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DATA COMPRESSION - THE END-TO-END INFORMATION SYSTEMS PERSPECTIVE FOR NASA SPACE SCIENCE MISSIONS

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Abstract. The unique characteristics of compressed data have important implications to the design of space science data systems, science applications, and data compression techniques. The sequential nature or data dependence between each of the sample values within a block of compressed data introduces an error multiplication/propagation factor which compounds the effects of communication errors. The data communication characteristics of the on-board data acquisition, storage and telecommunication channels may influence the size of the compressed blocks and the frequency of included re-initialization points. The organization (i.e. size and structure) of the compressed data are continually changing depending on the entropy of the input data. This also results in a variable output rate from the instrument which may require buffering to interface with the spacecraft data system. On the ground, there exist key trade-off issues associated with the distribution and management of the science data products when data compression techniques are applied in order to alleviate the constraints imposed by ground communication bandwidth and data storage capacity.

Missions that anticipate utilizing data compression could improve their information throughput efficiency by influencing sensor and instrument design that are synergistic with the spacecraft data acquisition and data management schemes, the science application requirements (including quick look data analysis), and characteristics of the data collection and downlink communication channels. In summary, data compression, its application and effects, must be understood in the context of an end-to-end information system.

1. Introduction

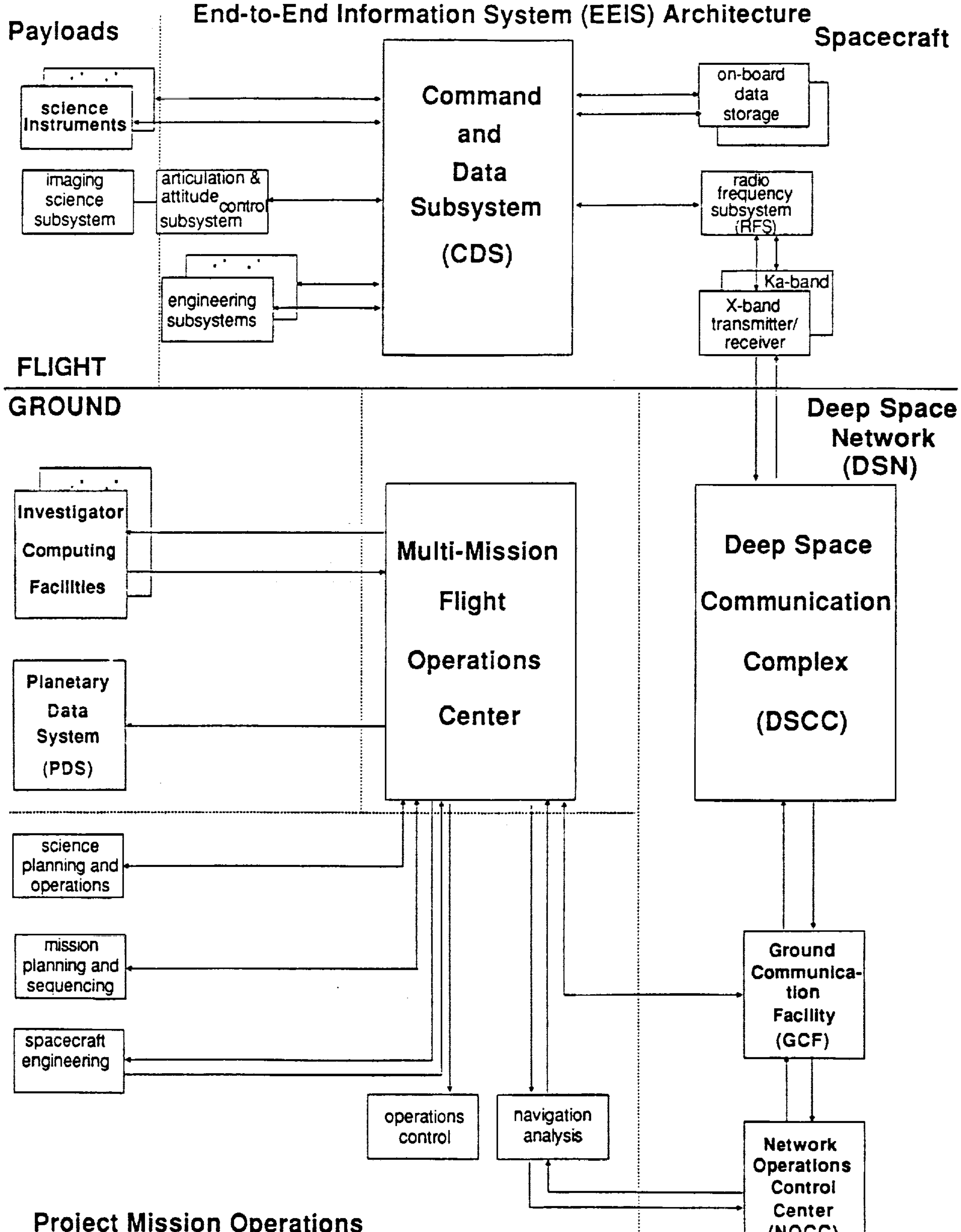
This paper gives an overview on the architecture of the end-to-end information system (EEIS) for NASA planetary missions, its major constraints, and the effects on the system due to the application of data compression techniques. Issues surrounding data compression cannot be viewed as technological issues alone, nor can they be confined to the elements where compression and/or decompression take place. For a NASA planetary mission, data compression has profound implications to science, mission design, flight and ground data systems, and mission operations. It is believed that the application of data compression as a technology onto space missions environment must take into account its propagating effects on elements throughout the EEIS. As such, a system engineering perspective is crucial to the successful implementation of a system architecture using data compression.

