DESIGN OF A DATA ACQUISITION SYSTEM BASED ON THE DECOMMUTATION OF AN EMBEDDED ASYNCHRONOUS DATA STREAM WITHOUT PRIMARY AND SECONDARY FRAME SYNCHRONIZATION

Michael A. Kvasnak, James P. Koonmen, and Vivian L. Grajeda
Space Technology Directorate
Phillips Laboratory
Kirtland AFB, NM 87117-6008

ABSTRACT

The use of embedded asynchronous data streams is becoming a popular means of expanding existing telemetry systems and acquiring subsystem data. In such systems, synchronization between the primary and secondary system(s) clocks is usually considered a prerequisite. The Phillips Laboratory has developed a software/hardware approach to the problem of decommutating an embedded asynchronous data stream without primary and secondary frame and clock synchronization. The methodology employed is easily implemented and adapted to many system configurations, and represents a low-cost option in the acquisition of subsystem data. More importantly, the use of such a system greatly reduces the amount of systems integration effort required to incorporate multiple subsystems into a host telemetry system.

INTRODUCTION

Two-phase (liquid/vapor) flow thermal management systems are more efficient than single phase systems, and are therefore of great interest to the space community as a means of reducing spacecraft mass (Best et al 1988, Mahefky 1982). The Air Force's Phillips Laboratory has embarked on an experimental program to investigate the operational performance of a small two-phase flow loop during a seven minute sounding rocket flight. As the first-ever pumped two-phase loop flown in space, the experiment is designed to demonstrate the feasibility of using a liquid/vapor mixture for the cooling of spacecraft components. A similar boiling and condensing thermal management system has been baselined by NASA to provide thermal control on the space station Freedom, and other spacecraft designers are also investigating the advantages (reduced launch mass, increased payload delivery to orbit, greater operational flexibility, etc.) achieved by using this technology.

The Two-Phase Flow in Microgravity Experiment will piggyback into space on a booster provided by Sandia National Laboratories. The experiment will be launched into a suborbital trajectory from the Kauai Test Facility in Hawaii onboard the first STARS booster in the fall of 1991. Although the experiment is the primary payload on the flight, the main objective of the mission is to demonstrate the successful launch and flight of the booster. The Phillips Laboratory was granted free access to the payload volume by the mission organizers, and few restrictions were placed on the utilization of that volume and on the nature of the experiment to be carried into space. In addition, the payload was allocated ten words in the main Pulse Code Modulation (PCM) telemetry stream controlled by the third stage of the booster. Due to the loss of the payload upon reentry into the atmosphere, the experiment relies solely on the booster's telemetry system for all data transmission to the ground station.

The experiment controller inserts the payload data into the designated words in the telemetry stream, each sampled approximately 256 times per second. In order to make accurate measurements of the experiment's performance, Phillips Lab researchers require continuous readings from a minimum of 32 instruments. The temperature, pressure and flow fluctuations being monitored in the experimental loop occur primarily in the 0-10 Hz frequency regime. A hardware and/or software data acquisition system was required to match the unique data requirements of the experiment with the payload's allotted space in the Primary Data Stream.

INTERFACE DESCRIPTION

The high reliance of the payload on the booster telemetry system mandated strict adherence to all payload/booster interface specifications. The actual interface consisted of 10 data words located at various points in the 512 word Primary Data Stream as seen in Figure 1. The telemetry system samples these data words 256 times per second and digitizes the analog (0-5 volt) signal present at the input into an 8 bit digital signal. These 8 bits are then converted to NRZ-L format and transmitted to the ground site.

An embedded asynchronous data stream (EADS) format was employed to condense the 32 instruments into the ten data words dedicated to the experiment. Properly defined, an EADS is a secondary stream which has major frame characteristics and is inserted into a host major frame in a manner which does not allow the prediction of the location of the embedded synchronization information based only on the host format timing (IRIG Standard 106-86 Telemetry Standards, 1987). Specific word positions in the host minor frame are dedicated to the embedded asynchronous format; the subsystem then multiplexes the secondary data stream, along with frame

