TELEMETRY FROM METEOROLOGICAL SATELLITES

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Meteorological Satellites have proven to be useful ever since the first launch of Tiros in April 1960, by delivery of large quantities of television pictures and infrared maps, To the system designer they present a challenging problem because of the variety of sensors they carry and the large data source they represent. Flexibility in their design must be accomplished to meet the demand for rapid incorporation of research results into operational systems. These satellites have further achieved the distinction of useful system performance for all launches performed, that is, Tiros I - IX and Nimbus I. Usefulness of Meteorological Satellites is not limited to measurement of reflected solar radiation as in TV and of emitted IR radiation -- the availability of an orbiting spacecraft designed specifically for weather data can serve for efficient collection and dispersion of data gathered on ground or within the atmosphere.

Choice of telemetry techniques and components for implementations have undergone profound changes since 1958, the year when the design of Tiros I was well advanced. The trend has shifted from analog modulation, specifically FM-FM, to digital telemetry such as PCM and it has been stimulated by the availability of reliable logic modules built as integrated solid state circuits. Consistant and predictable reliability will eventually be achieved because of the inherently higher reliability of these components and the agreement between theoretical analysis and actual performance.

Three types of spacecraft systems are in use in the Meteorological Satellite program; i.e., the Spin Stabilized Tiros, the three axis stabilized, earth oriented Nimbus and the cartwheeling Tiros operational system's,(TOS). Fig. 1 illustrates Tiros and TOS in orbital flights and the significance with regard to television operation. The Spin Stabilized Tiros launched in orbital inclinations of approximately 50° has TV cameras mounted so that the optical axis is parallel to the spin axis and pictorial coverage of the earth is restricted. The Tiros Operational Spacecraft is oriented so that the spin axis is normal to the orbital plane and controlled to remain within a small error angle by magnetic torquing. Magnetic torquing is a proven technique on the regular Tiros and other spacecraft and singly uses a coil wound around the circumference of the Tiros structure. Since the spacecraft rolls along the orbit like a wheel, a camera mounted looking radially outward will point at the earth once per spin revolution. If the camera shutter is simply synchronized to a suitable multiple integer of satellite revolutions, a continuous strip of TV frames can be recorded. The use of two cameras mounted inclined to the plane of rotation enhances coverage and resolution greatly.

The choice of a sun synchronous, retrograde orbit for TOS as was flown in Nimbus I adds further advantages. Fig. 2 illustrates the Nimbus orbit and its significance to television. When Nimbus is launched in a southwesterly direction in an inclination which is altitude dependent, the orbital plane will process due to equatorial bulging of the earth in the same direction as the earth moves around the sun. Proper choice of inclination permits selection of a mean rate of approximately 1° per day so that constant sun attitude is maintained, i.e., synchronism is achieved. This results for TOS and Nimbus in constant illumination conditions from orbit to orbit and constant solar power input into the power system. The Nimbus spacecraft is earth oriented so that cameras are pointing toward the earth continuously. Solar power collectors perform one rotation per orbit so as to face the sun at normal incidence. A tri-metrigon camera array provides complete daytime coverage at resolutions rom 1-3 m while an IR scanner provides nighttime coverage at 10 km resolution. An additional camera transmits continuously at reduced resolutions and without complete earth coverage, i.e., between 30° North and South latitudes there are uncovered gaps between adjacent orbits.

The 300 lbs. Tiros with an average continuous power capability of 20 watts, day and night, provides telemetry for two (redundant) television cameras, for telemetry of sun angle and horizon sensor signals, and for general engineering performance analysis. Their characteristic design has been discussed extensively and it may suffice to state their general features.

Fig. 3 shows a diagram of the redundant TV cameras and recorders. 32 pictures can be taken by each camera at programmed starting time. The 500 line, 62.5 Kc video bandwidth picture modulates an 85 Kc FM subcarrier ± 15 Kc on one type recorder track. A second track records a 10 Kc amplitude modulated subcarrier which carries a coded signal generated from solar cells mounted on the periphery of the structure. Upon command from the ground, the recorder plays back the two multiplexed signals over a 235 Mc-2 watt transmitter. High gain antennas at Wallop Island, Va., San Nicolas Island, Calif. or Fairbanks, Alaska, can receive the signal where films are prepared for picture analysis. An example of a picture taken by Tiros VII after 1-3/4 years continuous operation in orbit is shown in Fig. 4.

The satellite carries two 50 m watt, 136 Mc beacons for tracking and telemetry of either horizon sensor signals or engineering telemetry. Locking radially outward, a 1° field of view horizon sensor scans the earth and generates a signal which modulates a 1300 cps voltage controlled oscillator. The VCO amplitude modulates the beacon. These horizon signals can be used for spin attitude determination as can the pictures themselves, if horizons are visible. When within command range of a ground station, a 40 point electromechanical commutator can sample once suitable test points which modulate the VCO and beacon in the fashion just described so that a PAM-FM-FM message is received.

Some of the Tiros satellites carried a five channel radiometer to measure reflected solar and terrestrial thermal radiation. The spin of the satellite and its forward motion in orbit was used to generate a line scan. In each channel a 45 cps chopped optical signal is amplified and regenerated in a synchronous detector in the conventional fashion. The 0-4 cps video signals modulate five VCO's which are summed and recorded on an endless loop recorder for playback at 30:1 speed ratio. In this fashion, information from one orbit can be received in less than four minutes. An FM-FM signal is received over 238 Mc links at the same ground stations mentioned before when the subcarrier composite goes on intermediate storage. A centrally located processor demultiplexes the information and converts all channels to a compatible digital tape. For timing reference and flutter and wow compensation a 550 cps tuning fork generated subcarrier is recorded in the satellite which serves as the clock from which the word rate is derived and fed through a discriminator -- offers a flutter and wow compensation signal to the five channel outputs. A radiation map measured in the 12μ window by Tiros III, produced photographically based on computer calculations is included in Figure 5.

