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Data Compaction of Rocket Booster PCM Telemetry Data

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Three typical channels of Rocket Booster data have been studied to determine the amount of bandwidth reduction that is possible with an adaptive telemeter. The three channels included a flow measurement, a temperature measurement and an ignition pressure measurement. The time period studied was 220 seconds, starting 142.583 seconds before first stage cut off, and for 77.417 seconds after burn out. During this time 2640 ten-bit samples were taken on each channel. Therefore, the original data studied was composed of 79,200 bits. The results of the study show that this could be reduced to 493 bits, when the peak-to-peak pickup on each channel is used as a means of determining the selection tolerance. This method includes two code words for each transmitted data word. One word of 8 bits to indicate which channel was being transmitted and a second code word of 10 bits of timing. In other words, a reduction of 161 to 1 is possible without the loss of any data. The total PCM system was composed of 216 ten-bit channels, each sampled 12 times per second. This would require a video bandwidth of about 13 KC. If the three channels studied are an indication of the average reduction, this bandwidth could be reduced to about 80 cps of binary transmission.

Redundancy Reduction

The heart of any adaptive telemeter will be some means of removing redundant or non-significant data. Any scheme to be devised is based upon a priori knowledge which allows one to reconstruct the data on the ground from only the non-redundant samples. Further, any process is related to the sampling of the original data. If data is sampled fast enough to capture the highest frequencies that may be present, there is a surplus of samples when these frequencies are not present. During this period these samples can be removed and the bandwidth saved can be used by some other channel. The flow measurement studied in this report is a good example of this. During the steady state flow conditions the sampling rate can be very low, but during the time while the flow is beginning and ending there are high frequencies present which require more samples to obtain the desired accuracy. Rather than actually change the sampling rate during these periods a method can be devised that will predict where the next sample will be, and if that value is within a given selection tolerance the sample is discarded.

Two redundancy reduction methods were used to study the data in this report. The first was a zero order predictor or Step Method. This method establishes a selection tolerance around the first example, and as long as future samples fall within this tolerance they are considered redundant. When a sample exceeds this tolerance
it is considered non-redundant and the selection tolerance is established around it.

The second method, known as the Fan Method, is a first order predictor. In essence it is more than a predictor in that it predicts a point, reconstructs the data and checks (interpolates) to see that the sample when reconstructed on the ground will be within the selection tolerance. In effect it draws a series of lines between the first and successive samples, always assuring that all samples between the end points are within the selection tolerance. In this manner it will draw the longest possible straight line and when a sample falls outside the tolerance it will transmit the previous sample and start over. The details of these methods are covered in Ref. 1.

It is obvious that there are many possible schemes which are based on higher order polynomial predictors. Quite naturally these schemes will work better on higher order data just as a fourth order differential equation will draw a curve between three points better than a third order equation will. The amount gained is small, however, and the complexity of anything beyond the first order builds up rapidly.

**Study Program**

Realizing that bandwidth saving is extremely important in order to better utilize our limited spectrum, and to be able to retransmit the data in real time over limited bandwidth, a study of typical liquid propulsion telemetry data was planned. The data available covered a time period starting just after take off and goes for several seconds beyond burn out. The channels selected for study all had a rather large amount of high frequencies present, which was either high frequency data or electrical pickup. The peak-to-peak value of this pickup was used as a means of establishing the selection tolerance reported in the introduction. When studying a plot of this data, as shown later, it is quite obvious that in no case is the sampling rate adequate to capture the noise since there are less than two samples per cycle present. This is not serious if the desired measurement is the average area under the curve, which is usually the case in propulsion data, that is, if there are enough samples to provide a true average. The Fan Method will accomplish this average as can be seen later. The sampling rate is dictated by the rise and fall times of the various propulsion measurements, and in the pressure measurement studied, it was not adequate to obtain the data to the accuracy of the peak-to-peak pickup present.

The Step and the Fan Methods were mechanized on a digital computer and the 500 samples for each of the three measurements processed, with selection tolerances ranging from 0.1% to the maximum range, based on a full scale of 1024.