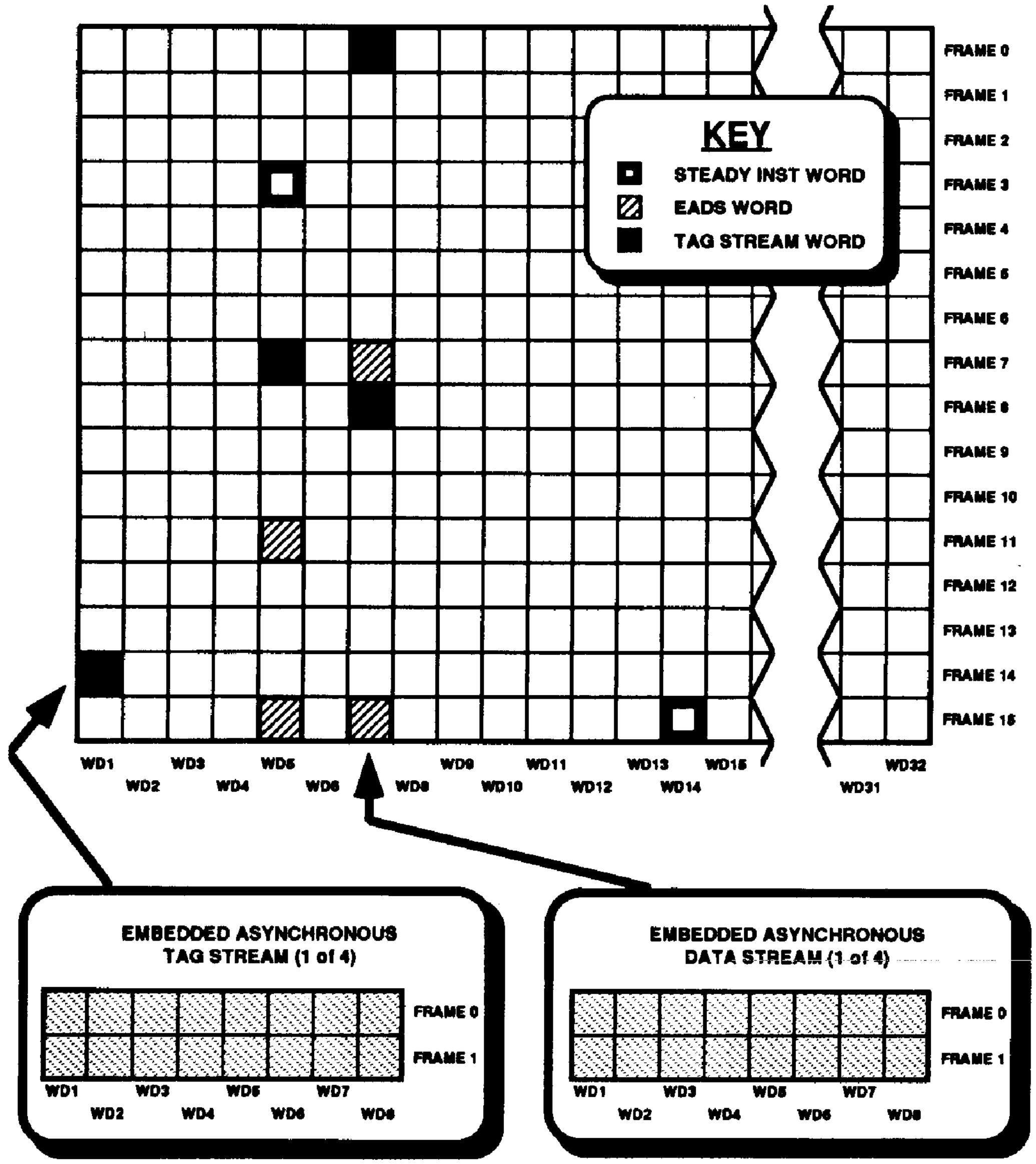

Figure 1. Payload Word Locations In the Primary Data Stream

synchronization information, into those specific word positions. Implicit in the standard use of EADS formats is the understanding that the subsystem knows when its allocated words in the main PCM stream are being sampled. With this knowledge, the subsystem can index through the data words in its secondary stream while that stream is not being sampled by the host telemetry system. Synchronization between the subsystem and the host ensures that only steady, accurate data is sampled and transmitted through the primary PCM stream. Without clock synchronization, data loss will inevitably occur whenever the host telemetry system samples the secondary data stream as it is changing state.