FM analog modulation for television and IR telemetry has been the work horse of Meteorological Satellites to date and performed well as is indicated by Table I. A more recent result from the Nimbus I high resolution infrared scanner is shown in Figure 6. This picture was scanned near midnight from the Arctic North-Canada to the South Pacific and Antarctica. 60° North and 291° East of Greenwich lies approximately at Hudson Strait with the dark pattern showing a compressed view of Hudson Bay. Hurricane Dora stood over Florida on the 9 Sept. 1964 when the picture was taken with its eye clearly visible. The white area underneath the 70° South and 80° South circles in the lower part of the picture are clouds over Antarctica with a coast line barely visible.

The advantages of digital telemetry such as PCM have been well known for many years but their introduction to space telemetry systems was slow. This had its reasons in a number of influencing factors. Although low power transmitters having relatively poor efficiency can be used, the power saving resulting from the advantages of PCM over FM is only a minor item in the total spacecraft d. c. power budget. Prior to availability of integrated circuit logic modules weight and volume of PCM systems was not competitive with VCO's and the added complexity hard to justify. On the other hand, only an ultimate data accuracy of 4-5% on the 5 channel IR data could be achieved primarily due to tape recorder properties. Conversion to binary form prior to recording, offers the only convenient means for accuracy improvement. Engineering Telemetry in Nimbus I and telemetry for five medium resolution IR channels in the Second Nimbus profits by the use of PCM. The former, still uses conventional logic modules while the medium resolution IR (MRIR) PCM telemetry system makes use of integrated circuits to the largest possible extent. A system description of the Nimbus I PCM telemetry has been published elsewhere and its performance during the Nimbus I flight enabled complete spacecraft analysis primarily of the power and controls subsystems at all times. The rather versatile use of a computer for ground handling made possible “out of limit” checks display of means and extremes and complete subsystem sheckout within minutes after reception at the ground receiving site. A total of over 500 test points was recorded every 16 seconds and 30 points at a 1 second word rate. Recording in the spacecraft the PCM wave train continuously yields in the order of 200,000 data points, to be checked each orbit so that use of a computer for information handling is mandatory. The capacity of the system is limited by the storage capability of the recorder. The development of a miniature recorder using the transverse limit recording method of computer tape memories made possible PCM telemetry of MRIR data.

The scanner output consists of five 16 cps bandwidth channels to measure reflected and emitted radiation similarly as in Tiros, except that higher video bandwidth is needed to achieve the same ground resolution for the higher Nimbus altitude. A sampling rate of 33-1/3 words/second thus suffices and amplitude definition of a seven bit code is compatible with basic radiometer accuracy. Conversion in 320 u sec. makes inclusion of a “sample and hold” circuit unnecessary, so that a conventional electronic commutator and hybrid microelectronic A /D converter provides a seven bit parallel output to seven record amplifiers and heads in the recorder. The recorder is of the endless loop type recording at 0.45 ips, 254 ft. of tape so that 113 min record time of new data is available which compares favorably with the 107 min orbital period of Nimbus. The conventional transverse saturation recording of an NRZ signal is used on seven tracks. One of the two center tracks (four or five) records a clock signal 90° delayed with respect to the data limits. This clock signal is used for trigger which, of course, makes it necessary to provide an eighth recorder track. Following a synchronization word consisting of all “ones” are the five IR channel measurements, as special code word, another five measurements and repetition of the sequence with a frame sync. The special code word is derived for timing purposes. The satellite carries a one year unambiguous clock which generates the standard missile range code. It may be noted that this consists of four bits, “binary coded decimals”, of units and tens of seconds, minutes, hours, and days plus four bits for hundreds of days. T his total code group changes every second, thus almost 17 frames are available to record 100 timing bits (nine groups of four plus 6 filler bits and a tenth group of ten for timing). A six bit counter sequences the data samples and alternates between frame sync and timing for the frame sync 6th word. During the 60m sec. frame, 6 timing bits are stored. In their turn they are recorded with a zero added to complete the seven bit word. Correlation of time with data is of prime importance because it constitutes the only correlation between a given data point and its geographical position, assuming knowledge of satellite position vs. time. Computer analysis is greatly aided by insertion of an unambiguous time code which is thus achieved. The phasing uncertainty between the measured sample and the recorded time code which is practically an absolute reference, is eliminated by a marker on the tape recorded at the time of playback command. The recorder uses a packing density of 450 bits per linear inch so that a total of more than 10 x 7 bit storage is achieved. Extensive tests have shown that errors occur on the outside tracks predominantly due to curl of tape and are less than 0.001% per orbit. Tape dropout neglecting tape path imperfections appear to be in the order of 10^{-7} per orbit.

Bit synchronization can best be achieved if the transmitted bit rate is constant making it desirable to compensate for speed variations of the recorder. This is accomplished by choosing a slightly higher readout rate, than mean when the pulses are converted serially from the tape. A stable clock signal of 66-2/3 Kc is chosen which completes one word readout sooner than the next word can follow on the tape at the highest speed tolerance. A one for word synchronization precedes the word it then suffices to generate zeros when the tape readout register is empty. Logic must exclude readout and register shifting to coincide. The ground system must be designed to accept a variable word length of 9-15 bits per word. Figs. 7 and 8 show photographs of the tape recorder and the assembled electronics.

Special purpose or general purpose PCM ground stations can be employed. For limited operation such as spacecraft checkout during tests, equipment has been designed and is produced by Roebach, Inc. of Pennsylvania. A general station such as produced by Telemetrics is well suited for continuous routine operation. A bit rate up to 1 M bit/sec. can be accepted in a shift register and read out into an arithmetic unit as desired. The small arithmetic unit can be programmed to decommutate the IR channel words, identify sync and recompose the time code. Formatting of the data for large computer handling is achieved in separate standard equipment which drives conventional tape memories. Analog outputs are also available.

