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A MULTIPLEXER/DEMULTIPLEXER SYSTEM FOR THE MULTI-COLOR SPIN SCAN CLOUD CAMERA ON ATS-C*

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SUMMARY

The ATS-3 spacecraft has transmitted many high quality color pictures of the full earth disc. This paper describes the design of the multiplexing/demultiplexing system for the multi-color camera. This system, which employs time division multiplexed pulse amplitude modulation (PAM), is described from a block diagram standpoint. Circuit design highlights and packaging details are also provided. Finally, the test results of the actual equipment are given.

INTRODUCTION

The spin-scan camera on the first ATS flight launched in December, 1966, returned the first high-resolution black and white pictures of the Earth from synchronous altitude.[1] ATS-3 launched on November 5, 1967, repeated the experiment with color capability added. Both of these cameras use the spacecraft spin motion for sweep in longitude and a mechanical stepper which physically tilts the camera optics for the latitude motion.

The spin-scan color camera experiment requires the transmission of three times as much data as the black and white camera because three color signals are necessary. Since only one spacecraft voltage controlled oscillator (VCO) for modulating the microwave transmitter was available, some type of multiplexing scheme was required for near-simultaneous transmission of the three signals. A corresponding demultiplexer at the ground station was necessary to separate the green, red, and blue signals for photographic processing.

In addition the multiplexer had to incorporate provisions for transmitting pulses from a spacecraft Sun sensor on two channels and a tone signal on one channel. The tone signal indicates to the ground equipment when the camera has stepped in latitude. The Sun pulses provide spacecraft spin reference information to the ground equipment for synchronization purposes.

Other salient performance requirements of the multiplexer/demultiplexer combination exclusive of the R.F. link are: Color channel bandwidth 0 to 150 kHz, channel linearity better than 1 percent, crosstalk between channels less than 1 percent, input signal dynamic range 1 mv to 0.5 volt (54 db), and gain stability of each channel better than 2 percent for the picture frame time of 20 minutes.

Although some of these requirements are more severe than necessary to obtain a subjectively pleasing picture, they were imposed because the picture data was to be computer processed in order to obtain the maximum amount of information from the experiment. Of course, since the multiplexer portion of the equipment was spaceborne, it was required to have minimum size, weight, and power consumption.

SYSTEM DESIGN CONSIDERATIONS

The types of multiplexing considered were frequency division by both AM and FM modulated subcarriers and time division by both direct pulse amplitude modulation (PAM) and pulse code modulation (PCM). These techniques were examined with respect to the program constraints (performance requirements, delivery schedule, etc.) before a final selection was made.

For those schemes which process the information in a sampled data manner, the sampling rate for each channel must be at least twice the maximum frequency of interest or 300 kilosamples per second. Assuming 9 encoding bits per sample for the PCM case (a dynamic range of 500 to 1 is required), a bit rate of 2.7 Megabits/sec/channel or 8.1 Megabits/sec for 3 channels is needed as an absolute minimum. This bit rate uses up almost all of the available 5 MHz baseband of the ATS VCO and no allowance has been made for synchronization or for sampling at a safety factor greater than twice the maximum information frequency. For this reason, PCM is eliminated from further consideration.

In the frequency division multiplex case (either AM or FM modulation of the subcarriers), the three channels may be handled by modulating one channel directly on the spacecraft VCO and placing the other two channels on subcarriers, or by placing all three on separate subcarriers. If one of the channels directly modulates the spacecraft VCO, some form of DC restoration scheme must be employed since the spacecraft VCO is AC coupled. For each of the frequency division possibilities (AM or FM, 2 or 3 subcarriers), there is sufficient baseband to achieve the desired channel separation.

The FM modulated subcarrier case offers the potential for the best S/N ratio. However, the need to process DC information creates a problem because subcarrier frequency drifts would have to be individually compensated. A voltage controlled crystal oscillator to minimize this drift problem cannot be used because it is not possible to get enough center frequency deviation with this type of device. For example, for a 1 MHz subcarrier frequency deviated

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*Following its successful launch the spacecraft is now called ATS-3.

±1 percent (a typical value for a crystal oscillator), a modulation index of only 0.06 is obtained for a 150 kHz signal frequency. Thus, the design of an FM non-crystal voltage controlled oscillator which will provide reasonable deviation (>10 percent) and yet have minimal center frequency drift must be undertaken if this method is to be used.