**Pressure Measurement**

The first measurement studied was ignition pressure which was measured with a strain gage transducer with a natural frequency of 23,500 cps. The pre-amplifier
used was a chopper type with a 3 db point at 3,000 cps. The output of the preamplifier was fed directly into a multiplexer sampling at 12 samples per second. This output was then coded to 10 binary bits. With the available frequency response, the channel is extremely susceptible to noise and with the low sampling rate, aliasing or foldover error due to inadequate sampling, will be very high.

Fig. 1 shows a plot of the measurement around cut off. The fall time is measured to be 0.167 sec. This is accomplished by measuring the values at 85% and 15% of the maximum value, and linearly interpolating the time between these values. This will then roughly represent one fourth of a sine wave. Although the waveform of one fourth of a sine wave does not exactly match the rise or fall time it is a good approximation. In this case the required response would be 1.5 cps. This is only an approximation of the rise time since we don't really know when the rise time started and stopped to any better than one sample time. It is a minimum case however, and undoubtedly the required response is higher. The accuracy to which this fall time is reproduced is therefore a function of the number of samples available. At a sampling rate of 12 samples per second, eight samples per cycle are available. The RMS and Peak interpolation errors for Step and Linear interpolation of a sine wave for different sampling rates have been calculated and are shown in Fig. 2. The data is plotted in samples per cycle on the Y axis, required to produce a given error on the X axis.

**Determining Proper Sampling Rate**

Linear interpolation is the process of determining values between samples by connecting two samples with a straight line, and calculating values along this line for specific times. As can be seen in Fig. 2 the RMS error of a sine wave for 8 samples per cycle, using linear interpolation, is 4% which is the approximate error due to original sampling of the ignition pressure measurement. If it were desired to decrease the peak error to 0.25%, 33 samples per cycle or 50 samples per second would be required with reconstruction by linear interpolation.

Step interpolation is a method of reconstructing sampled data which assumes the values between samples remain the same as the last sample until the new sample is taken. If step interpolation were used the 8 samples per cycle would yield an RMS error of 31%. Further it would require about 1000 samples per cycle to reduce this step interpolation error of a sine wave to 0.25%.

Another way of determining the proper sampling rate, when the rise or fall time is known, is covered in Ref. 2. Ref. 2 takes into account that the waveform of the rise time is not a sine wave but is a complex wave which is determined by the frequency response of the device that originated the data. The rise time determines the break-point in the frequency response curve and the order of the data describes the final slope of the curve. First order data decays at 6 db per octave and second order data at 12 db, with each succeeding order adding 6 db per octave. Methods for determining the order of data will be discussed later.

In order to compare results of the two methods it is assumed that this data is
third order (decays at 18 db per octave), and the breakpoint is 1.5 cps as calculated earlier. From tables in Ref. 2, 8 samples per cycle will yield an RMS error of 5.4%. In order to reduce this 0.25%, 38 samples per cycles or 57 samples per second would be necessary. These results compare quite favorable with those of a sine wave, and are probably more accurate. This is because it takes into account that there are frequencies present higher than the cut off or break frequency. These results show that this data was originally sampled nearly 5 times too slow to stay within the static accuracy of the PCM system. This fact will be shown by another means later in the report.

High Frequency Content

The frequencies shown before cut off are probably a result of the extremely high frequency response of the transducer and the pre-amplifier. This is a case where the high frequency pressure variations are producing noise like data which should by all means be eliminated with a pre-sampling filter before the sampling process. A blowup of this noise is shown in Fig. 3. As can be seen there are frequencies higher than two samples per cycle and their amplitude is about 8% of full scale. It is impossible to tell how high the actual peaks were since the slow sampling rate obviously did not occur at the time of the peaks. The value at the time the sample did occur is correct to the static accuracy of the PCM system. Therefore, if enough of these samples are averaged, the area under the pressure curve can be obtained quite accurately. However, a more suitable means of obtaining data would be with a transducer with a much lower frequency response and a pre-sampling filter. Further proof that the variations present before cut off are being caused by high frequency components out of the transducer, is borne out by the fact that they are not present after cut off. If Fig. 1 is checked it can be seen that after cut off (sample 463) the peak-to-peak noise is less than 1%. Had the noise been electrical pickup the amplitude after cut off would have been the same or even greater than before cut off. The amplitudes were checked for 100 samples beyond the 500 shown and in no case was 1% peak-to-peak exceeded.