Telemetry for communication of large quantities of data gathered by the satellite suggest the possibility to augment the system through other sensors and use the satellite as an efficient relay. Meteorology suffers from a lack of data many times and from insufficient geographical coverage. Presently, the vertical temperature distribution of the atmosphere on a global scale is anticipated to be measurable from a satellite. However, pressure and wind distribution data are best gathered by in Situ measurements. Restriction to local temperature, pressure, and wind is unnecessary, indeed any message that can be encoded compatible with a flyable system is suited for transmission, storage, and distri bution. Value to meteorology is most apparent and potential savings could be significant, but applications to other scientific disciplines can be seen immediately. Oceanography, tracking of icebergs to reduce shipping hazards and even pure scientific endeavors like animal migration studies are being discussed.

A system has been developed which can readily fill most requirements of these applications and can be extended to include balloon borne sensory platforms with minor advances in technology to be strived for. As designed, it can establish the location of an earth platform such as buoys or balloons by ranging and triangulation, receive and store the data in the satellite and transmit all accumulated data to a central interrogation station like Fairbanks, Alaska, for processing and data dispersion to users. This interrogation recording and location system -- IRLS -- is planned for flight on the third Nimbus in 1967.

The ground platforms transmit to the satellite, when interrogated so that the receiver must be in operation continuously. When the satellite transmits a 16 bit address code redundant by three bits, it will be received by all platforms within receiving range, decoded and compared against its assigned address. When found correct, data transmission starts using the same subcarrier modulation as is Used for transmission of addresses to be stated below. A total of 2048 addresses can be assigned so that wide flexibility in operations results. The sequence of operations starts by instructing the satellite via the Fairbanks station which addresses are to be interrogated on the upcoming orbit and these codes are stored in a local address memory. It is further necessary to store times when the address is to be transmitted, the initiation of which is established by comparison with the satellite clock. Because ranging will be performed each time, two transmissions, each lasting approximately 3 seconds to each platform allow triangulation. It is readily apparent that general knowledge, as to the platform location; that is, within a 6000 Km circle must be available. It is assumed that Nimbus is at 1000 Km altitude in a circular orbit. This is no serious restriction since movement over such a distance even within a 24-hour period in virtually impossible. For the range code and data transmission refer to Fig. 9. A code word consists of a fixed pattern -10101100- and a four bit binary number counting from 1 to 16 when the pattern is then repeated. The bit rate of 12500 Kb/sec. and the count of 16 guarantees that this period is longer than the time delay encountered even in, the longest distance to be ranged since one 12 bit word corresponds to a 150 km increment as long as orbits lower than 1500 km are considered. For higher orbits, ambiguity can still be resolved logically. This bit stream is used as a coherent digital subcarrier by choosing the fixed portion of the range word as “0” or its complement as “1” illustrated in the figure. The continuously changing four bit group is not modulated. In this fashion, address words can be transmitted from the satellite and data words from the ground at a 1041 bit/sec. rate. The choice of the split word enables convenient correlation detection for word synchronization once bit synchronization is established by a conventional phase locked oscillator. Ranging can be accomplished in three steps: The algebraic difference between four bit groups of the transmitted and received signals gives the range in 150 km increments. Note that the group delay of the receivers must be known and constant to enable elimination from the propagation delay. To refine the measurement in a vernier, the phase of the signal to the nearest bit is measured and can be because synchronization is established. Ranging is thus accomplished to the nearest 125 km increment. In order to achieve ranging resolution to .3 km a 1μ sec. increment in the 80μ second bit duration must be measured. Digital gating at a countrate of 1.6 M bits /sec. is readily achievable at a cost in power consumption. A phase discriminator and conversion of the analog output to digital form needs less power and yields the acceptable resolution of ± 0.5 km. Given a certain range resolution, the location accuracy depends on the distance from the suborbital ground track. Fig. 10 shows this function and indicates that ± 2 km will be achieved for cases where the platform is at least 200 km from the satellite ground track.

While the data transmission requirements influence the choice of carrier frequencies and needed bandwidth very little, required ranging accuracy which depends on the pulse shape and S/N ratio points to preferred ranges of carrier frequencies. Naturally, the power requirements shall be minimized and the state of the art in low noise, space qualified receivers, efficiencies of solid state and hybrid transmitters as well as achievable antenna gains vs. carrier frequency enter into the consideration. A parametric analysis reveals that the 400 Mc region is well suited for the purpose and near optimum. A further advantage is offered by the fact that 401 Mc are assigned for Meteorological use and 465 Mc has been suggested for Meteorologic satellite use. Since a diplexer with high isolation must be used to allow a common antenna for reception and transmission the 65 Mc spacing is desirable. The choice of antenna pattern, thus achievable gain, is governed by the orbital geometry and physical stability of a floating platform. For a Nimbus satellite in its lowest orbit of 1 000 km the antenna must radiate into a 120° cone so that only 6 db gain can be achieved at the Center. For the ground antenna a broad pattern is also desired to minimize the influence of ocean wave or wind disturbance on a rocking antenna pattern. These considerations lead to the choice of a reflector backed turn stile and further to a 25 watt tube-hybrid transmitter. A tolerance analysis of the communication system was performed and its conclusions confirmed by measurement as given in Fig. 11.

A surface station may it be ground based or a floating balloon contains a receiver and address decoder; further a transmitter, telemetry electronics and sensors. It is only necessary to keep the receiver and decoder on while the rest can be turned off until interrogated. The frame format is illustrated in the lower part of Fig. 12. The 16 bit address word is retransmitted for positive identification. A maximum of 28 - 7 bit data words is arranged as shown so that in the column of zeros, the range word determined in the spacecraft can be inserted and stored in a core memory with the data. Horizontal and vertical parity is computed for error correction. By choosing a quasi random sequence of even and odd parity criteria, both horizontally and vertically, it can be and is used for frame synchronization. Satellite memory logic and capacity is designed so that each station can transmit up to a maximum of six frames.

Telemetry from Meteorological satellites has performed consistently with high dependability and its design has not met major limitations. The magnitude of the data source and the requirement to process it in real time, present some of the most challenging tasks in future developments. The glaring discrepancy between the information content in total bits of a television picture and its content in form of a cloud analysis points to exploration of data compression techniques on one hand and pattern recognition on the other. The meteorological data content can be expressed as a small number of bits and the benefit of these satellites and their efficiency in design and use will increase greatly when practical solutions to these problems can be found.