The need for good linearity over the entire dynamic range limits the techniques that may be considered for generating AM modulated subcarrier channels. Many "conventional" AM modulation schemes involve multiplication via some non-linear device (such as a diode) characteristic. However, such methods do not provide the performance with respect to wide range linearity that is required here. An excellent method for meeting this requirement is to use the synchronous switch. In this approach an analog switch operating at the subcarrier frequency opens and closes between the signal and the load. This produces a suppressed carrier form of AM signal that does provide the necessary linearity. It is interesting to note that this same type of modulator can be used in a PAM system.

In the time division multiplex case, a sampling rate must be used that is high enough to handle the maximum information frequency and low enough to be consistent with the available baseband. A good compromise is to use a 2 MHz basic PAM commutating frequency. This provides a sampling time of 0.5 μs. The three channels then require a total time of 1.5 μs. Allowing an additional 0.5 μs for a synchronization channel results in a total PAM frame time of 2.0 μs. Therefore, four PAM channels are required and each is sampled at a 500 kHz rate (once per 2 μs). It may be seen that a 500 kHz sampling rate provides 3 1/3 samples/cycle (150 kHz) and that the 2 MHz commutating frequency is consistent with the available 5 MHz baseband. Therefore, PAM is feasible for this application. Since the PAM composite waveform does have a DC component, it is necessary to provide some compensation for the AC coupling network of the spacecraft VCO. However, this is easily done via the synchronizing channel (discussed in more detail later). Note that only a single device is being compensated here rather than separate subcarrier devices as would be required for the FM frequency division multiplexing case.

It is desirable that the three information signals be processed in as near an identical manner as possible in order to ensure color balance. That is, distortions which might come about due to phase nonlinearities, temperature drifts, etc. should be nearly the same in each channel. This requirement gives an advantage to the time division multiplex scheme. In the PAM case, each channel is processed by identical circuitry. All filters, buffer amplifiers, and scaling networks are of the same design. However, in the frequency division case, different filtering must be used in the three channels since different subcarrier frequencies are used for each.

Among the multiplexing systems considered no single technique clearly stands out as the obvious choice. However, based on the above considerations PAM was chosen as the multiplexing technique that offered the best chance of meeting all of the design goals with a minimum of implementation problems. It was concluded that the PAM technique offered the best channel similarity, handled DC information satisfactorily, and provided the required linearity.

BLOCK DIAGRAM DESCRIPTION

The time division multiplexing system switches each camera signal in sequence to a summing amplifier which drives the VCO in the spacecraft repeater. A known DC voltage (+0.5 volts) is sampled by a fourth channel and is used for synchronization and DC restoration in the ground equipment. The step tone signal (20 kHz) is added to this channel at a peak to peak value of 50 millivolts. The demultiplexer receives the multiplexed signal from the discriminator in the ground receiver, samples each channel in the correct sequence (guaranteed by proper synchronization) and thus separates the four channels. Filters in each channel eliminate the sampling frequency and other noise. The 20 kHz step tone is filtered out of the synchronization channel so that it does not interfere with the DC restoration function of this channel.

The block diagram of the multiplexer is shown in Figure 1. The green, red, and blue camera signals (0 to -0.5 volt) are amplified and then filtered by a second order Butterworth active filter to remove unwanted components above 200 kHz. Because of the 500 kHz sampling rate, frequencies above 250 kHz would cause aliasing errors and must be attenuated. A positive-going sun pulse (obtained from a spacecraft sun sensor) is passed through a threshold circuit to eliminate the sensed, but lower amplitude, earth pulse. The sun pulse is amplified and limited to 0.2 volt maximum and then summed with the green and red video signals (two channels are used for redundancy). The polarity of the sun pulse is opposite to that of the camera video signals which are always negative. This feature together with the fact that the geometry of the sun sensor and camera do not permit the sun pulse and the video to occur at the same time permits easy separation of sun pulse signals from camera signals on the ground. The tone signal is summed with the +0.5 volt reference in the fourth channel.