Reconstructed Data Evaluation

Five hundred samples of the pressure data were processed by the Fan and Step Methods at selection tolerances from 0.1% to 68%. The results are shown in Fig. 3. The curves show the number of non-redundant samples for each value of selection tolerance. It is interesting to note the similarity of these curves to ones produced using theoretical data. When controlled theoretical data is processed by various redundancy reduction methods, the effects of inadequate sampling rate, noise, quantizing error, etc., can be determined. This has been performed in a previous study and is covered in detail in Ref. 3.

When the original data is adequately sampled to describe it to better than the accuracy of the selection tolerance the number of non-redundant samples will follow a straight line on log-log paper. The slope of this line is an indication of three things. First, the order of the input data, secondly the order of the redundancy reduction process used and thirdly, the order of the reconstruction (interpolation) method used.
The actual interactions of the three are currently being studied by feeding band-limited white noise into the various methods. That is, white noise that has been filtered with known orders of filters. By comparing this slope with known orders of input data and interpolation methods, a resulting slope by a particular redundancy reduction process will be an indication of the order of the input date. In this case the slope is $2/3$ or $40$ db for three decades, and for the step redundancy reduction process shown later it is one or $20$ db per decade. The study to date indicates that this combination results from second order or higher data. The results are probably third order since tests used for determining the required sampling rate of the fall time check very closely with the third order interpolation tables.

The point that the redundancy curve breaks below the straight line portion of the curve indicates the peak interpolation error due to the original sampling. This point as seen in Fig. 4 is about $35\%$ for the Fan Method. If the value is normalized to the same scale was used for determining peak and RMS errors of a sine wave, the peak error would be around $25\%$ and the RMS error around $15\%$. A peak error of $25\%$ would indicate only 4 samples per cycle instead of the 8 as indicated in the calculations shown earlier using rise times. This means that the required frequency response is doubled, and is more nearly $3$ cps than $1.5$ cps. In other words the decay time started nearer sample 464 than 463 as shown in Fig. 1. In the case of $0.25\%$ error, the required sampling rate will be about 100 samples/second instead of the 50 shown earlier.

Therefore, the break point of the non-redundant curve is a better way to determine the required sampling rate than the measuring rise time. In either case the fewer samples available during rise or fall time makes the problem more difficult.

Fig. 4 also shows the result of both the Fan and Step Methods. It appears that the Step Method does a better job than the Fan Method above about $5\%$. This is because the original data was not sampled fast enough to recover it to anything better than that accuracy. If adequate sampling had been used the number of non-redundant samples would have fallen along an extension of the straight line portion of the two curves. At $5\%$ tolerance there would have been 15 non-redundant samples for the Step Method and 10 for the Fan Method. It is interesting to note that the two straight lines cross at around $15\%$, and for values greater than this the Step Method is more effective than the Fan Method. This is because the large jumps in reconstruction the data by the Step Method makes the data appear to be discontinuous in nature or to be zero order data. In actuality for any case where the order is larger than zero, the Fan Method will always be more effective than the Step Method.

**Effects of Noise On Redundancy Reduction Methods**

By studying theoretical data such as a sine wave, which has a known amplitude sine wave superimposed, the reaction to noise can be determined for various redundancy reduction methods. One must however be careful to have an adequate sampling rate of the basic sine wave at the amplitude of the noise. In Ref. 4 the problem has been studied in detail and results show that the high frequency or noise causes the redun-
dancy curve to break away above the line. The rate at which it goes to the number of total samples available is a function of the frequency of the noise. The Fan Method is affected at selection tolerances higher than the amplitude of the noise. At the amplitude of the noise however, there is an upward break. If the sampling rate is adequate to capture the noise the redundancy curve will again become a straight line parallel to the original slope. At the selection tolerance where there were not enough samples to describe the sine wave to that peak error, the curve would break below the straight line.