TABLE I

Tiros	Total Number of Pictures	Meteorologically Usable	% Usable	Neph - Analysis
I	22,952	19,389	84.4	333
II	36,156	25,574	70.7	455
III	35,033	24,000	68.5	755
IV	32,593	23,370	71.8	836
V	55,877	47,461	84.6	1783
VI	45,726	40,729	89.0	1401
*VII	95,573	87,901	91.9	3367
*VIII	62,377	57,458	92.1	2345

* As of January 1965

Table I-Tiros Television Performance

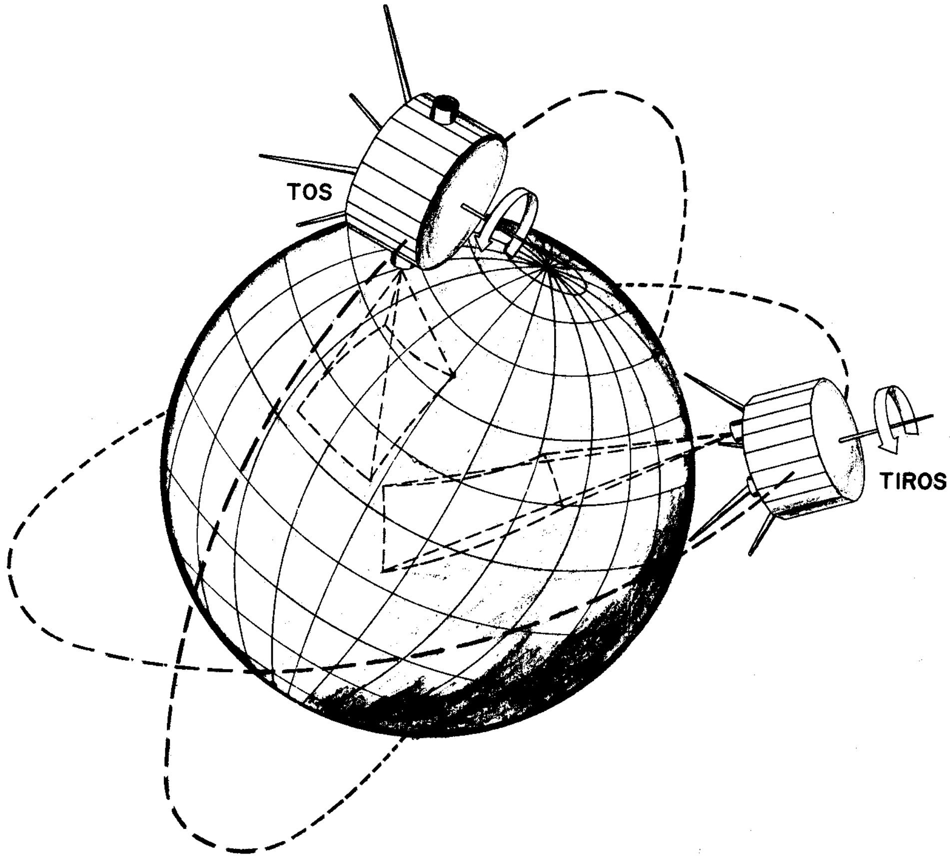