Electronic shunt switches in each channel ground that channel except when it is being sampled. The signals from all channels are combined in a summing amplifier which drives the spacecraft VCO. The full 5 MHz bandwidth of the spacecraft VCO is required to accommodate the combined channel sampling rate (2 MHz) since the rise time of the sampler must be preserved in order to minimize crosstalk between channels when decommutating. The summing amplifier is designed for optimum response to pulsed inputs. The transients produced by an input pulse from the commutator must subside before one-half of the sampling time (250 nanoseconds) has elapsed since the ground decommutator is delayed approximately this amount before desampling the same signal (detailed discussion follows later).

The block diagram of the demultiplexer is shown in Figure 2. The signal from the receiver discriminator is amplified with a gain of eight and applied to an electronic decommutator and pulse height discriminator. The amplitude discriminator rejects the lower amplitude Sun pulses but responds to the larger amplitude positive pulses from the output of the calibration channel in the multiplexer. These pulses are applied to a phase locked loop consisting of a phase detector, smoothing amplifier, VCO, and a countdown chain with associated logic. The countdown chain and logic furnish the control signals for the electronic decommutator. It should be noted that the basic clock frequency, for the countdown chain is twice the multiplexer clock frequency or 4 MHz. This is done to divide the sampling interval in half so that the decommutator sees only the last half of a received sample. A phasing control in the phase locked loop permits positioning the desampling pulse away from both the leading and trailing edges of the received sample to minimize crosstalk. The electronic decommutator uses shunt switches similar to those in the multiplexer; however, in this case, two switches are cascaded in each channel to minimize feedthrough from other channels (discussed in detail later). The X4 amplifiers are used to compensate for a factor of 4 attenuation inherent in the configuration of the demultiplexer switches. Low pass filters in each channel eliminate decommutation frequencies and other unwanted signals above approximately 165 kHz. The calibration channel is further filtered by an RC filter with 100 millisecond time constant (to reject high frequencies in the restoration loop) before it is applied to a differential amplifier. The differential amplifier with a gain of 100 amplifies the difference between the well filtered output of the calibration channel and a reference voltage equivalent to the reference voltage applied to the calibration channel in the spacecraft. The output of the differential amplifier is applied to the video amplifier to DC restore the received signal. Since this RC filter time constant of 100 milliseconds is inside a closed loop it is divided by one plus the loop gain making the time constant of the DC restoration loop approximately one millisecond. This is fast enough to properly restore the video for the length of time the camera sweeps past the earth but slow enough not to respond to the step tone signal. At synchronous altitude the earth subtends an angle of approximately 18 degrees. With a spacecraft spin period of 0.6 seconds (100 rpm) the earth is "in view" for only 30 milliseconds. A front panel "push to sync" switch disables the DC restorer for demultiplexer alignment purposes and to aid in initial synchronization of the phase locked loop.

CIRCUIT DESIGN HIGHLIGHTS

In this section, circuit design details relating to some of the more critical and/or interesting functions will be discussed. A complete circuit discussion is beyond the scope of this paper and thus, at best, only highlights are possible.

Multiplex Switching

Figure 3 provides an example of an ideal PAM waveform. This waveform would be generated if the multiplexer switches turned on and off in zero time and if the transmission media had infinite bandwidth. Figure 4 shows how finite switching time and finite transmission bandwidth affect the ideal waveform. The primary result of the non-ideal waveform phenomena is crosstalk. It may be seen that a given channel tends to "slop" over into the following channel. For this reason, the demultiplexer switch is not turned on until later in the sampling interval and remains on for only half the sampling interval as pointed out in the Block Diagram Description. Figure 5 shows sampling and desampling waveforms. Note that the sampling and desampling times are 0.5 μs and 0.25 μs respectively.

These sampling intervals are rather short and it may be easily appreciated that high speed analog switches are needed to implement the multiplexer/demultiplexer commutating functions. It is desirable that the switching time be less than 10 percent of the sampling interval so that variations in switching times with temperature, parameter drifts, etc. do not adversely affect the system transfer characteristics. Thus, multiplexer switching time should be less than 50 ns and demultiplexer switching time must be less than 25 ns. This system has achieved these goals with switching speeds of 50 and 20 ns respectively.