2. Architectural Overview of the End-to-End Space Science Data System

The End-to-End Information System (EEIS) for a NASA planetary mission can be viewed as a set of functions, distributed throughout the flight and ground systems that operate cooperatively to collect, transport, process, store, and analyze the data and information in the mission. Functionally, the EEIS can be decomposed into two processes: a downlink process and a uplink process. Architecturally, the EEIS consists of the following key physical components (Refer to Figure 1):

Figure 1

End-to-End Information System (EEIS) Architecture



Flight Elements -

Science instruments
Command and Data Subsystem (CDS) including the on-board mass storage
Radio Frequency Subsystem (RFS) including its transmitters

Ground Elements -

Deep Space Network (DSN)
The Multi-Mission Flight Operations Center at JPL
Project-specific Mission Operations Elements:
-- Science planning and operations
-- Mission planning
-- Scheduling and sequencing
-- Spacecraft engineering
-- Operations control
-- Navigation analysis
Planetary Data System (PDS)

2.1 Downlink Description

The downlink process begins at each science instrument or spacecraft engineering subsystem acquiring science data and/or engineering data. The various instruments and subsystems will concurrently output its data in the form of CCSDS source packets to the CDS. All data packets will be assembled by the CDS into CCSDS transfer frames for storing on-board before the transmission via the downlink channel provided by the Deep Space Network (DSN).

On the ground, the DSN Ground Communication Facility (GCF) is responsible for delivering the received data at the tracking stations, i.e. the Deep Space Communication Complexes (DSCC), to the Multi-Mission Flight Operations Center and DSN Network Operations Control Center (NOCC) at JPL. At the Multi-Mission Flight Operations Center, spacecraft engineering data and instrument engineering data are processed for spacecraft and instrument health monitoring. Furthermore, science data, in particular the imaging data, will be processed for science analysis in support of science and mission operations. The DSN NOCC will perform radiometric data conditioning, VLBI correlation, and generate earth rotation calibration information. It also has the responsibility for monitoring and assessing the performance of each DSCC. The facilities, tools, and data provided the Multi-Mission Flight Operations Center and NOCC will be used by the flight project-specific mission operations elements such as science planning and operations, mission planning, spacecraft engineering, navigation analysis, and operations control to perform downlink-related analysis functions. During the operational phase, the various science teams will access the science data and ancillary data to perform science analysis from their home facilities. The science data, ancillary data, and associated engineering data generated and maintained by the Multi-Mission Flight Operations Center will eventually be transferred to and archived at the Planetary Data System (PDS) for access by the general planetary science community.

2.2 Uplink Description

The uplink process begins with the development of a long term mission operations plan and a science planning guide for each mission phase or key subphase based on the mission plan. These long term plans will then be used to generate a set of short term plans such as a navigation plan, a conflict-free science plan, and an integrated mission timeline. All these planning activities are performed by the project-specific mission operations elements, i.e. science planning and operations, mission planning, spacecraft engineering, and navigation analysis, in a coordinated fashion using the data system services provided by the JPL Multi-Mission Flight Operations Center. The sequences for a mission phase or subphase will then be developed. The end result of the sequence generation activity is the weekly command load ready for uplink. To deliver the command load to the spacecraft from JPL via DSN GCF and DSCC, a set of CCSDS telecommand operations procedures will be executed at both the Multi-Mission Flight Operations Center and the CDS to ensure successful delivery and accountability.

On the spacecraft, the CDS will manage the execution of sequences by the spacecraft subsystems and deliver the commands to the instruments for execution. As part of the uplink process, the CDS is also responsible for on-board control of all flight elements in response to certain natural events and fault protection in response to significant anomaly conditions.

