missions requiring higher injection velocities are flyby missions which should not require two- and three-payload stages. The 1985, 30-day Mars-stopover mission with an outbound Venus swingby requires only 200 fps more ΔV than is available. Any performance gains resulting from engine performance improvements will place this mission within the capabilities of the discussed configurations. Only the 1978 Mars-stopover mission with an outbound Venus swingby and the 1983 Mars-stopover mission with an inbound Venus swingby require configuration II.

Conclusion

The results of this analysis have a significant impact on the necessary systems and technology developments for manned interplanetary missions. Studies based on direct injection techniques[2] indicate that thrust levels higher than 75,000 lb would result in payload gains of 9 to 16% for manned interplanetary missions. These thrust levels could only be obtained by a new engine, parallel engines, or parallel staging developments, used separately or in combination. These developments would require longer lead times and have higher costs than the 75,000-lb-thrust engine development. Any one of these operationally complex developments may require an expensive test program for development. As shown by this analysis, a performance penalty rather than a performance gain may result. The multiorbit injection technique eliminates the need for these developments.

References

[1] Schroeder, R. W., "NERVA—Entering a NEW Phase," *Astronautics and Aeronautics*, Vol. 6, No. 5, May 1968, pp. 42–53.
[2] "Mission Oriented Study of Advanced Nuclear Systems Parameters," Rept. 01977-6025-R0-00, June 1968, TRW Systems.
[3] Johnson, P. F. and Rom, F. E., "Perigee Propulsion for Orbital Launch of Nuclear Rockets," TR R-140, 1962, NASA.
[4] Blanco, V. M. and McCuskey, S. W., *Basic Physics of the Solar System*, Addison-Wesley, Reading, Mass., 1961, p. 178.
[5] Funk, J. and McAdoo, S. F., "Switching Logic and Steering Equations for Multiple Burn Earth Escape Maneuver," Paper presented at Institute of Navigation 1969 National Space Meeting, April 22–24, 1969.
[6] Ross, S., "Mars Stopover Mission Using Venus Swingbys," *Planetary Flight Handbook*, NASA SP-35, Vol. 3, Pt. 6, 1963.

Real-Time Compression and Transmission of Apollo Telemetry Data

BRUCE E. MEIGS*
UNIVAC, Division of Sperry Rand Corporation, Glenn Dale, Md.
AND
LARRY L. STINE†
The MITRE Corporation, Bedford, Mass.

FLIGHT control for NASA manned missions is conducted at the Mission Control Center (MCC) in Houston. Telemetry data from up to 800 sensors in the spacecraft are relayed from the remote tracking sites via the worldwide NASA Communications Network (NASCOM) based at Goddard Space Flight Center to the MCC. Two 2400 bps digital high-speed data (HSD) circuits and one voice bandwidth analog circuit from each site to Houston are provided by the NASCOM network. Up to four telemetry downlinks with bit rates of 51.2 kbps or 72 kbps each are received at the remote site. Presently, by a process of repetitive sample selection, processors at the remote site reformat the data to fit the capacity of the NASCOM circuits. Data compression is an alternative processing technique which will most efficiently use transmission bandwidth and is being considered for the future expansion of telemetry requirements.

Limited results from early Apollo flights indicate that the telemetry data appear to be sufficiently redundant that a data-compression scheme can be used.

The compression technique discussed in this Note is the zero-order predictor whose operation is described as follows. For each sensor output, a tolerance corridor of $\pm K$ (expressed in percent of full-scale range) is established around the first sample y_0 which automatically is considered significant. The next sample y_1 is read in and compared with y_0 as $|y_1 - y_0| < K$. If the inequality is satisfied, y_1 is discarded as redundant and the next sample y_2 is compared with y_0 in the same way. If the inequality is not satisfied, y_1 is output as a significant sample and a new corridor is established around y_1. Then y_2 is compared for $|y_2 - y_1| < K$ and the process continues in like manner. The maximum peak error is $\pm K$. Reconstruction is effected by drawing a straight line of zero slope beginning at each significant sample and continuing until the time of the next significant sample.

The present operational system is described because it provides a standard of comparison for a system using data compression. Problems arising from highly active data and false activity are examined, important considerations of system implementation are identified, and proposed design approaches are described.

