, in the interest of effective bandwidth management, ask hard questions of the flight controllers. A useful tool is a repeatable, rigorous, published checklist of questions to aid in the standardization of telemetry selections for specific formats. Some examples:

"What would you do differently if you got the data 10 seconds later?"
"What would you do if you got the data in a large data dump rather than cyclically?"
"What would you do if you didn't get the data at all?"

Flight Controller Disciplines

Command and Data Handling (CDH)	Extravehicular Activities (ERA)
Crew Health Care Systems (CHC)	Extravehicular Robotics (EVR)
Communications and Tracking (CNT)	Motion Control Systems (MCS)
Environmental Control and Life Support System (ECL)	Onboard Short-Term Planner (OST)
Electronic Power Systems (EPS)	Structures and Mechanisms (SNM)
	Thermal Control Systems (TCS)

Both parties in the negotiations appreciate human nature as well as the constraints of their respective jobs. Flight controllers understand the pressure to treat bandwidth as a precious resource. And data specialists understand that lack of experience with a subsystem component breeds a temporary desire for more data about it.

Cultivate teamwork. The organization that manages ISS telemetry bandwidth intentionally has team in its name: International Space Station Command and Telemetry Team (ICATT). The organization has a logo that includes the flags of the international partners. The logo is distributed freely among the international partners to further encourage identification with the ICATT organization.

Managing the production of commands and telemetry on this scale cannot be accomplished via directives from a single source of authority. Rather, successful methodologies are communicated and implemented horizontally. Flexibility is the watchword. Meeting operational objectives is only possible in an environment that seeks and values the experience and observations of all members.

Conclusion. Effective bandwidth management for multiple users of the international space station is an evolving process influenced by technology, international events and a growing track record. Success depends on many factors, including:

- guidelines for placing data in the appropriate packet at the appropriate speed.
- clearly documented operational concepts for telemetry formats.
- useful tools for analysis of bandwidth both quantitatively and operationally.
- documented processes for resolving data acquisition issues.
- willingness to ask experts fundamental questions about their areas of expertise.
- teamwork from all participants.

Glossary

x (page 3)	represents a numerical designation that is part of each format's name
Truss, *EXT1*, *C&C*, *INT*, *LAB* (page 2)	abbreviated names of processors on the station
scrub (pages 5, 6, 8)	[Slang] to cancel, abandon; or drop

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