Fig. 1-Tiros and Tiros Operational System Concepts

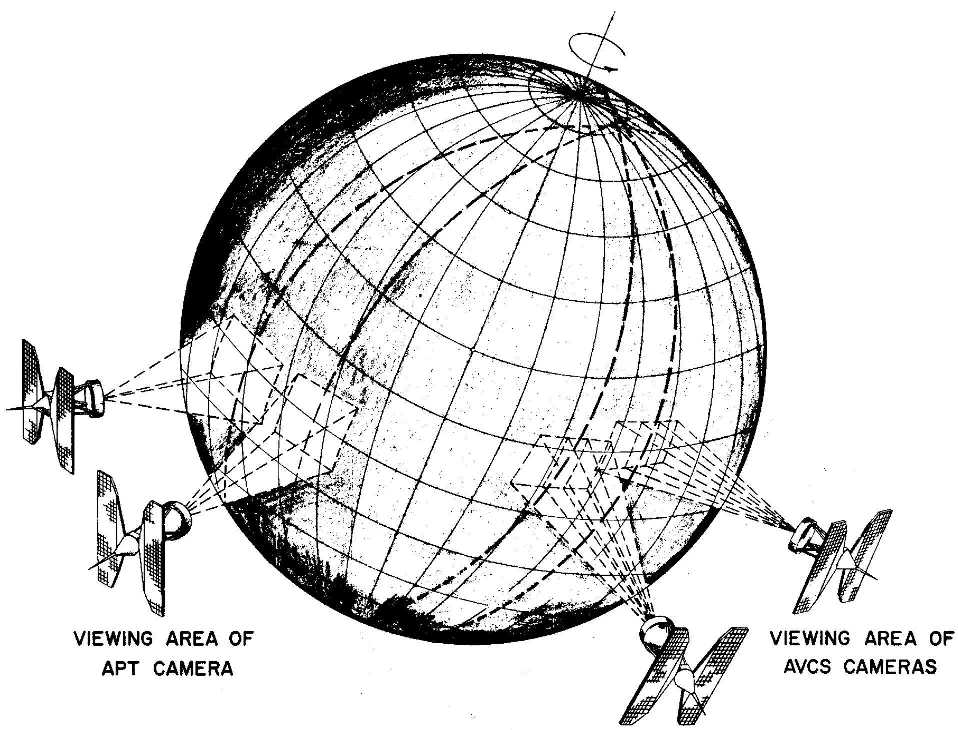

Fig. 2-Nimbus TV Coverage

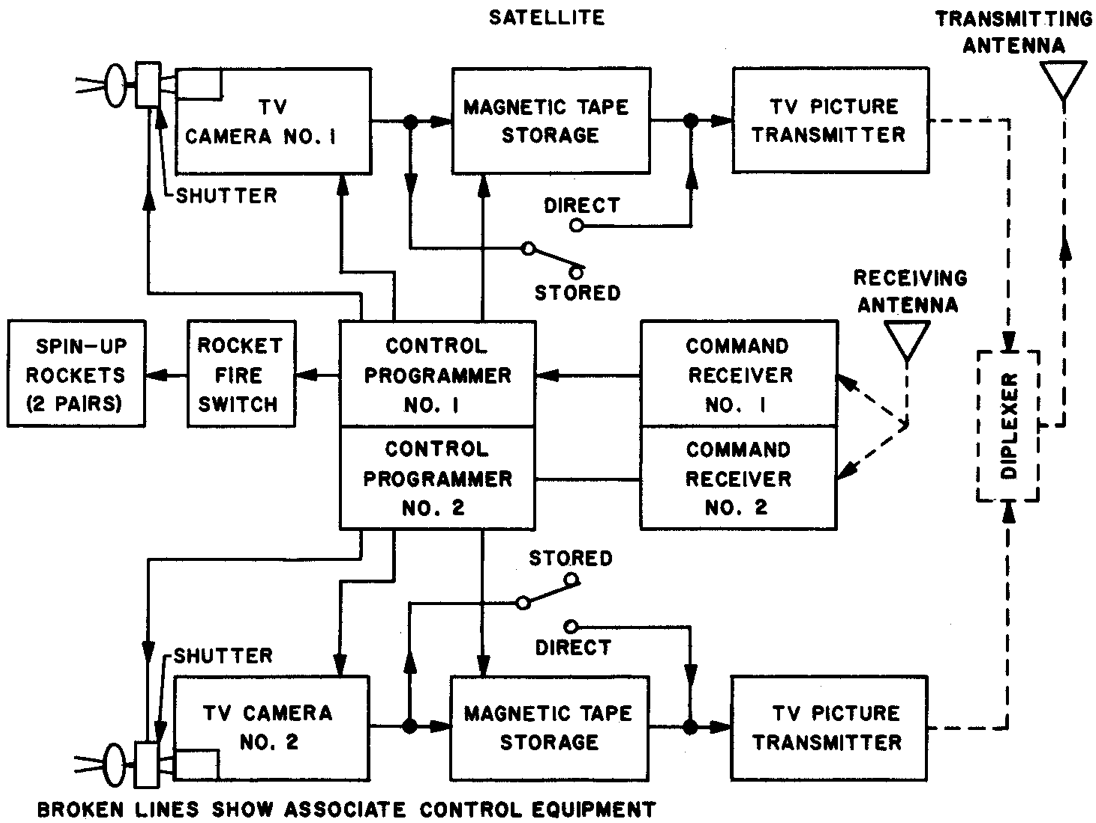

Fig. 3a-Tiros TV System, Satellite

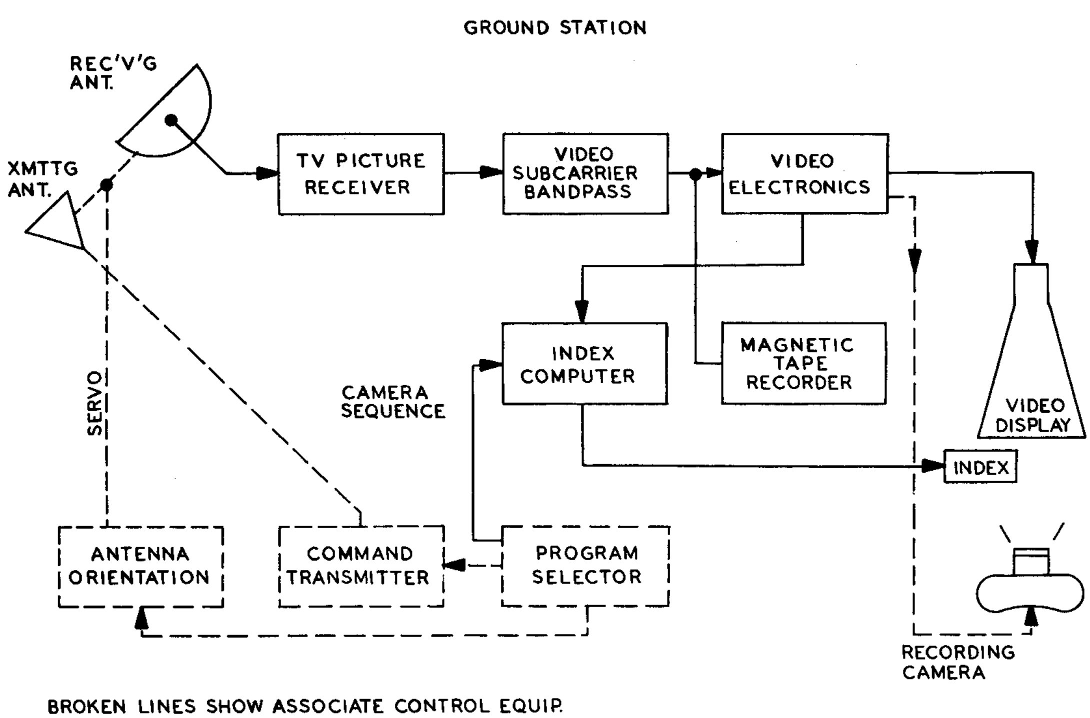

Fig. 3b-Tiros TV System, Ground Station

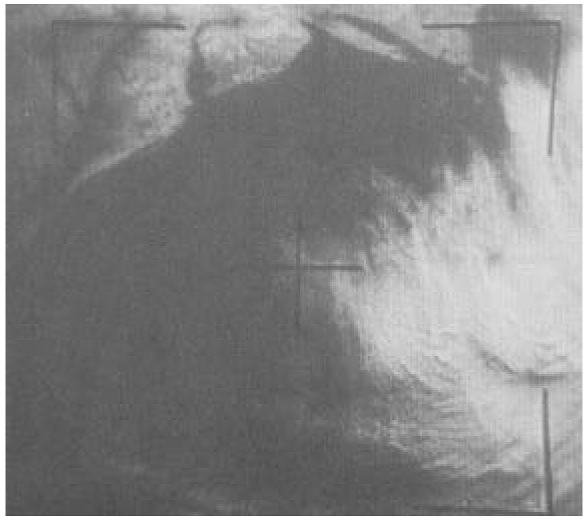

Fig. 4-Northeastern United States and Canad Taken by Tiros VII After 1-3/4 Years Orbital Life