Present System

The data flow through the system is as follows. Four PCM telemetry links carry the telemetry data from the Apollo vehicles once they reach Earth orbit. The links are from the Lunar Module (LM), Command and Service Modules (CSM), the Saturn booster third stage (S-IVB) and its Instrumentation Unit (IU). The links are received at whichever remote site is in line-of-sight of the vehicles. The data are decommutated and processed for transmission over the high-speed data circuits of the NASCOM network. Data compression will take place in the Remote Site Data Processor (RSDP) by a modified UNIVAC 642B computer with 65,000 words of core. Reconstruction will take place at Mission Control Houston by the Command Communications and Telemetry System (CCATS) and the Real-Time Computer Complex (RTCC). CCATS has a complex of three UNIVAC 494s, each with 131,000 core and drum storage of 1,310,000 words. The RTCC uses IBM 360-75 computers with 370,000 core and 1,048,000 words of auxiliary storage.

The types of telemetry data are 1) sampled 8-bit and 10-bit coded analog waveforms, 2) events or bilevels, 3) 16- and 26-bit data words from onboard computers (CMC, PGNS, LVDC), and 4) special words. The sampling rates range from 0.5 to 200 samples per second. During Apollo flights, the MCC monitors a total of approximately 1100 of the measurements. All of the measurements represent a remote site input-data rate of approximately 100 kbps. From the remote site to the MCC, a total high-speed line capacity of 4.8 kbps is available. In order to accommodate the wide differences in data rates between the space-to-ground and NASCOM links, two primary methods of data-rate reduction are used. The first method is sample rate reduction. For example, a given

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* Supervisor, System Design, UNIVAC/Apollo.
† Member Technical Staff, The MITRE Corporation.

vehicle measurement may be sampled and telemetered x times a second. The RSDP selects every yth sample for transmission to the MCC. The second method is format switching. At any given time, only a subset of the measurements are transmitted to the MCC. Additional methods are to reduce the measurement accuracy of 10-bit analogs to the eight most significant bits and to restructure the selected bilevel data.

In order to replace the present techniques with data compression, the data must be sufficiently redundant so that, after the addition of all overhead bits, the significant samples can be transmitted over the available NASCOM capacity without intolerable queue delays. The generation rate of significant samples can be varied for analog data by changing the tolerances of the compression algorithm. However, bilevel data is either "on" or "off" and the activity level is not subject to a choice in specification. This is also true for onboard computer data since any bit change is considered significant. The present remote site computer must be capable of performing the data-compression calculations at a rate compatible with the telemetry link input rates. Also, the MCC processors must be able to handle the compacted data. And finally, the flight controllers must be able to work with the data.

Data Redundancy Content Results

The redundancy content for the telemetry data is expressed in terms of a compression ratio which is the ratio of the number of telemetry data samples received and processed by the compression algorithm to the number of significant samples generated by the compression process. Results from a study by the MITRE Corporation[1] indicate that the compression ratios for analog and bilevel data from the CSM compare favorably with the average sample rate-reduction ratios used in the present system.

These compression-ratio results were confirmed by a UNIVAC study which analyzed the SPS burn over Bermuda of the AS-205 flight. Using the minimum tolerance of 1 PCM count (0.39% full scale), a group of 28 CSM analog parameters yielded an average compression ratio of 42.9. However, when one 10 s/s parameter, the outer-skin engine-nozzle temperature, was added to the group the ratio would be reduced to 20.1, even when its tolerance was raised to 12 PCM counts. A close examination of the values of this parameter shows that they are so erratic that the possibility of a faulty sensor in the spacecraft should be considered. If too many of these active sensors are present for long periods of time, total system performance can be seriously limited.

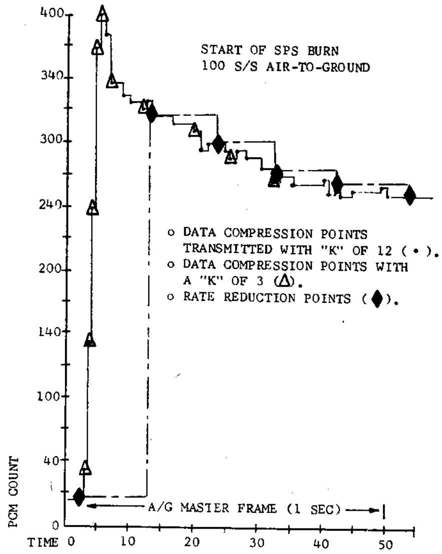

Fig. 1 Engine chamber pressure AS-502.