When the same data is processed by the Step Method, the redundancy curve breaks above the straight line at the selection tolerance equal to the amplitude of the noise, and immediately requires all samples available.

These results show how the amplitude of noise, superimposed on data, can be determined. It also shows us that the Step Method is less affected by noise than the Fan Method. However, the required high sampling rate for the Step Method more than outweighs this advantage.

Results on High Frequencies on Pressure Measurement

When the curve breaks above the line it indicates noise or lower amplitude high frequency data. This can be seen in Fig. 4 to occur around an 8% point. This value was shown earlier to be the approximate amplitude of the high frequency pickup. Using a selection tolerance of just over the peak-to-peak pickup will result in the redundancy reduction process taking an average of the noise. In this case 8.5% tolerance reduced the 500 samples to four non-redundant samples. If the sampling rate had been fast enough to reproduce the fall time to 8.5%, the extension of the straight line shows us that we would have then had seven non-redundant samples. The three additional samples would have all been chosen during the fall time shown in Fig. 1. The average as obtained by the Fan Method can also be seen in Fig. 1 and 3.

In order to show the effect of the high frequency noise on the redundancy reduction process, a running average of the noise before and after cut off was taken using a computer. The 500 samples of noise-free data was processed by the Fan Method and the results presented in Fig. 5. Examining the values at 1% tolerance shows that with noise present 290 of the 500 samples would be needed and with the noise removed only 6 would be needed. In other words 284 samples would be needed for the unwanted noise and only 6 samples for the data. The straight line extension shows that 32 samples would be needed to reconstruct the original data to a 1% peak error if it had been sampled adequately. The required sampling rate in this case calculated from the peak error shown, would have been 66 samples per second.

If a redundancy curve is made by the Fan Method for just the steady-state period, samples 1 thru 463, the results can be seen in Fig. 5. When the selection tolerance is just larger than the peak-to-peak noise only the first and the last sample are required. Therefore, at the peak-to-peak noise the non-redundant sample number becomes two. Interaction between the noise and the data in the operation of the Fan Method makes it require additional samples above the peak-to-peak noise.
Flow Measurement

The second measurement studied was a flow measurement using an 8 inch turbine type flow-meter. The pulses generated from a magnet imbedded in the spindle are picked up by a coil and fed into a converter. This converter produces a voltage which is proportional to the flow. The speed of the rotor may vary between 30 and 400 RPM. To go from zero to full flow requires 30 milliseconds when a step function of flow is applied. The converter alters the amplitude of the sine wave to a frequency from 0 to 300 cps. The maximum frequency present would therefore be 300 cps, however, higher frequencies of lower amplitudes which are oscillations of the turbine may be present. The output of the converter is fed into a multiplexer sampling at 12 samples per second, and in turn, into a 10 bit coder.

Fig. 6 shows a plot of the measurement around cut off. The fall time in this case measures to be 0.312 seconds which requires a frequency response of 0.8 cps. With 12 samples per second available, there would be 16 samples per cycle. Using the interpolation error (Fig. 2) of a sine wave indicates that the peak error for linear interpolation is about 2% and the RMS error is about 1%. For Step interpolation peak error is 10% and RMS about 4%. Based on methods described for the pressure measurement the flow data was determined to be fourth order. If the 0.8 cycle is used as the break point and the fourth order interpolation tables used, the RMS error is about 1.3% which again checks quite well with the sine wave method.

A study of the noise present during the steady state flow period indicates that the peak-to-peak pickup is about 1.7%. This pickup is again due to the high frequencies out of the flow meter and results in less than 2 samples per cycle. Again however, if only an average is desired it can be obtained quite accurately. The high frequency noise is not present after cut off which further verifies that the noise is coming from the flow meter and a pre-sampling filter should have been used.