The device selected as the basic analog switch was the diode quad. It was chosen because of speed, bi-directional signal handling, low offset in the "on" condition (devices are purchased already matched), and good availability. Fundamental operation is depicted in Figure 6. Best operation is obtained when the I_{drive}/I_{signal} ratio is 10 or more (a ratio of 20 is actually used). When I_{drive} is flowing, the diodes are turned on far into their conducting region and appear as low impedances. This allows I_{signal} to flow through a low impedance path. Note that even though I_{signal} appears to be flowing backward through some of the diodes, the net current through the diodes is still in the forward direction since I_{drive} is much larger than I_{signal}. Thus, a low impedance path (around 10 ohms in the actual system) is presented to the signal current and this current may flow in either direction. When I_{drive} is not flowing, the diodes will block current attempting to flow in the I_{signal} path.

Therefore, it can be seen that the switching action is controlled by turning I_{drive} "ON" and "OFF."

The manner in which the diode quad is used in the final analog switch configuration depends upon the selection of a single series switch, a single shunt switch or a combination of both of these (push-pull). The single shunt switch was chosen because it offered the simplest interface with the driving circuitry without requiring the use of magnetic components and did not present difficult timing problems as with the push-pull version. The basic circuit is shown in Figure 7. Because one side of the quad is grounded, a rather simple driving circuit may be used. It may also be seen that the interface with the timing circuitry is easily accommodated. Note that the analog switch is "ON" (allowing the signal to pass through) when the quad is "OFF" and vice versa.

The "ON" resistance of the quad determines the amount of signal rejection that will occur when the analog switch is supposed to be "OFF". Thus, it is desirable that this "ON" resistance be as low as possible. The "ON" resistance is governed by the I_{drive} level. By making I_{drive} as high as possible (within the limits of reasonable power dissipation), an "ON" resistance of 10 ohms was achieved. The equivalent circuit of the switch in the "OFF" condition appears as shown in Figure 8. With R_{quad} fixed at a 10 ohm minimum, it is desirable to have R_{series} large so that high attentuation will be achieved. However, R_{series} must charge whatever shunt capacity exists at the switch node during switch turn on and this requirement demands a small resistance. With an R_{series} of 10 k, a crosstalk component of 0.1 percent is obtained and a switch turn on rise time constant of 25 ns (10 k in parallel with the 10 k summing amplifier resistor multiplied by approximately 5 pf at the switch) is available. Thus satisfactory attenuation (the total crosstalk requirement is 1 percent) and rise time are obtained for the multiplexer switch.

The demultiplexer switch must turn on with a time constant of around 10 ns which requires an R_{series} of less than 2 k. However, 2 k results in a crosstalk component of 0.5 percent and this is unacceptable since it uses up a major portion of the acceptable total (1 percent) without even considering the contributions of switching dynamics, pickup, etc; therefore, a two level switch is required. A dual shunt switch is used because it enables the use of a common design and because no overlap timing problems such as with a push-pull switch exist. In this way, both high attenuation and low series impedance for high speed are achieved. The block diagram of Figure 2 shows the general arrangement.

Low Pass Filters

It is necessary to use low pass filters for presample filtering in the multiplexer and for final signal recovery in the demultiplexer. It is desirable that these filters have an essentially distortionless transfer characteristic in the time domain. That is, a transfer function which is flat in amplitude and linear in phase over the desired frequency band is required. The Butterworth function approximates this need. An active filter based on the use of an integrated circuit amplifier (μA709) was used as the basic building block. Figure 9 shows the configuration. Any multiple of two pole filters may be constructed in this manner by cascading stages. The presampling filter is two pole using a single amplifier while the final data recovery filter is a six pole three amplifier circuit. To determine the circuit parameters, one first determines the fundamental frequency and damping factor for a pair of complex conjugate poles based on desired filter characteristics.[2] These parameters are then used in the following formulae to compute component values.

$$\omega_{3db} = \frac{1}{RC}$$

$$e_o = -\frac{1}{1 + 2\xi\,\omega s + (\omega s)^2}\,e_i$$

where

ω = corner frequency of two-pole stage (rad/sec)

ξ = damping factor of two-pole stage (unitless)

R & C - as indicated in Figure 9

These formulae assume perfect amplifiers (infinite gain and frequency response). The validity of this assumption was checked using an ECAP computer simulation which incorporated the characteristics of the real amplifier. The results of the calculations based on the ideal amplifier, the results from the computer simulation, and the data taken on the actual circuit were in close agreement.