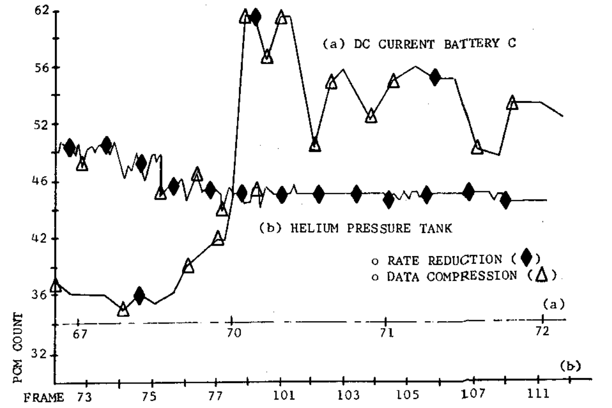

Fig. 2 Comparative results for data compression vs rate reduction.

Figures 1 and 2 detail selected results of a study program developed by UNIVAC to determine parameter representation as transmitted by a data-compression scheme vs rate reduction and to determine meaningful apertures of "K" tolerances.

Figure 1 is a plot of SPO661P "engine chamber pressure" during the early part of an SPS burn over Bermuda during AS-502. The data-compression points using "K" tolerances of 3 PCM counts reflect the sudden rise very accurately. However, the rate-reduction points (dashed line) show a delay of approximately 150 msec in reporting the rise, and the peak value is not accurately reported. Over the interval shown, there were 160 points received and 71 compressed points sent. It is obvious that by using larger "K" tolerances, the number of points sent could be reduced to 10 samples (see Δ points), and the information would still be meaningful.

Figure 2 shows "DC Current Battery C," also at the time of the SPS burn start. Note, here again, that a more accurate representation is given by data-compression points. This parameter was extremely active during the period given; however, in the previous 65 master frames, only 6 nonredundant samples were generated. Rate reduction during the same 65 sec would have sent 65 values. This is a good example of the advantage of redundancy reduction over rate reduction, namely, that only meaningful data is sent by data compression.

Figure 2 shows "Helium Tank Pressure" during a period of little activity. Note that a tolerance of 4 resulted in transmission of only five points during the 15-sec period; whereas rate reduction would have sent 15 points. Because of the data behavior, it may be argued here that rate reduction sent a more representative curve. On the other hand, it also is likely that the variance up to four PCM counts from point-to-point would have little significance to flight controllers.

If we were to assume that flight controllers would have wanted the accuracy afforded by a smaller "K," then we must recognize a problem with data compression that is bound to affect design of an acceptable system. The problem is that adaptive queue control (using variable K's) can result in loss of accuracy for some parameters when others become very active. It is a situation which can be minimized by: 1) Intelligently grouping parameters by their relative activity. If all parameters in a commonly controlled group can be expected to behave in a similar manner, then it is unlikely that any one will "mask" out others in the same group. 2) Filtering wild points.

Overhead Bits which Describe the Sample

Because significant samples are randomly generated and placed in the queue, extra bits must be added to each sample to identify to which measurement the sample belongs, when it was generated, and unless already known, the width of the algorithm corridor. Several different approaches have been considered for implementation in this system. Usually, the use of longer word lengths can simplify processing but reduces the rate at which samples can be emptied from the queue and transmitted over a data circuit of fixed capacity. Shorter, more complex words will increase processing but increase the sample transmission rate.

An additional complication is that most data are presented to the flight controllers on read-over tabular displays. Changes in parameters which occur at a rate faster than once per second would probably not be absorbed by the display viewer. Therefore, the sample should not be sent unless a time plot is used for the reconstruction process and time tag lengths would decrease accordingly.

Queues and Their Control

Significant samples occur randomly whenever a sensor data point falls outside the corridor projection of the zero-order compression algorithm. These samples are stored in a queue which is emptied at a fixed rate according to the available capacity of the NASCOM circuits. Because of the real-time nature of the system and the high-compression ratios, the conflicting requirements for short queues and a low probability of queue overflow must be satisfied.