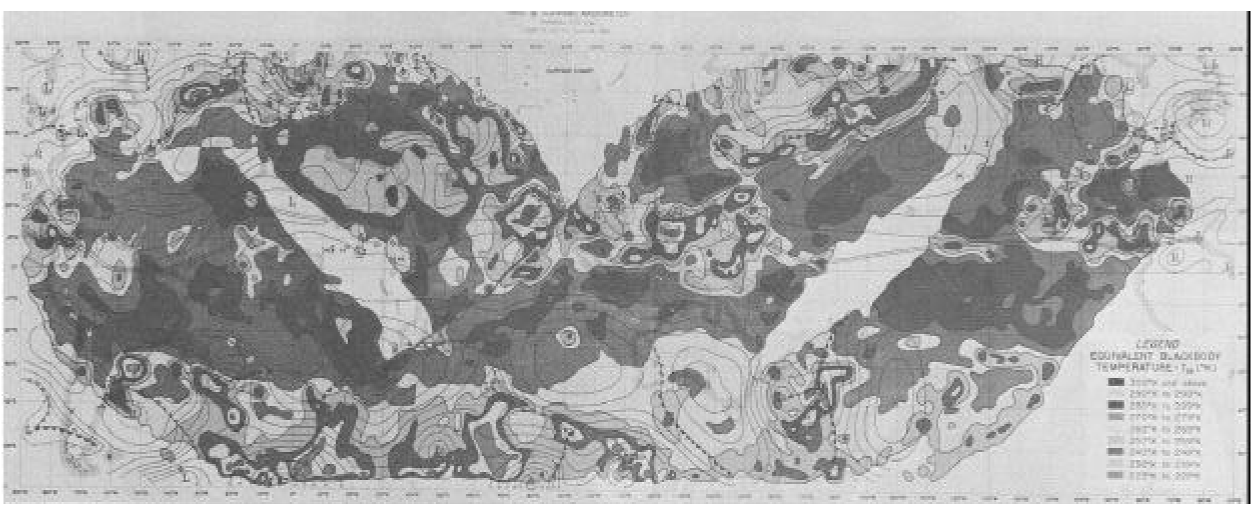

Fig. 5-Tiros III 12μ IR World Map

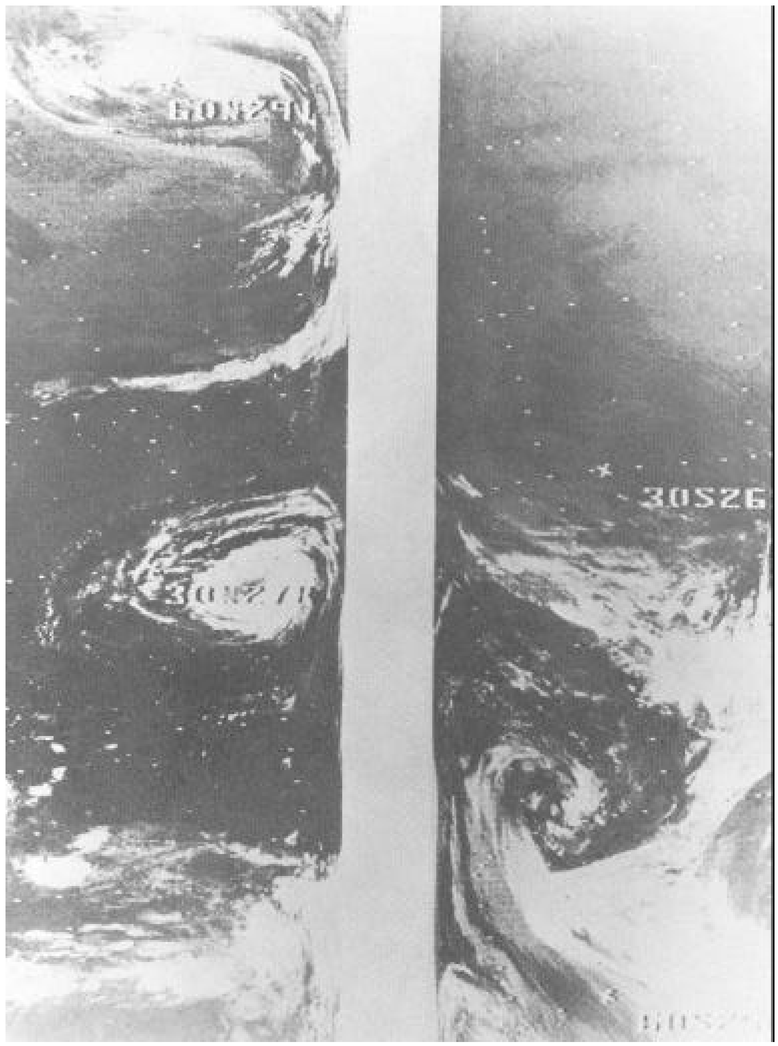

Fig. 6-Nimbus I High Resolution IR Picture Taken in the 3.4μ Window. The Numbers are Geographical Latitude and Longitude.