PACKAGING

The multiplexer was housed in a compartment which was separate and detachable from the camera frame. A photograph of the engineering model is shown in Figure 10. Because of the sharp rise times of the pulse type waveforms and the stringent crosstalk requirements between channels, special precautions were necessary in the mechanical design of the equipment. Point to point wiring was employed and special care was used in the physical layout to achieve maximum isolation between channels. The components were mounted on the insulated side of single-sided copper clad boards. The copper side was used as signal ground ensuring a good low impedance ground plane. The multiplexer electronics were mounted on two circuit boards and were stacked one on top of the other in the camera compartment.

The single-sided copper clad board and point to point wiring technique was also used in the demultiplexer. The equipment was mounted on two boards which were positioned on standoffs inside a box chassis. The chassis provided RF shielding to minimize interference with other ground station equipment. All input and output signals were brought into and out of the equipment via coaxial cables. A photograph of the demultiplexer and companion power supply unit is shown in Figure 11.

SYSTEMS PERFORMANCE

The multiplexer/demultiplexer system was tested with the multiplexer coupled directly to the demultiplexer, eliminating the RF link.

Figure 12 is a graph illustrating linearity of the multiplexer/demultiplexer system for dc signal inputs. The percentage deviation from the best straight line through the data points is plotted versus input amplitude. No data point deviates more than 0.4 percent from a straight line over the dynamic range of interest (-0.5 volt to +0.2 volt). Figure 13 shows linearity for signal frequencies of 100 kHz. Maximum deviation from the best straight line is 0.45 percent over the input range.

Figure 14 shows the frequency response of each channel. Response is quite flat out to 100 kHz with a maximum peaking of less than 1 db around 125 kHz. Response is down less than 1 db at 150 kHz, the maximum frequency of interest. Rolloff is quite rapid above 150 kHz being down approximately 11 db at 200 kHz, and continuing downward at a rate of 48 db per octave.

Table I summarizes the multiplexer/demultiplexer performance at various temperatures. The temperature of the multiplexer only was varied as the demultiplexer would normally be at a reasonably constant temperature in the ground station. Channel gain changes over the time for the camera to scan the earth (20 minutes) do not exceed 0.5 percent. Crosstalk between channels does not exceed 1 percent for signal frequencies up to 100 kc and is a maximum of 1.8 percent at 150 kc.

The spaceborne multiplexer weighed 1.7 pounds and required 4.8 watts of power.

CONCLUSION

A multiplexer/demultiplexer system for the spin scan color camera on ATS-3 has been described. The camera and associated electronics worked successfully and as of the date of this paper the system is returning useful color photos from orbit.

REFERENCES

1. W. S. Sunderlin, "The ATS-1 Spin Scan Camera Experiment," Proceedings of the Fourth Space Congress, April 1967, pages 4-19 to 4-30.

2. Philbrick Researches, Inc., "Applications Manual for Computing Amplifiers," Second Addition, June 1966, page 75.

3. D. G. Childers, "Comparison of Several FM Telemetry Systems," First IEEE Annual Communications Convention, Conference Record, June 1965, page 527.