In this specific application, clock synchronization between the payload and the third stage was impossible due to a number of interface design considerations. The impact of data loss due to the lack of access to the Primary Data Stream's clock is significant. No embedded asynchronous data stream will be immune to data loss periods as long as it remains truly asynchronous with the primary stream. The data acquisition boards used to multiplex the instrument data have a settling time of 12 μs. If the multiplexing frequency of the boards is set at 256 Hz (as it was in this application), the plateaus in the multiplexed stream where good data is available will last approximately 3900 μs. With those constraints, there exists a 0.31% probability that a sample of the multiplexed stream will occur during the 12 μs transition period, and the sample will therefore contain erroneous data. Figure 2 gives a pictorial description of just how that data loss occurs. There is absolutely no way to distinguish a good data point from one that is bad within a multiplexed stream of 16 instruments, all of which may exhibit normal fluctuations around their nominal values. Furthermore, the data blackout period, or data discontinuity (i.e., that word in the primary stream which is being sampled as the payload data stream is indexing between two consecutive points) will move through the Primary Data Stream's major frame at a rate dependent on the difference in the two systems' encoding frequencies. Every time the data discontinuity reaches one of the ten words allocated to the payload, incorrect data will be transmitted through the telemetry system.

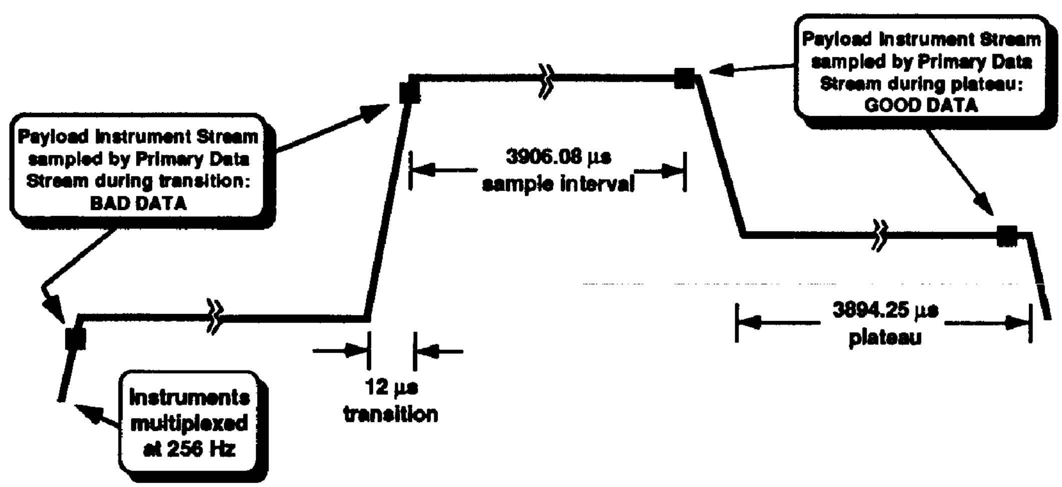

Figure 2. Lack of Synchronization Between Primary and Secondary Data Clocks Leads to Data Loss

The use of an embedded asynchronous format without access to the host telemetry system's clock presented a significant obstacle to the design of the experiment data acquisition system. The challenge was to design a data acquisition system which would mitigate the negative effects of a truly asynchronous embedded data stream.

DESIGN METHODOLOGY

To solve this unique data acquisition problem, a system was designed that determines the validity of the sampled data point by locating and tracking the position of the data discontinuity. This process does not require the use of any synchronization bits within the secondary stream, nor does it require subframe synchronization with the primary telemetry frame. Hardware was employed to minimize the occurrence of data loss regions due to the lack of synchronization between the two clocks. A software system was used to identify and remove those data points in the embedded stream which represented transition values in the multiplexed stream, and not actual instrument data.

The design of the data acquisition system alternates embedded asynchronous data streams (EADS) and data tag words containing information about the EADS into the primary telemetry frame to retrieve the embedded data. The specific EADS is placed in a given word with data tags placed in the two closest surrounding data words. The information placed in the data tags indicates to which instrument the data currently being read belongs. The data tag signals are obtained from a <u>completely</u> independent secondary data clock which is utilized to produce a binary counter which cycles from 0 to 15. The four signals constituting the binary counter are used on the experiment for two purposes: First, they are used to multiplex the 16 instrument channels (numbered 0-15) into a single data stream. Second, after conversion to analog signals, they indicate which channel is currently at the output of the digital acquisition board and being multiplexed into the telemetry stream. By monitoring the voltage of the surrounding data tags, the validity of any given data point can be determined. If the voltage values before and after the data point are identical, then the channel selected remained constant over the sample time and the data is valid and belongs to the channel indicated. If the voltage values before and after the data point differ, then the multiplexed data stream has changed state somewhere within the sample time. In this case, the origin and identity of the received data is not immediately clear. The data tags allow the data discontinuity to be located and tracked quite readily throughout the frame. Once the relative speed of the data discontinuity has been determined, accurate predictions can be made of exactly when and for exactly how long the data discontinuity will cause erroneous data to be transmitted as part of the payload's data streams.