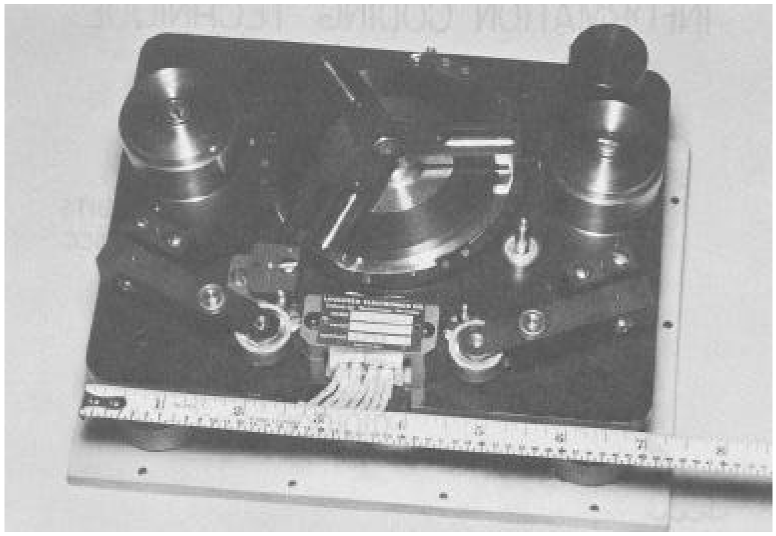

Fig. 7-Digital Tape Recorder for Transverse PCM Recording

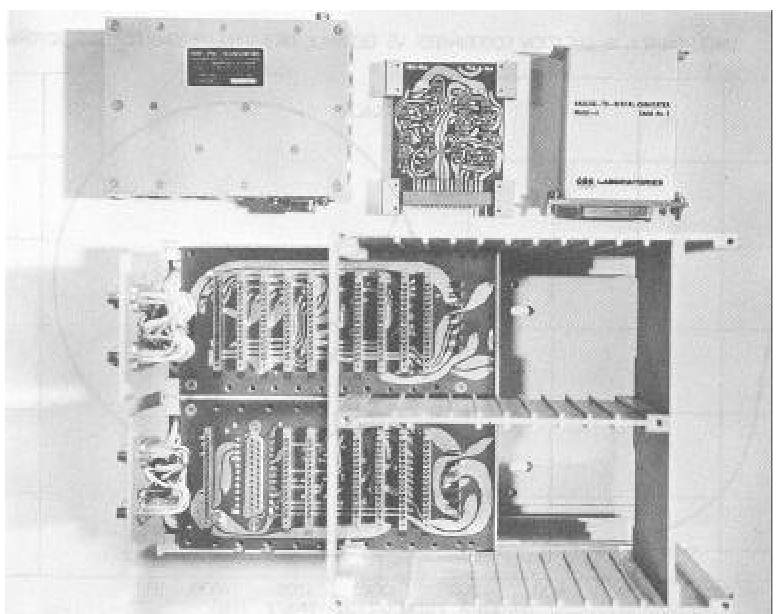

Fig. 8-PCM Electronics Assembly

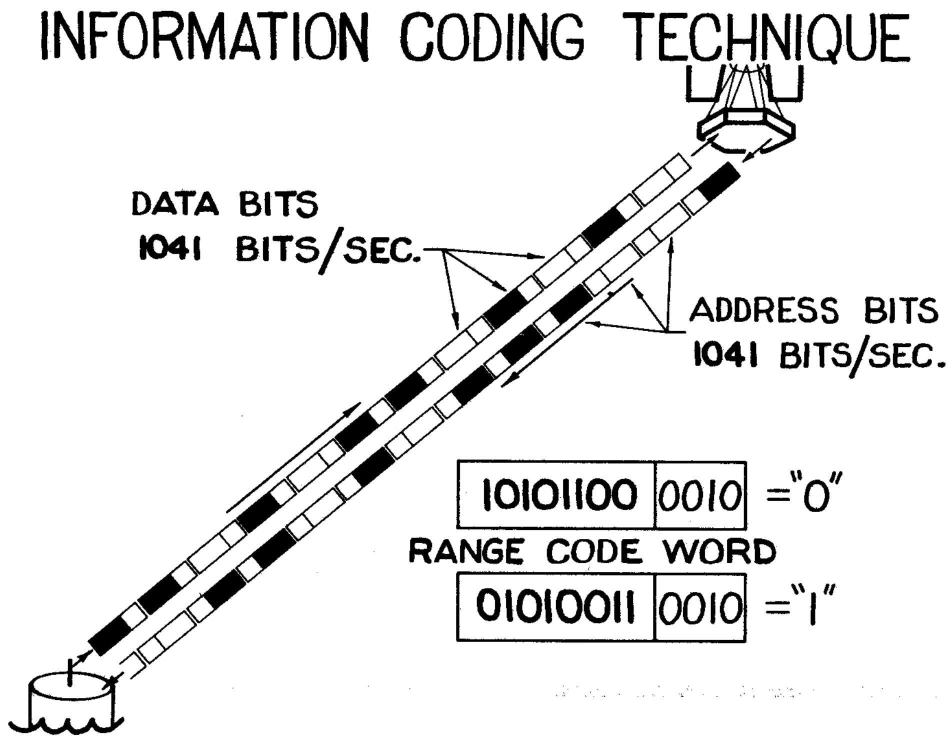