3. General Constraints of an End-to-End Information System

In general, the data and information system for a planetary mission is more constrained than its counterpart for an earth mission. In particular, on the flight side, the primary constraints such as power, mass, thermal control, and positioning for the planetary missions have direct effect on the design of the data systems on the spacecraft and instruments. To the science data collection process, the results is limitations on the data rate, processing power, physical memory size, on-board data storage capacity, and local communication bandwidth.

The quantity and quality of data transmitted over the space-to-ground communication channel are limited by the telecommunication link performance. For planetary missions, the distance between the spacecraft and the earth as well as transmitter power, weather conditions, background noise from target body, and other factors is a very important parameter for the determination of allowable data rates and error rates. In addition, from the mission operations perspective, the availability of receiver stations on the ground, in terms of their tracking time and relative geometry to the spacecraft, is also a constraint considering the fact that the ground stations of Deep Space Network (DSN) as a multi-mission resource have always been over-subscribed.

On the ground, as the computer technology advances there has been significant increase in demands on the ground processing and archiving systems. Pertinent to planetary missions, two chief demand-driven constraints are observed:

(1) The timely delivery of science data products in large volumes to a community of geographically distributed investigators is still considered a difficult task due to the limited bandwidth of the ground communication networks.

(2) As more remote sensing data become available to the general planetary science community, the rapid access to science data products in the data archive system is constrained by the need to have prior knowledge about the data formats and information contents (i.e. both in syntax and semantics) about the products.

Data compression as a technology has long been employed in the planetary missions as of the solutions to these constraints in order to maximize science return. In the course of its application, there has been precious lessons learned. The following sections summarize some of our engineering experience in this area.

4. Effects of Data Compression on End-to-End Information System

In general, compressed data has the following characteristics:

(1) Reduced data volume
(2) Asynchronous output data
(3) Variable length data
(4) Increased sensitivity to noise (or transmission errors)

These characteristics have important engineering implications to the EEIS. There are benefits and added complexity to the EEIS. Clearly, benefits gained by the EEIS through the use of data compression are primarily due to general characteristics (1):

Reduce the overall buffer size requirements throughout the breadth of the EEIS

For planetary missions, this is particularly true for those high-rate instruments employing data compression techniques to acquire observation data. Not only the instrument internal buffer size for science read-out data but also the overall telemetry collection buffer size on the spacecraft is reduced. As mentioned in Section 3, since the on-board memory size for planetary missions has always been a constrained resource reducing buffer size through sensor data compression certainly offers a viable approach to getting around this constraint.

Reduce communication data rate requirements

From the data transport perspective, the compressed data also reduces the communication data rate requirements by providing higher entropy in the data. For planetary missions, the beneficiaries are primarily the communication line between the instruments and spacecraft, the space-to-ground link, and ground communication network which carries the data to the ground system where decompression of the data is performed.

In data archive system environment, data in compressed form have been used for product distribution to minimize the medium capacity requirement. The application of compression techniques to generate browse data sets for near real-time distribution to the users has also helped the data archive system to overcome the constraint imposed by the need to have prior knowledge about the data formats and information contents about the products.

Increase coverage and/or resolution of the instruments

To the science investigators, data compression offers the flexibility for the instrument to compact the sensor data by reducing the number of bits required for each sample so that a larger area of coverage can be achieved by the instruments.

Accommodate the tailoring of data products generated for a specific application (through the use of lossy compression).

On the other hand, general characteristics (2), (3), and (4) inevitably add certain complexities to the system:

More stringent communications quality and continuity requirements for transported data

There is a sequential relationship between each of the sample values within a block of compressed data output. This relationship introduces an error multiplication/propagation factor which compounds the effects of communications errors. The error introduced by the communication channel in a sample value may invalidate all the subsequent sample values in the same block. Consequently, more stringent data quality requirements must be levied on the EEIS. For planetary missions, typically the end-to-end bit error rate requirement on compressed data is 1×10^{-6} whereas for uncompressed data (in particular for certain circumstances where the data by their nature possess redundancy) it is 1×10^{-3}.