SYSTEM ARCHITECTURE TRADE STUDIES

This design methodology described above was combined with the analysis of expected data streams and data rates to design a system that achieves a high degree of data resolution. Many factors played roles in the determination of the system's final design.

The first system architecture trade study centered around the number of data tags to be used given the total allocation of ten words in the Primary Data Stream. The ability to track and verify the position of the data discontinuity is determined by the number of tag words used. The use of additional tag-words improves the system's ability to ensure accurate tracking of the data discontinuity at the expense of reducing those words dedicated to transmitting data. If only one tag word is used, the location of the discontinuity can be verified only when it crosses the chosen tag word. With two or more tag words, the location of the discontinuity can be maintained within bounds at all times; however, the discontinuity's location can only be verified when it crosses one of the tag words. With the given location of the experiment's words in the Primary Data Stream and the possible instability of the system clocks (which can cause measurement and tracking errors), the decision was made to use four tag words to track the location of the discontinuity. The use of four words provides a reasonable balance between the desire to track the data discontinuity as much as possible and the need to transmit the experiment's data at die same time. In this configuration, six words are left dedicated to the experiment's data.

The use of the six data words was the subject of the second design study. The experiment's 32 instruments are multiplexed by two commercial data acquisition boards into parallel streams of 16 instruments each. In addition, those same 32 instruments are also routed to an entirely redundant set of multiplexing boards, providing four embedded asynchronous data streams in all. This parallel redundancy provides two key advantages: first, the failure of a single board during the mission will not lead to the loss of data on that board's instruments because of the existence of the backup board; second, and more importantly, the effect of the data discontinuity can be minimized with two words transmitting the same data throughout the flight. Although the data within one word may be discarded for a certain length of time, the same data is successfully retrieved at the same time from the redundant word in the telemetry system's major frame. There are no data blackout periods; only periods of time when data is collected at a reduced frequency because one of the two streams had to be omitted due to the presence of the data discontinuity. The remaining two data words are dedicated to the experiment's two most critical instruments. The signals from these two instruments are fed directly into the telemetry system, and are transmitted without the induced disturbance and inherent complexity of an EADS format.

The third system architecture trade study involved the placement of the tag words, multiplexed data streams, and steady instrument channels into the ten data words. The sampling intervals between consecutive words varied greatly because of the random nature of the location of the words in the Primary Data Stream. The desired objective was to alternate multiplexed data streams and data tags, minimizing the amount of space within a single tag/data stream/tag group. The sampling intervals between all possible three word groups were calculated, and the eight tags and EADS words were carefully placed into those words in such a way as to enhance the ability of the system to ascertain the validity of the data. The position of the steady instrument channels was far less important because of the ability to identify the data discontinuity merely by inspection of the steady, non-multiplexed stream. The remaining two words were therefore used to transmit the steady channels.

The choice of the frequency at which to encode the secondary data streams was the topic of the fourth system trade study. The knowledge of the primary telemetry clock frequency and the ability to select the frequency of the secondary data clock allowed the rate at which the data discontinuity moves to be established by the system designers. By selecting the primary and secondary frequencies very nearly the same, the region can be made to move very slowly and very predictably through the telemetry frame. In fact, if the secondary frequency is chosen such that the primary clock rate is an integer multiple of the secondary frequency, the data discontinuity becomes much easier to track. If the secondary clock rate is chosen to vary widely from the frequency of the primary clock, the data discontinuity will move great distances in consecutive frames and become more difficult to track. The direction of movement of the data discontinuity is likewise easily set. If the frequency of the payload's clock is slower than the telemetry system's clock, as it was in this application, the discontinuity appears to move forward through the data stream at a rate relative to the difference in frequencies. To minimize any tracking problems, the frequency of the secondary clock was chosen to be within .03 Hz of the primary frequency.

The last major system design trade study was the determination of the optimal format of the secondary data stream. The redundant nature of the embedded asynchronous data streams permitted a twofold increase in the achievable sampling rate of all the instruments. Because a single set of digital counter lines are used to select channels on all data acquisition boards simultaneously, all instruments on the same channel on different boards are fed to the telemetry system at the same time. By placing redundant instrument signals on different data acquisition boards 180 degrees out of phase, the sampling rate of each instrument is effectively doubled, with minimal added system complexity. For example, the water flowmeter signal was placed on data acquisition board 1 channel 0 and on data acquisition board 3 channel 8. Each instrument is therefore read twice during each cycle of the 16 channels, once on board 1 and once on board 3 a half cycle later. The result is that each instrument is sampled at 32 Hz instead of 16 Hz, which would have been the maximum achievable sampling rate of 16 instruments with a clock frequency of 256 Hz. The placement of consecutive instruments was a carefully thought out complementary design decision.