Reconstructed Data Evaluation

The results of the Fan Method are shown in Fig. 7. The redundancy curve for the 500 samples is a straight line down to about 3.5%. At this point the curve breaks above the straight line indicating noise. This being the high frequencies present during the steady state flow. The value of the pickup is something less than the 3.5%. If a redundancy curve is run on the samples where these frequencies are present (Samples 1 thru 463), the amplitude will be indicated by the place that the curve goes to two samples (1.75%). This is also shown in Fig. 7. If the high frequencies during steady state flow are smoothed, and the noise free data processed by the Fan Method, a different redundancy curve is produced. As noted this curve breaks above the straight line at about 2.5% and then bends back across the straight line. This is a normal action of the Fan Method as it runs out of samples to meet a given selection tolerance. It will take more samples until such time that the samples are not available, at which time it will break back across the straight line. The place where the curve breaks back indicates the peak interpolation error of the original sampling. Since this point is obscured by the noise in the original data its value cannot be accurately determined. It is less than 3.5%, however, which makes this agree quite
favorable with the previous methods for determining a sampling rate. The reason for this agreement is that the original data was adequately sampled and more samples were available during the fall time. Therefore, it is possible to determine the rise time more accurately.

Fig. 8 shows the redundancy curves for the Step Method on the flow data. The selection tolerance where the curve breaks below the straight line is 27%, which checks with the peak step interpolation error of a sine wave shown in Fig. 2. That is when the sine wave amplitude is normalized to 1024. If the original data had been sampled adequately for reconstruction by Step Interpolation, the number of non-redundant samples would have followed the straight line, whose slope is one, or 20 db per decade. The sampling rate required to obtain a peak error equal to the peak-to-peak noise present would have been about 250 samples per second and these would have been reduced to 37 non-redundant samples, compared with only 7 for the same data using the Fan Method. The curve breaks up at 1.8% indicating that amount of high frequency pickup.

The data between samples 1 and 463 was computer smoothed and again processed by the Step Method. The results are also seen in Fig. 8, and show a continuation of the smooth curve before the amplitude of the high frequency pickup was reached. It is interesting to note when a 0.5% selection tolerance is desired, 88 non-redundant samples are required before smoothing and only 13 afterwards. This means that 75 samples are used to transmit the high frequency pickup occurring during a steady-state flow. The amplitude of the pickup is also indicated by the place that the redundancy curve, on the pickup only, (1 thru 463) goes to one non-redundant sample.

If reconstruction is done by linear interpolation, the sampling rate of 12 samples is adequate to obtain an accuracy equivalent to the pickup. In fact it appears to be good to about a 1% peak, but is obscured by the pickup.

As was the case of the pressure measurement, a presampling filter is needed. The Fan Method can however be used as a filter to provide an average pickup. If 1% peak error was desired the 500 samples could be reduced to 29. Nine of these are needed for the data and 20 to get a 1% average of the pickup.

Temperature Measurement

A temperature measurement made with chromel/alumel thermocouple was the third measurement studied. The time response of the thermocouple was 200 to 300 milliseconds, and its output was amplified by a chopper amplifier whose 3 db point was 20 cps. This output is sampled 12 times a second and then encoded to 10 binary bits. Fig. 9 shows a plot of the first 100 samples of the 500 studied. As can be seen, there are high frequencies present which are higher than two samples per cycle. The frequencies may be electrical pickup but are more likely actual temperature variations measured by the thermocouple. Under any circumstance the high frequencies should not be allowed to be present at the existing sampling rate. If these frequencies
are of interest the sampling rate should be increased, if not, they should be filtered before the sampling process.

The sampling rate is certainly adequate to capture the slow rise from 588 at sample 1 and 596 at sample 100. However, to get the measurement to any accuracy, an average of some kind must be taken which will require a great deal of computer time. The same thing could be accomplished by a pre-sampling filter or by performing a redundancy reduction process with the Fan Method, where the selection tolerance is selected to be just over the peak-to-peak value of the high frequency. The straight line between 588 and 596.5 in Fig. 9 shows the average obtained by the Fan Method.