ACKNOWLEDGMENTS

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Characteristic	Temperature	Frequency	Channel		
			Green	Red	Blue
Drift in 30 minute period.	Room	DC	1. 1 mv	1. 6 mv	1. 2 mv
	+70° C	DC	0 mv	0. 5 mv	0. 3 mv
	-20° C	DC	2. 0 mv	1. 5 mv	2. 9 mv
Linearity	Room	DC	0. 51 percent	0. 57 percent	0. 61 percent
	+70° C		0. 42 percent	0. 41 percent	0. 63 percent
	-20° C		0. 39 percent	0. 39 percent	0. 49 percent
	Room	10 kHz	0. 19 percent	0. 23 percent	0. 41 percent
	+70° C		0. 38 percent	0. 28 percent	0. 48 percent
	-20° C		0. 28 percent	0. 26 percent	0. 39 percent
	Room	100 kHz	0. 50 percent	0. 46 percent	0. 21 percent
	+70° C		1. 10 percent	0. 34 percent	0. 57 percent
	-20° C		0. 17 percent	0. 26 percent	0. 23 percent
3-db bandwidth	Room	—	>150 kHz	>150 kHz	>150 kHz
	+70° C	—	170 kHz	170 kHz	170 kHz
	-20° C	—	165 kHz	165 kHz	160 kHz
Crosstalk	Room	50 kHz	0. 39 percent	0. 33 percent	0. 36 percent
	+70° C		0. 06 percent	0. 16 percent	0. 21 percent
	-20° C		0. 41 percent	0. 36 percent	0. 25 percent
	Room	100 kHz	0. 98 percent	0. 50 percent	0. 48 percent
	+70° C		0. 98 percent	0. 47 percent	0. 43 percent
	-20° C		1. 00 percent	0. 52 percent	0. 29 percent
	Room	150 kHz	1. 62 percent	0. 40 percent	0. 48 percent
	+70° C		1. 74 percent	0. 42 percent	0. 50 percent
	-20° C		1. 55 percent	0. 54 percent	0. 14 percent
Change in gain, over 20 minute period	Room	DC	0. 40 percent	0. 10 percent	0. 20 percent
	+70° C		0. 40 percent	0. 56 percent	0. 40 percent
	-20° C		0. 31 percent	0. 21 percent	0. 21 percent
	Room	10 kHz	0. 40 percent	0. 40 percent	0. 59 percent
	+70° C		0. 10 percent	0. 00 percent	0. 20 percent
	-20° C		0. 10 percent	0. 00 percent	0. 10 percent

Table I. Performance characteristics at various temperatures, flight multiplexer and S/N 1 demultiplexer.

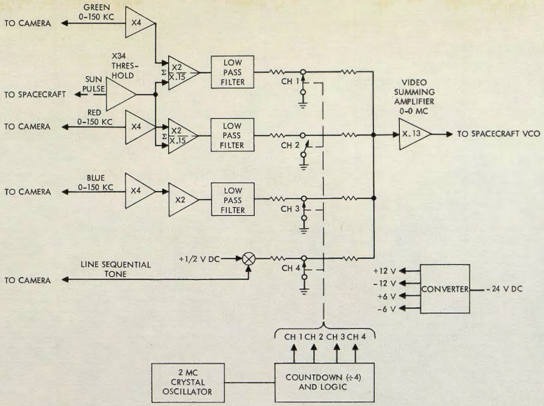

Figure 1. Multiplexer block diagram.

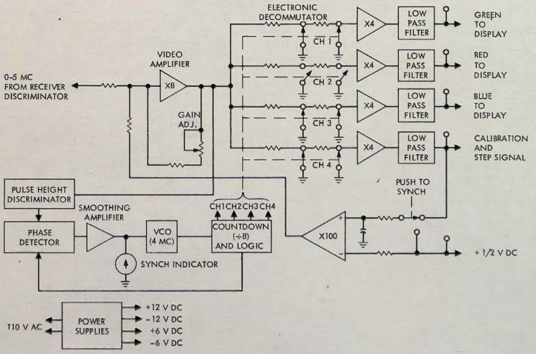

Figure 2. Demultiplexer block diagram.

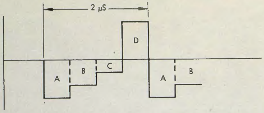

Figure 3. Ideal PAM composite waveform

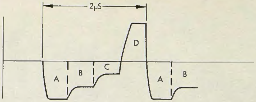

Figure 4. PAM composite with finite rise times.

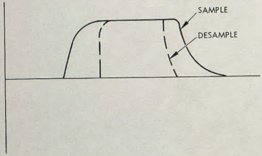

Figure 5. Sampling/Desampling relationship.

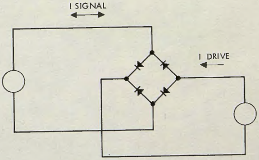

Figure 6. Diode quad.

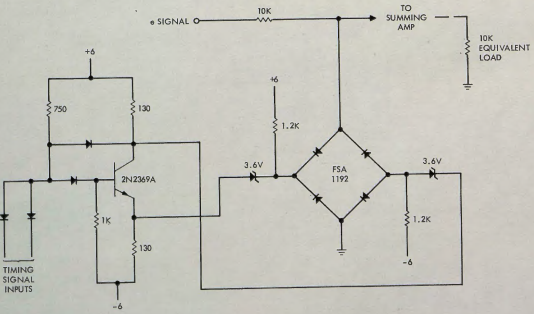

Figure 7. Analog switch.