By placing instruments typically generating higher voltages next to those generating low voltages, the ability to discriminate signal sources is enhanced. The instrument signals were arranged on each data acquisition board such that dissimilar values were placed on consecutive channels. Minor modifications to the format of the embedded data streams were thus responsible for doubling the sample rate of each instrument and eliminating any ambiguity which would have been caused by the collocation of instruments with similar values.

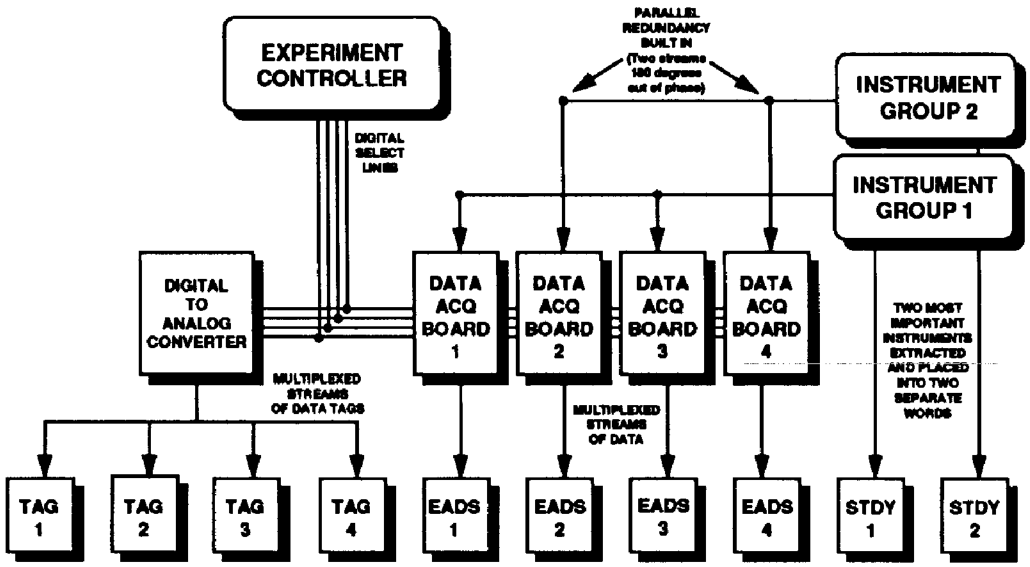

Figure 3. Hardware System Schematic

These system trade studies were performed in order to arrive at the most efficient design given the existing hardware systems and interface requirements. Figure 3 provides a description of the final hardware design used in this application, emphasizing the built-in redundancy provided at the data acquisition boards and the simultaneous, parallel creation of the data tags. The large amount of flexibility in the design parameters requires a good deal of thought to arrive at an optimal configuration for a specific application. On the other hand, it also makes the design method and approach inherently easy to adapt to systems with different requirements and constraints.

SOFTWARE DESIGN AND IMPLEMENTATION

The performance capabilities of this design rely primarily on the system's ability to locate and track the data discontinuity. Software algorithms have been developed to perform the locating and tracking processes. A standard telemetry decommutation system is used to lock onto the Primary Data Stream and extract the ten words allocated to the experiment. To reiterate, eight of the ten words are embedded asynchronous streams: four contain raw experiment data in a 16 word pattern, and four contain the data tags necessary to successfully decommutate the embedded data streams. The remaining two words are dedicated to the two most important instruments on the experiment and do not use an embedded asynchronous data stream format. An overview of the entire software algorithm structure is given in Figure 4.