Fig. 10 shows the results of the temperature measurement being processed by the Step and Fan Methods. It should be noted that the error scale is from 0.01% to 10% rather than 0.1% to 100% as in the two previous measurements.

The same type of correlation to theoretical data can be shown as has been done previously. The relationship of the slopes of the straight line portions between the Step and Fan Methods, when referred to theoretical results, indicate that the data is first order. Which is to be expected from a thermocouple. For the Fan Method the redundancy curve breaks above the line at just over 1% selection tolerance, indicating that amount of high frequency content. This also indicates that the sampling rate is adequate to recover the basic data to some error less than 1%, both by step and linear interpolation. Had the sampling rate not been adequate, it would have broken below the line. The high frequency content obscures the operation of the basic data, below 1%, and it cannot be determined to what accuracy the data was sampled. If there had been an adequate sampling rate to reproduce the high frequency, the curve would have again become a straight line after the tolerance was less than the peak-to-peak value of the high frequency. There would be a transition portion between the two slopes which would be during the portion where the peak error was not always less than the tolerance. As can be seen in this case, the curve below 1% does not become a straight line, indicating that there is not adequate sampling. This is obvious when looking at Fig. 9, in that most cycles are represented by only two samples. The actual peaks having been missed since a sample did not occur at the correct time.

As can be seen the main reduction obtained refers to the high frequencies and once they are removed the amount of redundancy is small thus making very little difference between the Step and Fan Methods. However, the Fan Method is slightly better and the mean error for fan is considerably better. Meaning that the data when reconstructed by the Fan Method more nearly matches the original data. This can be seen by examining the straight line referred to previously in Fig. 9 as can be seen the maximum peak error occurs at sample 74 and is .29%. If the Step Method at 1% selection tolerance were used to reconstruct data, the data would have been a horizontal line through 588. Peak error would have occurred at sample 99 and is .98%.
System Design

By studying the entire flight of 292 seconds or 3504 total samples per channel, the non-redundant samples for the entire flight can be determined. This, of course, is only possible where the measurements are well known and perform according to very predictable patterns.

Pressure

Since the decay time is known for the pressure measurement the number of non-redundant samples for the rise time can be approximated. A total of 8 samples would have been required had the rise time been available on the record processed. In addition to this four calibrations, each of five levels, were transmitted during the flight time. Each of these levels require a sample plus one at the beginning and one at the end. Thus 28 samples are required for calibration during the flight. A total of 36 samples during the 292 seconds would have recovered the data to a mean error of 1%. The longest period between non-redundant samples was 76.5 seconds. This was the time between two calibrations. A maximum of 76.5 x 12 or 9180 samples must be accounted for in our timing word transmitted with each sample. This would require a 10-bit word; however, the time is close to the maximum count which suggests the use of an 11-bit word. Thus allowing a maximum of 2048 redundant samples between transmitted samples.

An 8-bit word transmitted within the data word and the timing word will tell us which of the 216 channels is being transmitted. Therefore, our total sample transmitted is 28 bits long. This gives us 28 x 36 or 1008 bits required to transmit the original 35,040 bits to a mean error of 1%, or a reduction of 34.76 to 1.

There are many possible combinations of identifying frame, time, and channel number. The above method is good in that it allows for a large amount of redundancy. If however the count giving the number of samples removed between non-redundant samples is lost, the remainder of the channel may be lost. A way to avoid this is to make each channel complete within each transmission. Then if one is lost and a later one received, we know the time and which channel it is. This, of course, would require a great deal of bandwidth. A compromise of this would be to make each frame complete. A word, long enough to describe the total number of frames expected, could be placed at the beginning of any frame that contained non-redundant data. Along with this word would have to be some kind of sync. in order to tell when the word started. Each channel transmitted would be coded and its location in the frame known, therefore, the frame count would also provide timing. In frames where there were no data to transmit the frame, count would not be transmitted.

