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Summary

In the coming decade, we can expect to see an expansion in the utilization of space vehicles for the benefit of society. System design studies for resource measurement and management, meteorology, oceanography, mapping and indeed in all areas where space technology can provide a cost effective means of gathering data on a global scale are in progress now. In the first part of the paper, the resulting growth in requirements for data storage on spacecraft is discussed, as well as the technology at hand for storing required data in the most appropriate form and at suitable input and output rates. It also suggests the most economical means of storing data in spacecraft.

The second part of the paper will discuss the servo-driven tape recorder approach to meeting these requirements. It is shown that, by use of the servo approach, a very flexible and simple mechanical design can be employed having only eight rotating parts. An analysis of the servo loop response is presented and it is shown what system parameters are important in obtaining minimum flutter.

The last part of the paper is concerned with processing the data before and after recording. Equalization needs for FM and digital data systems are discussed. In addition, the computer aided design approach to the analog and digital data channels of the High Data Rate Storage System for the Nimbus B and D meteorological satellite is described.

Future Requirements and Available Technology

Since April 1, 1960 when TIROS I, the first weather satellite, was launched, the data storage requirements of unmanned spacecraft have steadily grown,[5] as illustrated on Figure 1. Extrapolating this trend into the 1970's indicates that geophysical satellites will require a data storage capacity of 500 megabits, or double this for the duplicate redundancy normally specified. But if we consider recent developments in visual and infrared sensors, there is likely to be a quantum jump of at least two orders of magnitude in data storage needs. Sensors now in use have the same resolution as commercial television, around 500 lines per frame; the new sensors have a resolution of around 5000 lines per frame and this will be coupled with improved optics and scanners. As an example, an earth resources satellite has been proposed which will orbit at 500 nautical miles carrying a 2-inch return beam vidicon equipped with a 5-inch focal length f/2.8 lens. This would provide ground coverage of 250,100 × 100 nmi frames with a resolution of 100 feet per TV line.[1] Allowing 6 bits of information per TV element, there would be 150 megabits per frame, or 37.5 gigabits per orbit. Clearly it will be necessary to be selective or otherwise to provide some measure of on board data reduction.[2] Even so, we can safely forecast the need to store several gigabits of data in the next generation of this class of vehicle.

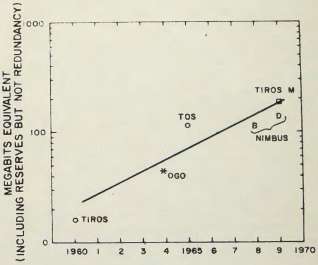

Figure 1. Growth of Satellite Data Storage Requirements

Present technology and the advances we can expect in the next few years offer a wide variety of means of storing electrical data. Anticipated costs for space qualified solid state data storage devices range from 10 cents to 1 cent per bit while anticipated costs for space qualified magnetic tape recorders range from 0.1 to 0.01 cent per bit. These estimates are for deliverable hardware and do not include the $4000 to $6000 for each pound placed in orbit and $9000 to $15,000 for each watt of power system capacity required. These factors give a trade-off strongly favoring the magnetic tape recorder and this is borne out by the fact that over the past 8 to 10 years, the government has made a large and continual investment in the development of magnetic tape recorders for spacecraft.[3] But the challenge is still to design, build, and test equipment which has the reliability and absence of fatigue or wear-out for several years of continuous duty without maintenance of any sort.

Drive Systems

A tape recorder along with other mechanisms needs a constant speed drive. This is required to transport the tape across the record and playback heads with great regularity often at more than one speed and in either direction. Only small variations in speed are permissible. Specifications commonly call for the rms flutter not to exceed a figure in the range of 0.1 to 0.5 percent.

The lower part of the flutter spectrum is determined by the dynamic behavior of the drive system. Various schemes may be compared by considering to what extent the drive scheme prevents a torque disturbance from becoming a speed disturbance. Figure 2 shows two schemes compared; the lower curve shows the relationship for a direct coupled phase-locked servo drive, and the upper curve shows the relationship for a mylar belt coupled synchronous hysteresis motor drive. Both schemes have the same inertia at the capstan. The comparison brings out the beneficial effect at the lower end of the spectrum of the much greater stiffness obtained by the use of a servo drive.

craft. Figures 3 and 4 show this machine from below and above. The servo is a phase-locked system. That is to say, it is a positional servo with a con stantly changing demand rather than a velocity servo, or velodyne. In this class of system, the torque required to drive the load at the desired speed is produced by a positional or phase error. Once locked in, there is no steady-state velocity error at the capstan. The stiffness of the drive is defined as the torque developed at the capstan per radian of capstan positional error.