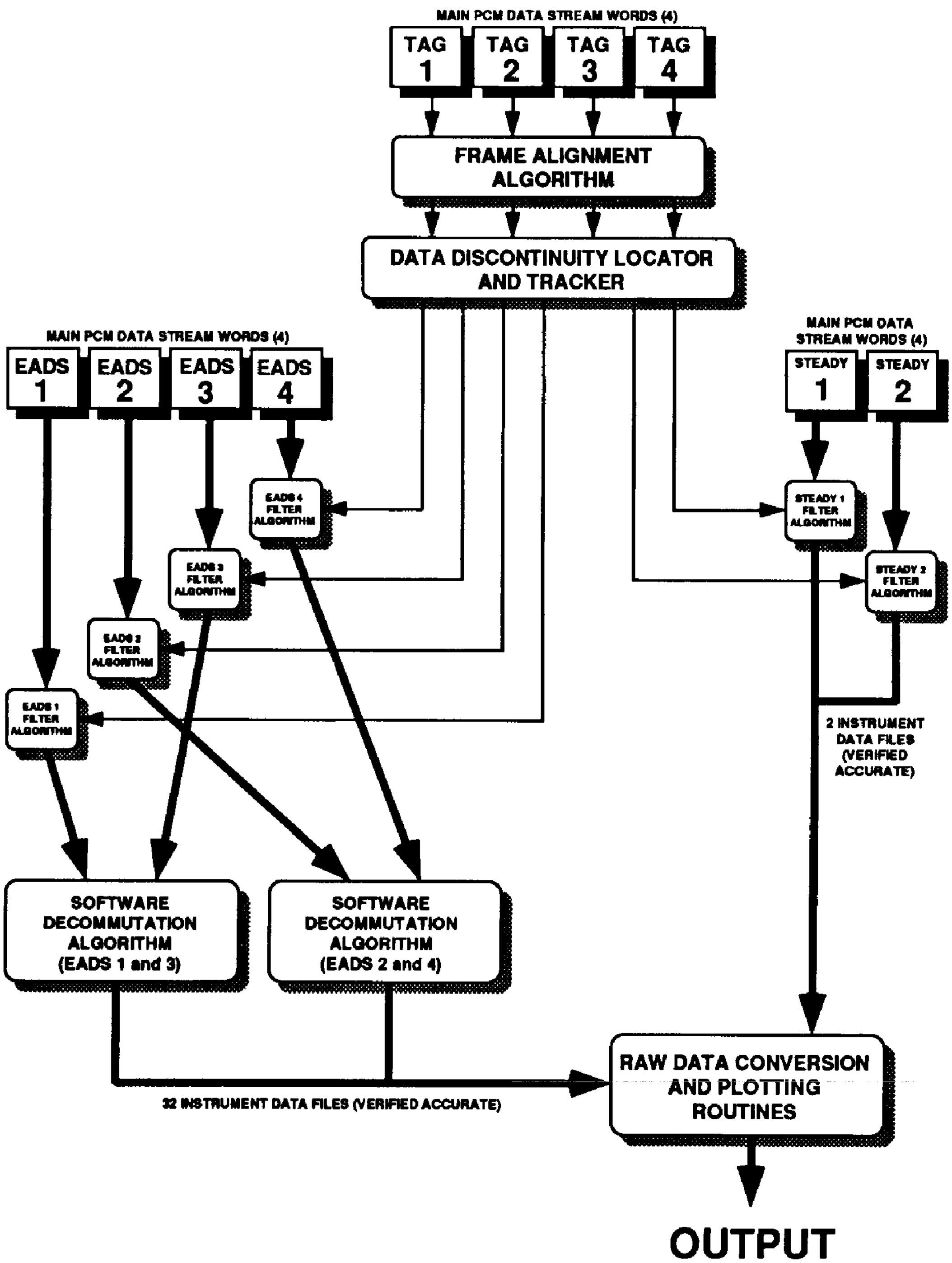

Figure 4. Software Algorithm and Logic Structure

The four tag words are routed directly to the Frame Alignment algorithm. The primary function of the Frame Alignment algorithm is to artificially establish an initial condition between the primary and the secondary streams such that both streams appear to begin multiplexing at the same time. Because the encoding frequencies of both streams are so similar (the secondary stream multiplexes at a rate which is less than 0.03 Hz different from the rate at which the primary stream samples each word), the payload controller essentially places a different data point into each of the ten words in the primary frame every time those data words are sampled. The lack of clock synchronization between the two systems prevents any prediction of the initial location of the data discontinuity. The Frame Alignment algorithm locates the starting position of the data discontinuity and subsequently refers to that position as the first word in the Primary Data Stream. The algorithm creates a repeatable initial condition, simplifying the interface with the remaining algorithms.

The Data Discontinuity Locator and Tracker algorithm is designed to identify every time any of the data streams in the ten payload words may be compromised due to the proximity of the data discontinuity. The algorithm uses the four tag words to locate, track, and monitor the progression of the data discontinuity. Once the data discontinuity has been successfully tracked through the tag words for the entire mission, the periods of time when the data discontinuity affects actual data channels can be calculated. The Data Discontinuity Locator and Tracker algorithm outputs six files, each of which contains the times for each data word during which the data should be discarded.