Flow

By the same type of analysis it can be shown that 38 out of 3,504 samples need to be transmitted for the Flow measurement studied. The slower decay and the two additional samples over the pressure measurement decrease the mean error to 0.5%.
Thus 28 x 38 or 1064 bits are required to transmit the original 35,040 bits for the Flow measurement yielding a reduction of 32.93 to 1.

**Temperature**

The temperature measurement showed a slow rise of about 35% of full scale during the 220 seconds studied. The first 72 seconds before and during take off would be changed much more rapidly. Based on the response of the thermocouple it certainly would not require more than 5 samples. Three samples during the 500 samples studied in detail yielded a mean error of only 0.30%. Thus, the total requirement for the 292 second flight would have been 28 for calibration and 5 for data or a total of 33 samples. This would give a total of 33 x 38 or 924 bits, or reduction of 37.92 to 1.

**Average Reduction**

The average reduction for the three channels over the entire flight is 35.20 to 1. Although it is realized that not enough measurements were taken to give a good average, the three are typical of the 216 digital channels. In most of the pressure cases it is expected that the sampling rate of 12 samples per second will be low. However the temperature channels, if the high frequency is removed, have more samples than needed. If a study were made on all channels, probably the total sampling rate of 2592 samples per second is about correct.

**Buffer Requirement**

All of the reduction shown previously is based upon storing the non-redundant samples as they occur non-synchronous and transmitting them at a fixed rate. There will therefore be a delay which will be determined by the buffer length and the transmission rate. The values given are for a buffer length that would be capable of storing all non-redundant samples and transmitting them during quiescent periods.

Using the average given for the three channels would then reduce the 7,860,640 bits for the entire flight to 223,310 bits. These would be 28 bit words or a total of 7,839 words. The entire flight could be stored in 219,949 bits. This, of course, would not be necessary since the words stored in the buffer at an uneven rate can be transmitted out of the buffer at a fixed rate. The buffer must be long enough so that during a period of activity there will be storage space in the buffer. Also it must be assured that the buffer will not become too empty so that the constant output rate cannot be maintained. The greatest amount of activity for the channels studied came during the four inflight calibrations. In this case each channel required seven successive samples. An adequate buffer could store 10 samples for each channel before a transmission was made, which would mean a buffer capability of 28 x 2,048.

The output rate could be determined by the amount of information to be transmitted in the total flight time. That would be 7839 words in 292 seconds or only
27 words per second, or 756 bits per second.

Again, as a safety factor, the rate could be increased and the length of the buffer decreased. In round figures 64 words per second or 1792 bits per second could cut the memory requirements to $28 \times 1024$. This would mean that a total of 18,688 words would be transmitted during the flight yielding a reduction of 15 to 1 over the original data. The additional words over the 7,839 non-redundant samples could be redundant samples, added to the buffer when it became too empty. In case something unsuspected should happen and the buffer should start to overflow, a priority could be previously arranged. This would increase the selection tolerance or completely drop lower priority channels. The selection tolerance on the high priority channels should not be increased because it is during the active periods that information on them is needed.

The above examples were given, only to show what can be done when a detailed study of actual measurements is made. Actually each channel should be processed, as the three were done in the above study, for the entire flight. The relationship between activity on various channels could then be determined, and statistically evaluated. Also the inflight calibration methods used in the case studied would certainly not be used. It is not necessary to apply a calibration on all channels one after another. Nor is it necessary to have four calibrations during a flight. One set of calibrations just before take off and one during flight would certainly be adequate. If these calibrations could be spread out such that only one occurred during any frame, the maximum required number of samples to be stored would be a result of the rise times, on each channel. For that matter, calibrations are no different than data, and if they do not change there is no reason that they should be transmitted.

Re-Transmission of Data

Often it is desired to re-transmit data to a central location in real time, such as up range over the submarine cables. If this were done on the system studied, the 25,920 bits per second would require a bandwidth of about 13 KC. The reduction that is easily possible allows the same information to be transmitted in 1792 bits per second or a bandwidth of about 900 cps.