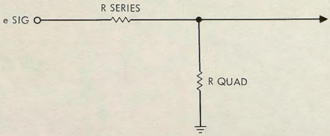

Figure 8. Switch equivalent circuit.

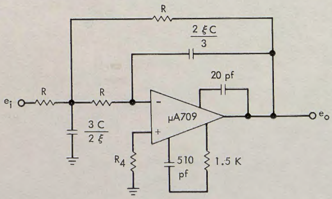

Figure 9. Active butterworth filters.

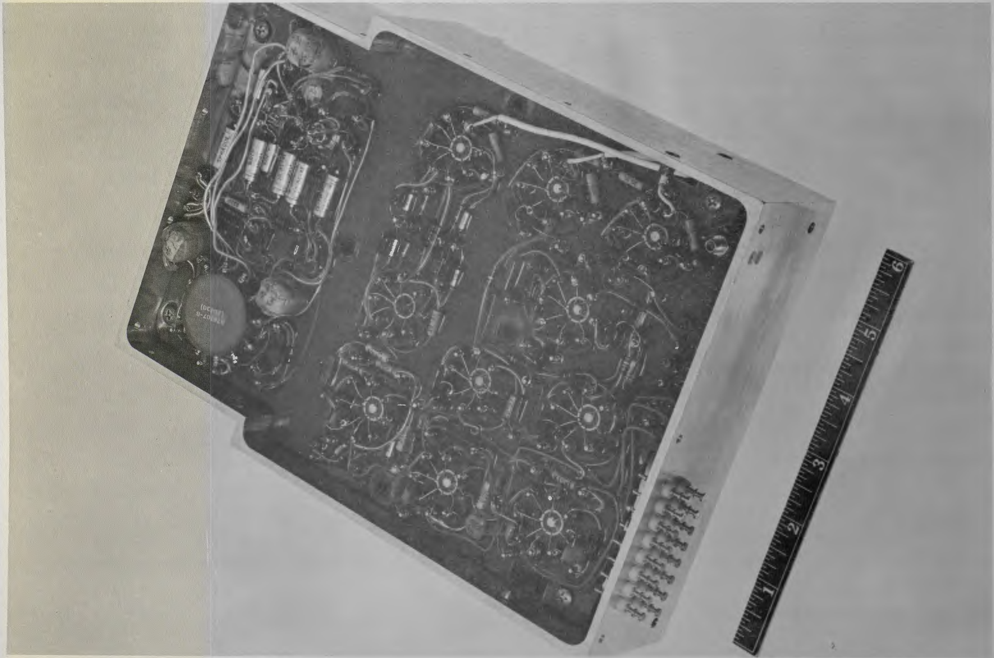

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Figure 10. Spin scan 3 color cloud camera multiplexer experimental model.