The six filter algorithms accept the time files outputted by the previous algorithm and use them to discard raw data which may have been affected by the data discontinuity. The algorithms include a buffer with a length of one word on each side of the specific data word in question. The one word buffer length is a factor of safety to ensure that no questionable data is passed through and labeled as accurate. The output of the filter algorithms is a stream of data which can be labeled as valid with a high degree of certainty.

The final algorithm decommutates the embedded asynchronous data streams which have been verified as accurate. Using the tag files and the outputs of the filter algorithms, the Software Decommutation algorithm can identify individual pieces of data and write them to specific instrument files. In addition, the embedded stream redundancy (EADS 1 contains the same information as EADS 3, and EADS 2 contains the same information as EADS 4) is dealt with as the program is designed to take data points from both streams and write them to an individual instrument output file.

SYSTEM TESTING AND RESULTS

The intense interest in verifying this unique data acquisition system design resulted in extensive validation testing of the telemetry system. A great deal of subsystem and system bench testing was augmented and verified by three complete and distinct system tests. The data collected during the system tests was analyzed and decommutated by the software algorithms exactly in the manner to be used for the actual flight data.

The first and second system tests used the same test set-up to establish whether or not the system design would function as expected. In preparation for the first system test, the necessity of fixing some of the input variables to facilitate the validation of system performance was apparent. Steady voltage values (0, 1, 2, 3, 4, and 5 Vdc) replaced the experiment's instruments on the data acquisition boards and created a distinctive, repeatable pattern when multiplexed. The software decommutation of a distinctive, steady pattern as opposed to actual fluctuating instrument signals was projected to be significantly easier to work with and to troubleshoot. Unfortunately, the first system test was cut short by an unforeseen electronics problem. Low input impedance on the D/A converter, which creates the data tags so crucial to the system design, resulted in an over-loading of the D/A output signals during the first system test. Certain output voltages were drawn down resulting in inaccurately low voltage readings and inaccurately tagged data. This impedance mismatch was corrected by the addition of an operational amplifier to the output of the D/A electronics. The function of the corrected electronics system was verified at the second system test, and the complete telemetry data stream was recorded. The software data acquisition routines were successfully able to identify the regions of data loss caused by the data discontinuity and extract the experiment's secondary embedded asynchronous data stream. Complete verification of the data acquisition system was achieved during the second system test, and a better understanding of the system's characteristics was gained.

After review and validation of the results of the second system test, a complete system qualification test was conducted with the booster. During this third system test, the experiment was connected to the booster telemetry system and a complete mission profile was simulated. The entire telemetry data stream (this time containing actual instrument signals) was recorded and processed through the software decommutation routines. The data discontinuity was easily located and successfully tracked by looking for its distinctive pattern. Figure 5 is an example of how a data tag stream is affected when the data discontinuity moves through its position. The steady, staircase-like pattern is briefly interrupted as the Primary Data Stream attempts to sample the tag stream just as the tag stream is indexing between consecutive values. The stream returns to normal within 250 ms.

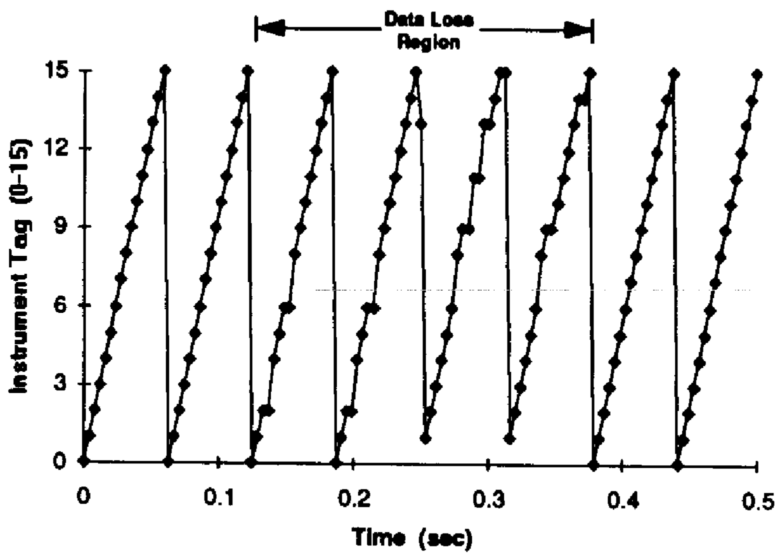

Figure 5. Impact of the data discontinuity on a data tag-stream

Actual flight hardware and software was used at all phases of the telemetry test program with the minor exception of the simulated instrument signals used during the first and second system tests. These three extensive tests verified the performance of the data acquisition system design and greatly increased the confidence in the system's ability to successfully retrieve the experiment's data from the secondary data stream embedded within the host major frame.