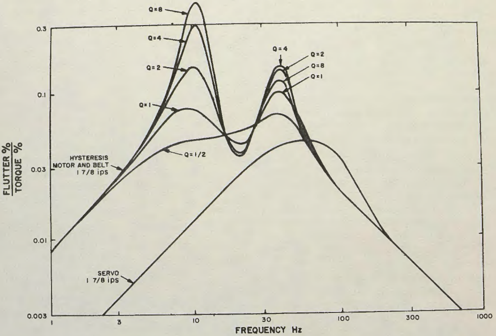

Figure 2. Drive System Flutter Correcting Capability

There are many other advantages that arise from the use of a servo to drive the capstan. A very wide speed range is possible without recourse to the mechanical complications of clutches, brakes, or epicyclic belt systems. During record or playback, the capstan speed may be locked to a reference frequency; but during playback, the output data rate may be locked to a reference frequency. In the latter case, the frequency of a signal recorded on the tape is used as a servo feed-back. Because of the high torque-to-inertia ratio of servomotors, short start and stop times can be achieved, especially if the circuits used allow dynamic braking. Power consumption can be minimized by using high efficiency d-c motors and pulse width modulation techniques. Mounting the motor directly on the capstan shaft results in a very clean and simple configuration with a minimum number of rotating parts.

A recent example of a servo-driven tape transport is that designed to store the data from a two wavelength scanning radiometer for the ITOS spacecraft.

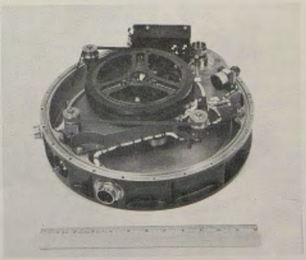

Figure 3. ITOS Scanning Radiometer Tape Recorder (With Housing)

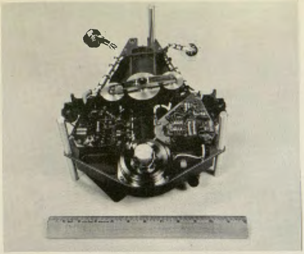

Figure 4. ITOS Scanning Radiometer Tape Recorder (Without Housing)

Figure 5 is a block diagram of the system. The motor is an 8 pole d-c torque motor developing about 20 oz-in. running at 0.6 and 10 rps in the record and playback modes respectively. The optical encoder has 1000 lines and produces a 600-Hz signal at the record speed of 1 7/8 inches per second and a 9600-Hz signal at the playback speed of 30 inches per second. The encoder uses a pair of gallium arsenide diodes and silicon photo-transistors placed 180 degrees apart both mechanically and electrically as a detector system. The light sources have a peak output at about 9000 Å, and the electrical difference output is about 1 microamp for each milliamp at 0.5 volt supplied.

In the record mode, the servo mechanism was designed to have a gain margin of about 9 dB, a phase margin of about 51 degrees, and a bandwidth of 110 Hz. The open loop response was precisely claculated using a nodal analysis computer program. The response is plotted as a Nyquist diagram (curve A) on Figure 6. The closed loop response has been measured using a transfer function analyzer. The open loop response was derived graphically from the test results and plotted as curve B on Figure 7. The measured gain and phase margins are adequate although a little less than predicted. There is a reduction of loop gain of 6 dB during playback, thus increasing the stability margins at the expense of stiffness. The power consumption of the drive system is 2.1 watts during record and 4.5 watts during playback. The cumulative flutter is between 0.2 and 0.3 percent with spectral peaks corresponding to the capstan rate, the commutation rate, various tape/idler resonances, and a 5-kHz frequency due to the tape rubbing against the head.

The next step is to replace the mechanical commutator in the d-c torque motor by a solid state optical/electronic system. Work on this now has started at the RCA Astro-Electronics Division. By using an optical device for end-of-tape sensing, by the avoidance of edge guidance, by the use of an erase head which does not actually touch the surface of the tape, and by the use of a brushless motor, it will be possible to build a tape transport whose only rubbing interface is between the magnetic tape and the record and playback heads. By careful design, it should only be at this interface that the vulnerable iron oxide and binder surface of the tape comes into contact with anything other than the tape substrate. The present servo recorder has only eight rotating parts. This could be reduced to six by eliminating the negator-type tensioning system but it would then be necessary to add a brake to lock the mechanism when unpowered.