Assume that each significant sample is described by a 30-bit word and that 4800 bps of HSD transmission capacity is available. Of this capacity, 1393 bps would be used for message overhead, error control, and uncompressed data. Therefore, 3407 bps, or 113 significant samples, could be emptied from the queue every second. To avoid queue overflows, the average activity of the compressed data must be held below this level. One way of doing this is to use a sufficiently wide corridor tolerance for the analog data. Figure 3 shows an estimate of how the average total activity of all the compressed data would vary for different tolerances applied to the analog data. The activity curve can be compared with the "clip level" of the 113 s/s read-out to arrive at an estimate for the expected range of tolerances for the analog data which, for this case, would be between 1% and 3%. This curve also shows the sensitivity of these tolerance ranges to the queue read-out rate.

However, short bursts of highly active data could force the analog-data tolerances to the upper range of acceptable values without preventing the danger of overflow. In this case, a priority list would be used to prevent some measurements from being processed by the compression program. Only significant samples from critical data would be allowed to enter the queue. In some instances, processing would stop completely until the queue length has decreased to a safe level.

Another consideration in the design of the queue and its control techniques is the burst of significant samples which occurs when the compression algorithm for every measurement is initialized. Packed "initiation blocks" are being most favorably considered to satisfy this function.

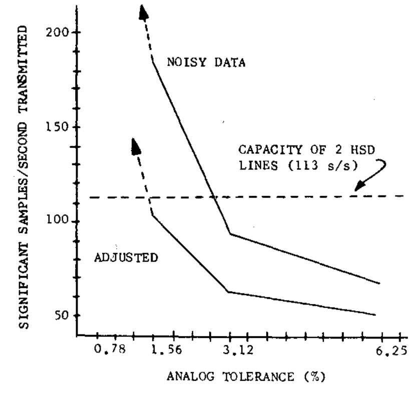

Fig. 3 Total data activity vs analog tolerance.

Error Control Requirements and Techniques

Because compression ratios are so high, it is possible that only one significant sample from a measurement may be generated during an entire pass over a remote site rather than at the present maximum interval of once every ten seconds. An error-control system must be used to guarantee the error-free arrival of each significant sample.

The selected system was a type of hybrid forward-acting and retransmission system. Most communications circuits are characterized by random errors of a few bits and bursts of very high error rates. The forward acting capability of the system will correct at the reception point the random errors. In order to minimize the number of error-control parity bits sent over the circuit, bursts would be handled by an error-detection code which initiates the transmission of a repeat request to the transmission point. Retransmissions due to random errors would be prevented by the forward-acting code but a low probability of accepting bad data would be attained with the use of the error detection code and the retransmission technique. Thus, a high level of transmission reliability can be attained with a low-overhead penalty.

Various schemes are being considered, a Binary Detector Corrector based upon a N-bit Hamming encoding scheme shows much promise being faster than others evaluated. The Zierler-Gorenstein symbol code, Reed-Solomon error detection code as well as BCH error-detection devices have been considered.

Use of Compressed Data by the Flight Controllers

Until a complete system is available for operational simulation, it is difficult to state what reactions will be generated by the flight controllers when presented with compressed data. Depending upon the performance of the system, the presence of varying queue delays, extreme variation in update arrival rate from many per second to once every several minutes, and varying tolerances may or may not be acceptable. If all these characteristics are acceptable, confidence in the system and its method of data processing and presentation will follow as the operational time increases.

Reference

[1] Stine, L. L. and Barrows, J. T., "The Application of Data Compaction to Apollo Flight Control Telemetry Data," MTR-498, Oct. 1967, The MITRE Corp., Bedford, Mass.

An Error-Detecting Test Using Generated Number Sequences

Richard I. Hess*
Logicon Inc., San Pedro, Calif.

Introduction

Before launching a space vehicle or missile it is necessary to somehow ascertain that the onboard program will perform its functions properly. Of particular importance in this regard is the verification of the targeting constants needed for guidance and other flight computations. These constants, typically a few hundred in number, must be computed before liftoff; this is necessary because generation is fairly time-consuming.

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* Member of the Technical Staff; also Part-Time Lecturer in Mathematics, California State College at Dominguez Hills.