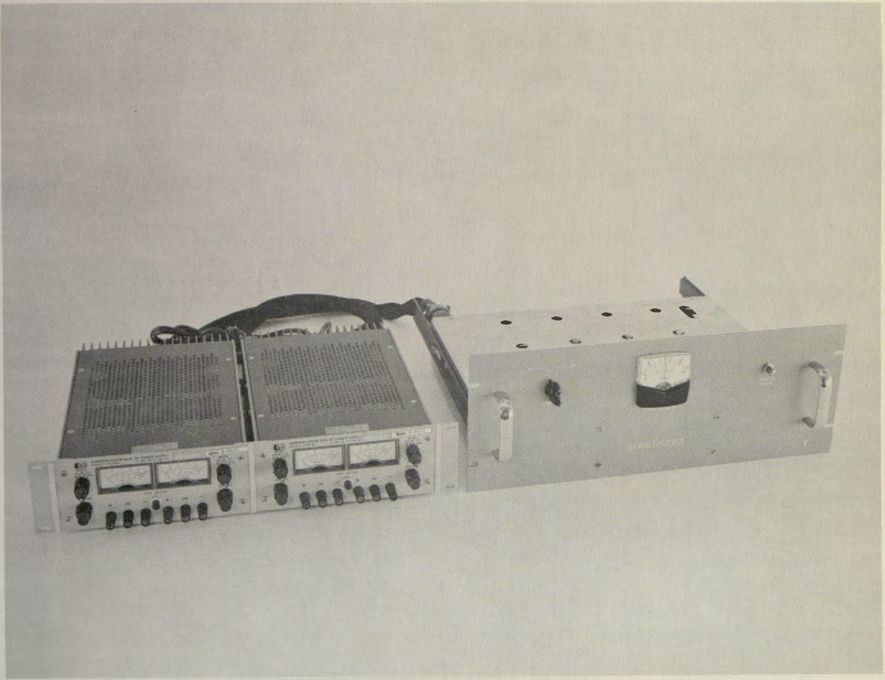

Figure 11. Demultiplexer and power supply.

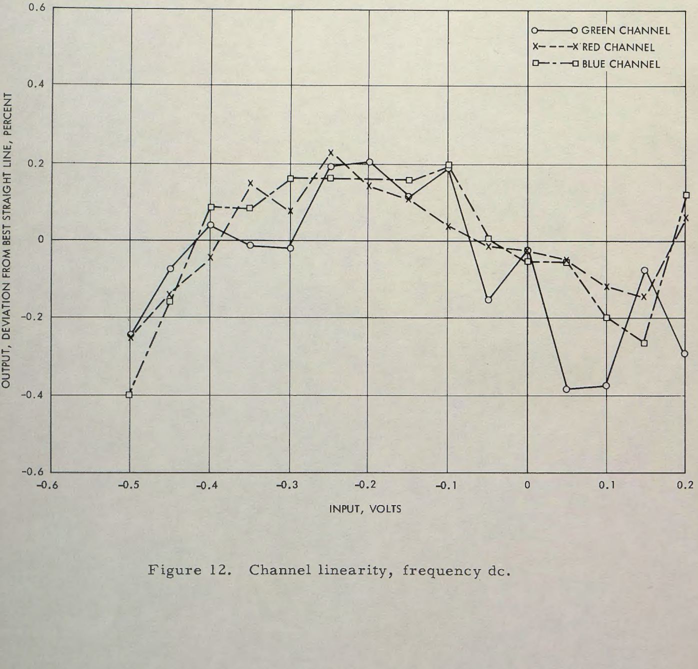

Figure 12. Channel linearity, frequency dc.

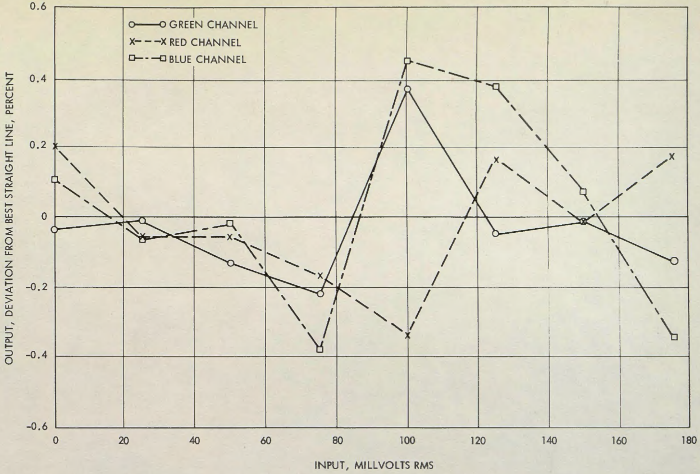

Figure 13. Channel linearity, frequency 100 kHz.

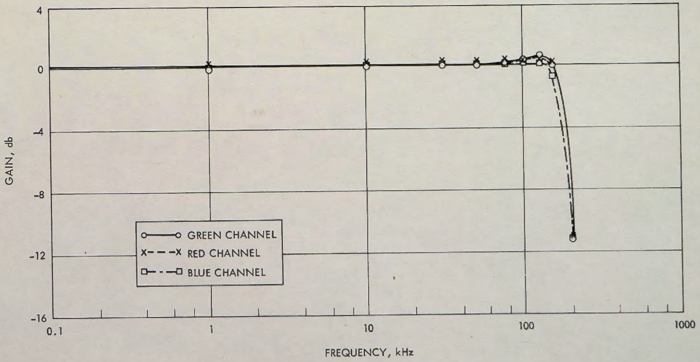

Figure 14. Multiplexer/Demultiplexer channel frequency response.