Added complexity in on-board buffer management due to variations in data compression profiles

As stated in Section 3, local communication bandwidth is also a constraint for spacecraft in planetary mission. The conventional telemetry data collection scheme on the spacecraft for planetary missions can be characterized by a deterministic approach where packets of data generated by the various instruments and spacecraft subsystems are picked up by the spacecraft in a time synchronized manner based on a priori knowledge about the outputs from these instruments and subsystems. This deterministic approach appears to be simple but is problematic to science instruments using data compression for maximizing their data returns. It requires the output data from each source remain constant during a telemetry collection "mode" based on the pre-defined parameters such as data rates, destinations, and packet lengths associated with all the instruments and subsystems during a period of interest. Compressed data, which is non-deterministic and variable in output rates, asynchronous in output timing, and variable in length, certainly does not land itself very well in this conventional telemetry collection environment. To compensate for this problem and make instruments compatible with the deterministic scheme, one of the methods is to include in each instrument a buffer management capability which allows it to match the variable data rates of the output from the compressor to the fixed data collection rate imposed by the spacecraft. However, there are two potential drawbacks in this remedy:

(1) When the output data rate during a pick-up cycle is lower than the scheduled and allocated data rate, filler data must be generated, negating some of the advantages of using data compression mentioned above.

(2) When the output data rate during a pick-up cycle is higher than the scheduled and allocated constant data rate, portion of the data in the instrument buffer will not be picked up by the spacecraft in time for the current cycle. The delayed transfer of bursty data, if persists through subsequent pick-up cycles, may eventually result in buffer overflow and data loss. To control the data loss, one may apply a lossy compression scheme as an option to force the compression ratios to a limit. An alternative is for the instrument to provide buffering capability accommodating long-term averaging of the data rates.

Obviously, in the context of the conventional telemetry data collection scheme, an important instrument design issue is the determination of the optimum fixed data rate as part of scheduling and allocation of on-board resources. It involves the trade-off between acceptable data loss and benefits gained for using compression but reduced because of filler data, and data rate allocation. For example, in order to avoid losing data, the fixed-rate scheme would have to allocate the maximum possible rate, negating the advantage of reducing communication data rate requirements offered by general characteristics (1).

A conclusion one may draw here is that even with a deterministic scheme it is difficult to expect a deterministic knowledge in the completeness of data collection. Under the resource constraints, the data loss will occur and there is no way to predict the amount of data loss.

An alternative to the conventional telemetry data collection scheme would be the data-driven approach which allows each instrument to output its data in variable length at variable rate asynchronously. In this non-deterministic scheme, at least three services must be provided by the spacecraft:

(1) The flight data system of the spacecraft will provide the rate buffering capability.

(2) Given a pool of consumable resources with certain margins allocated to each instrument, the flight data system must be capable of keeping track of the utilization of data rates and other related on-board resources, e.g. memory buffer, by all the instruments.

(3) The flight data system must be sufficiently robust to detect and respond to the "overdrawal" of data rate resource by any instrument.

On the instrument side, data rate is allocated to each instrument not in terms of a fixed, absolute number but in a range which may or may not vary as a function of time. The instrument must be capable of ensuring that its output data rate never exceed the upper bound of the range.

Overhead in uplink sequence development

During mission operations, a challenge encountered in developing the sequences for science data collection is the determination of the output data rate from the instruments using data compression. Assumption has to be made about the average compression ratio. In the case of the data-driven data collection approach, the stochastic property of resource utilization by each instrument and the more dynamic allocation of the collective, pooled resources must be modeled. Both average and worst-case situations will have to be evaluated. The amount of potential data loss as an additional parameter of the model also imposes extra complexity to the ground operations. To the science investigators, more options are available for them to make trade-off between the observation cost and science benefit by considering the competing factors such as data rates, data volumes, and data coverage. On the whole, the overhead in sequence development is caused by the added flexibility in flight offered by the more adaptive data collection design.

Increased computation required on-board and in ground systems

The process of compressing and decompressing data demands additional computations in both the flight and ground systems. Compressor performance must be compatible the readout rate of the sensors. Associated with this are a couple of key design issues:

(1) Location of the compressor - Should the spacecraft provide the compression (especially noiseless compression) as a service to all the instruments requiring compression on their data, or should each instrument contain a compressor as an integrated part of the instrument?

(2) Flexibility of the compressor - Can a flexible, generalized noiseless compressor be designed such that an off-the-shelf product can be available to reduce the development cost of the compressor chips?

5. Conclusions

For the future NASA planetary missions, more extensive application of data compression to the data and information systems seem to be dependent on the resolution of some of the system issues discussed above. There seems to be the need to carry out the following suggestions :

(1) Implementation of a data-driven telemetry collection scheme on the flight data systems.
(2) Extensive use of solid state recorder as rate buffering between the following processes on board:

On-board data collection
On-board data storage
Downlink

(3) Adopt a standard compressor for all NASA flight instruments requiring data compression service.

(4) Use of Reed-Solomon encoding on the downlink channel to minimize the effect of noise on the quality of compressed data.