Although the costs involved for submarine cable are not known, a comparison over similar distances can be made with commercial circuits. If the data were to be retransmitted from down range to Cape Kennedy a distance of 5000 miles, the leased cost for a 48 KC Telpac A circuit would be $904, 200. 00 a year. The Telpac A circuit being the nearest commercially available circuit which could retransmit the original data without any reduction. After reduction it can be transmitted over a Model 201 Data Phone circuit. This circuit can transmit 2400 bits per second over a 2 KC voice circuit. Data Phone cost for the same distance is $105, 600. 00 per year.

This type of saving would certainly be worthwhile, and in many cases could not otherwise be done.
In addition to the cost savings, there are other advantages. Since the redundancy reduction process must have memory for each channel processed, this memory could be used to provide zero shifting and scaling. Each channel could be processed whereby the retransmitted values were in engineering units, which is essential for real time presentations.

Computer VS Special Purpose Equipment

In the case of an adaptive telemeter there is no question but that the telemeter could be adapted to perform the redundancy reduction easier than a computer. For instance the divisions necessary for determining the slope could be done in an analog fashion during the coding process. This method would be much faster and cheaper since it is part of a process that is already being performed.

In the case of re-transmission, a general purpose computer could be used to remove the redundant data. However, if the Fan Method is implemented on a computer at a 3.6 KC word rate, the cycle time must be 3.5 microseconds or less. This means that the computer must be one similar to the IBM 7094 Model II.

When the Fan Method is performed by special purpose logic it can be implemented with about 300 standard digital logic modules at a hardware cost of about $10.00 per module plus the necessary memory.

Conclusion

The results of this study have shown what is believed to be the present day state-of-the-art as far as digital data acquisition is concerned. All channels studied (many other than the three reported here) showed serious problems in selection of the sampling rates on errors due to inadequate sampling. Also the interface between the transducer and the data transmitter is not properly handled, nor is the interface between the data receiver and the computer.

Many measurements being taken today are completely useless without a great deal of computer processing, such as averaging, scaling, linearizing, zero shifting, etc. If more were understood about the data all of these things as well as redundancy reduction could be done in real time in the adaptive telemeter.

The only answer to all the problems is a detailed study of each measurement, before the system is designed. This study is not difficult, particularly in the case of Rocket Booster Data. The proper system could be devised during the static testing phase and the mass of data as it is now being done could be reduced to a reasonable amount.

The current procedure of using up to ten separate RF links cannot continue, when it is realized that the really meaningful data can be transmitted over one link. Also it is physically impossible to process all this redundant data. An adaptive telemeter would make it possible to use computers much more efficiently by only processing
Adaptive telemeters must be designed where they can easily be changed to meet unknowns. The sampling rates on all channels should be such that they can be directly changed without the current bunglesome process of sub and super commutation. The accuracy on each channel must also be flexible and different for some channels. It is foolish to waste bandwidth on poor accuracy channels.

The example shown in Fig. 8 shows that 290 samples are needed to get a 1% peak-to-peak error. Of these only six are data, and the other 284 are necessary to obtain an average of the high frequency pick-up present. If the system had been properly designed with the proper transducer, pre-sampling filter and sampling rate, this would not be necessary. Something just over six samples would have provided the data to a better accuracy.

The final answer as to how to build adaptive telemeters will come from the study of real telemetry data, and the building of systems for retransmitting this data over limited bandwidths.

References


Fig. 1 Pressure Data

Fig. 3 Pressure Data

Fig. 2 Interpolation Errors of a Sine wave

Fig. 4 Pressure Redundancy Curves
Fig. 5 Pressure Redundancy Curves by Fan

Fig. 6 Flow Data

Fig. 7 Flow Redundancy Curves by Fan

Fig. 8 Flow Redundancy Curves by Step
Reconstruction by Fan Method

Original Data

1.0% Tolerance

0.5% Tolerance

Reconstruction by Step Method at 1% Tolerance would be a horizontal line through 45.

Fig. 9 Temperature Data

Fig. 10 Temperature Redundancy Curves