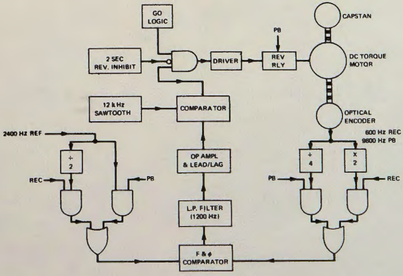

Figure 5. ITOS SR Tape Recorder Servo Drive System, Block Diagram

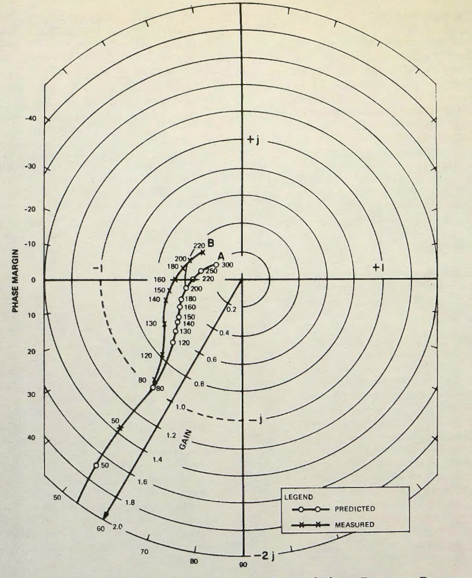

Figure 6. ITOS SR Tape Recorder Open-Loop Gain and Phase-Frequency Response

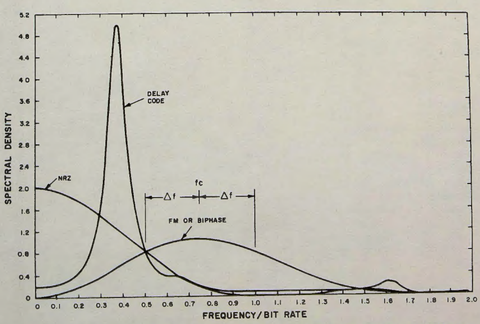

Figure 7. One-Sided Spectral Densities of Delay Modulation, NRZ, and Biphase Data (Normalized to 1 Bit/Sec)

Signal Processing

Direct recording with or without d-c or a-c bias is not commonly used in spacecraft tape recorders. This is because imperfections in tape, tracking errors, and variations in head-to-tape separation of a few microinches modulate the signal amplitude to an extent sufficient to make the signal-to-noise ratio unacceptably low. Most recording is either FM or digital. Digital codes which are self synchronous, such as Manchester or biphase, as preferred since this avoids the need for a timing track. The elimination of the timing track overcomes timing errors due to track-to-track skew or jitter. In both FM and digital recording, the information is carried by the relative location of the zero crossings. At high frequencies, losses due to the finite gap in the record head and head-to-tape separation and the 90-phase lead due to the flux-rate sensing property of the heads lessen the sharpness of the zero crossings and cause a time shift in the waveform pattern transitions.[7] This can be substantially reduced by gain and phase equalizing networks designed to give an overall linear phase versus frequency response and an amplitude response, which is balanced about the frequency mode of the spectral density curve. Computer programs have been developed which enable responses to be rapidly evaluated and related to pattern transition time shift. The equalizer is usually followed by a 20 to 40-dB hard limiter, which cuts out amplitude modulation and greatly reduces the number of drop-outs due to tape imperfections. Packing densities of 6000 cycles per inch and 3000 bits per inch are now in common operational use, and 20,000 bits per inch is regarded as state-of-the-art. Efforts continually made to increase packing density and programs with target densities of 50,000 bits per inch are in hand. Bit error rates which are almost entirely due to tape drop-outs of 1 in 10^6 bits are par, and specifications usually call for less than 1 in 10^5. In FM systems, flutter is the predominant noise source.[6] Signal-to-noise ratios are well predicted by the relationship:

$$snr_{p-p/rms} = 20 \log \frac{2 \times \text{Deviation}}{\% \text{ flutter} \times 100}$$

Approximately 40 to 45 dB is typical for present systems.

Saturation recording is usually chosen for digital recording. This minimizes the effect of tape drop-outs but the high frequency tape/head response is worse than when recording at somewhat less than saturation level. FM systems often have less stringent requirements on drop-outs than digital systems, and for this reason there has been a tendency to use lower recording flux levels. However signal processing requirements for FM and digital data are essentially the same. This is borne out by the similarity in spectral density curves for a typical FM signal and biphase shown on Figure 7.

The system trade-off between FM and digital systems is finely balanced. At lower packing densities, an FM system is more economical but the ease of data compression and reduction of digital data often outweigh this. We can expect to see wider use of digital systems and the employment of sophisticated mixed analog and digital systems during the next decade.

Record drive amplifiers, playback preamplifiers, equalizers, and limiters are primarily linear circuits whether the data is digital or FM. Hybrid integrated circuit technology is now being applied to packaging these circuits. This will ease the preferred location of these circuits, which is as close to the magnetic heads as practicable to avoid crosstalk and pick-up.

Conclusions

To measure the earth's resources and explore other planets, the spacecraft of the 1970's will use magnetic tape recorders to store the vast mass of data gathered by the high-quality multispectral sensors on board. At the same time, we can expect to see the increase in the data storage load stemmed by the employment of on-board data reduction systems and data relay satellites. The engineering development of versatile ultra-reliable long life tape transports and associated signal processors, such as those described in this paper, will no doubt continue but we may even now be near the limits of performance set by the fundamental physics of the head/tape interface. The challenge to magnetic recording will come from research on static mass data storage techniques. It remains to be seen whether advances in this field will eventually the tape recorder from its present dominant position.

References

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