Fig. 9-Ranging Code and Information Modulation

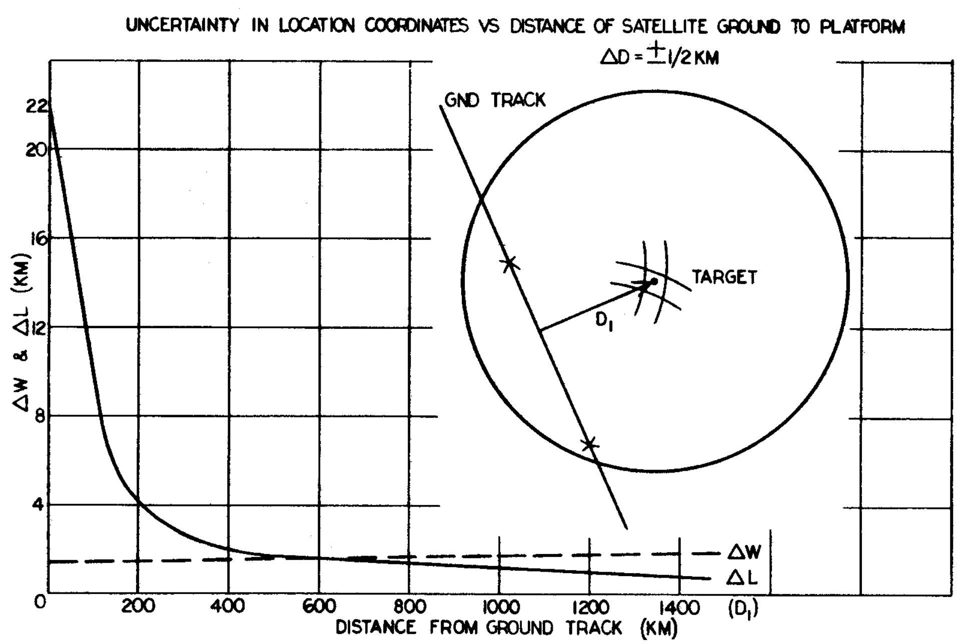

Fig. 10-Location Uncertainty

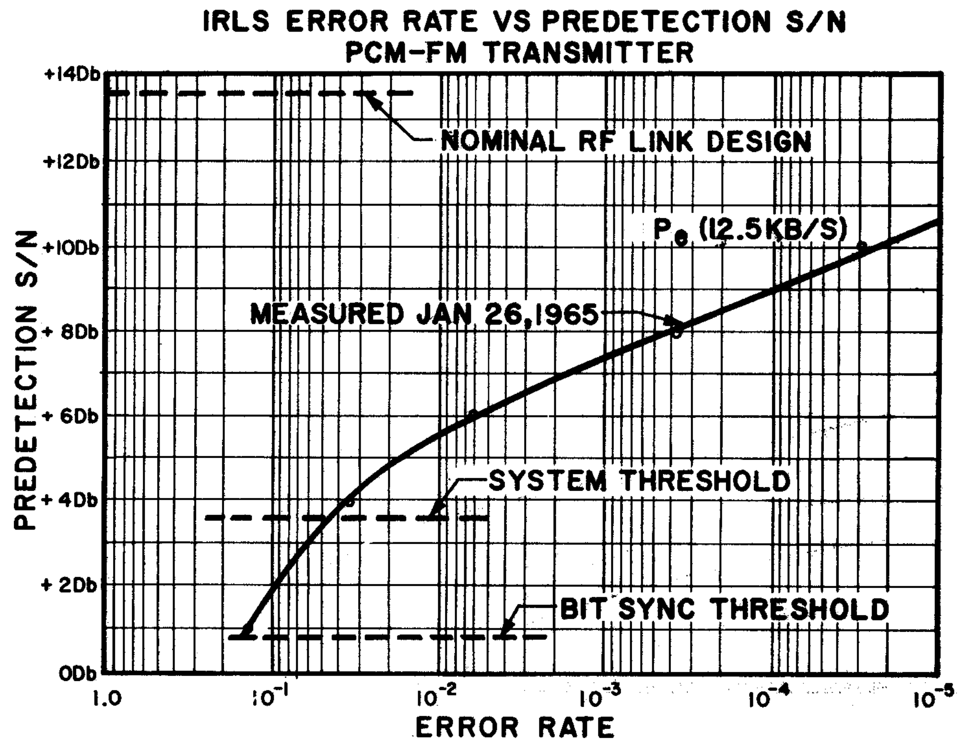

Fig. 11-Probability of Error

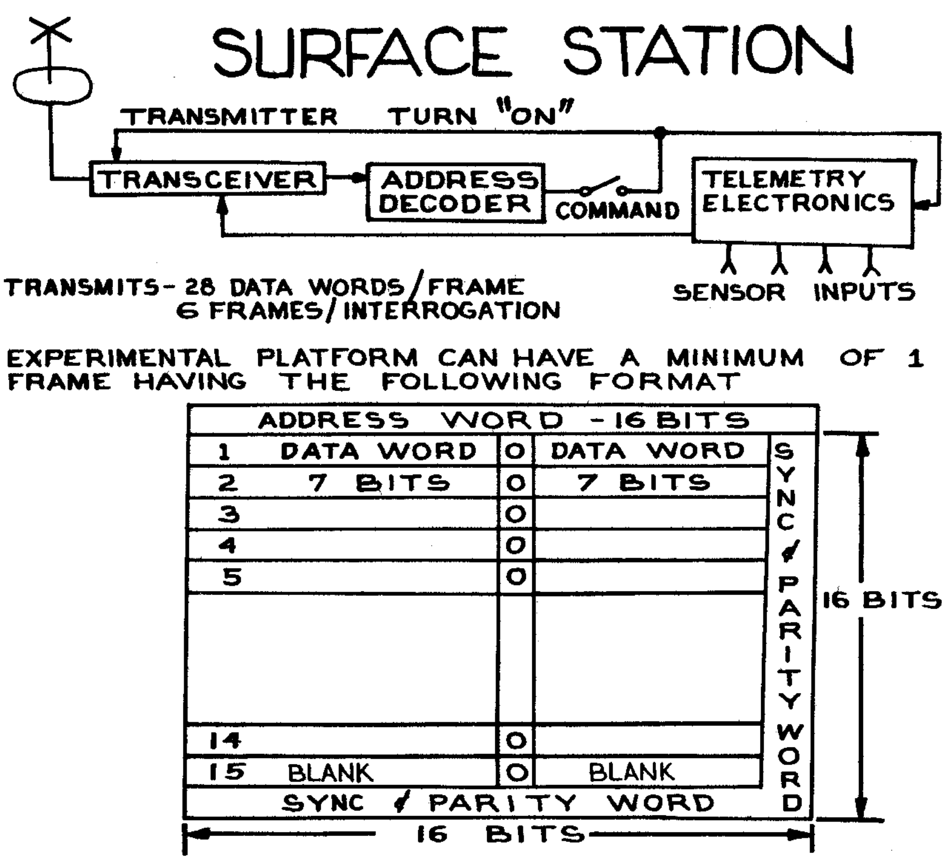

Fig. 12-Surface Station