A large amount of effort was also placed into quantifying the performance of the system as achieved during the third system test. The data discontinuity was measured to move forward through the primary major frame at a rate of 11.57 words/second, for a dwell time on each word of .086 seconds. At that rate, it takes the data discontinuity about 45 seconds to traverse the entire 512 word frame. The amount of data lost on any one embedded stream is easily calculated. In any given 45 second period, the data discontinuity will move through each of the ten words a single time. The software uses a one word buffer on either side of the words containing embedded asynchronous data streams, for a total data loss period of 0.259 seconds. A 45 second stream of data will therefore have a 0.259 second gap due to the data discontinuity, meaning over 99.4% of the data on any single stream is retrieved successfully at 16 Hz. By combining the parallel redundant streams which have their instrument positions and respective data loss regions out of phase, data can be collected at 32 Hz approximately 98.8% of the time, with the balance of data collected at 16 Hz. This last figure is especially important. Given the number of instruments within each stream, the number of streams used, and the primary encoding frequency (256 Hz), 32 Hz is the theoretical and practical limit for <u>any</u> system which employs an embedded data stream format. The rate at which the embedded data is encoded can never be faster than the primary data rate, or data will be lost continuously (Smith et al 1986). The fact that this practical limit is very nearly achieved without the benefit of primary and secondary clock synchronization is noteworthy. The more general result of this effort is the development of a data acquisition system that utilizes an embedded asynchronous data stream without primary and secondary frame synchronization to retrieve all experimental data without modification to the existing telemetry system.

ADVANTAGES

Extracting valid data from a truly asynchronous embedded data stream is no simple task. The methodology employed here presents a number of attractive advantages for future telemetry system designers. First, the system does not require any primary frame-to-frame dependence; all the information necessary to extract valid data is contained within one frame's grouping of the ten words allocated to the payload. The ability to track and record the position of the data discontinuity throughout the flight (as was accomplished in this application) does increase the amount of valid data able to be extracted from the raw data stream. However, the system can work quite effectively without looking forwards or backwards through the Primary Data Stream. An embedded data stream structure which may extend over several primary frames and rely on synchronization bits transmitted far back in the Primary Data Stream is inherently susceptible to loss of synchronization during dropout periods in that stream. Indeed, those dropout periods may be extended as the decommutation system attempts to reestablish synchronization with the embedded stream. If the system presented is given only one primary frame of data, it can extract embedded asynchronous payload data in a straightforward manner.

Second, the hardware/software system described can be adapted for many different applications. Differences in primary telemetry system characteristics, payload data requirements, payload/rocket interface issues, and secondary data stream format can all be tolerated using this methodology. A number of trade studies will have to be performed to determine optimal system configuration, but the general approach remains the same. In the future, requirements for real-time extraction of the data from the embedded asynchronous data streams can even be supported with a hardware implementation of the software algorithms described above.

Most importantly, though, the use of such a system drastically reduces the system's interface issues and systems integration effort required prior to final payload mating with the booster. The limited access to space currently provided microgravity researchers in the United States has forced the space test community to search for innovative and cost-effective means of placing their payloads in orbit. Small experiments may very well be given more “piggyback” rides into space if they can limit the systems integration impact on the host booster. By developing a low cost, low impact expansion to a standard telemetry system, the Phillips Laboratory was able to gain access to space without impacting the STARS rocket program in a major way. The Phillips Laboratory payload requires no synchronization signals from the rocket's telemetry system in order to successfully transmit the data from the experiment. All the payload requires, and all that future small payloads may require of a host system, is a number of spare words in the Primary Data Stream into which they may place truly asynchronous embedded data and data tag streams.

CONCLUSION

Methods for reducing the complexity, integration effort, and cost of designing and producing space qualified hardware are major considerations of any space system engineering effort. Described is a method for acquiring spacecraft subsystem data that requires low systems overhead, minimal integration effort, and can be adapted to support a large range of systems. The design incorporates the use of embedded asynchronous data streams to obtain subsystem data without synchronization of the primary and secondary data streams. The system, designed to integrate the Two-Phase Flow in Microgravity Experiment with the STARS rocket, can be adapted to interface a wide variety of other data formats to standard telemetry systems without requiring multiple redesigns.

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