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TELEMETRY PROCESSING FOR NASA SCIENTIFIC SATELLITES

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

ABSTRACT

More than 10^8 data points per day will be received from NASA Scientific Satellites. This paper gives a description of the techniques now in use and shortly to be used at GSFC to process this large volume of telemetry data. It also discusses attendant problems and possible future plans for coping with this explosion from the analysis viewpoint.

CONTENTS

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INTRODUCTION

The data processing requirements for space related data have increased in magnitude during the past six years. Prior to the advent of the satellite, this problem was characterized by the processing of data from a sounding rocket where a successful flight would produce approximately 5,000 data points per second for 600 seconds; thus 3 million data points would have to be processed per flight and these flights were relatively infrequent. In contrast, the GSFC's worldwide network of data acquisition stations presently receives and records data from some twenty-six satellites, performing both national and international scientific missions, with an accumulation rate of 100 hours of data per day. The fourteen satellites for which GSFC has complete mission responsibility, produce data at the average rate of 60 million data points per day, where a data point is defined as a single complete reading taken from a sensor. In the near future, it is anticipated that this will grow to more than 200 million data points per day.

The expected volume of data points, averaged over the year, in millions of data points per day is shown in Figure 1. These values were arrived at by considering the number of satellites and experiments involved, the satellites' expected lifetimes and the individual data-gathering schedules.

The large growth beginning in 1964 is due to the introduction of the observatory class satellites. Although not included on the figure, a cursory examination·has indicated a correlation between data volume and total number of experiments per year.

Various types of satellites and telemetry systems with data productivity are compared in Table 1. The maximum number of data points is based on the maximum satellite data rates and available ground contact time. The expected number of data points is based on the satellite's data-gathering schedule. The first one, IMP (Interplanetary Monitoring Platform), was specifically designed as a low data rate satellite, because its major purpose was to serve as a monitoring system at extreme distances in addition to being a low weight satellite. The S-3C is an example of a small satellite which uses a medium data rate telemetry system.

Table 1

Satellite Data Transmission Rates

Satellite Title	Telemetry Type	Data Points (Per Day)	
		Maximum	Expected
Explorer 18 (IMP)	PFM	0.27	0.27
Explorer (S-3c)	PFM	4.3	4.3
Orbiting Solar Observatory (S-17)	PCM	4.5	4.5
Advanced Orbiting Solar Observatory	PCM	39.0	39.0
Orbiting Geophysical Observatory (S-49)	PCM	610.0	90

The data rates of the OSO (Orbiting Solar Observatory) series are constrained by the fact that nearly continuous data coverage is required. By recording the data on on-board tape recorders at a low speed and then speeding up the tape recorders for playback during the short, ground-station contact time, continuous data coverage is obtained. Similarly, data from the AOSO (Advanced OSO) series is obtained on a continuous basis through the use of on-board tape recorders at a rate of 39 million data points per day.

The OGO (Orbiting Geophysical Observatory) series presents the possibility of the greatest amount of data through the use of a data transmission rate of 64,000 bits per second (more than 600 million data points per day). Nearly 100 percent of its highly eccentric orbit can be covered by existing data acquisition stations. If all ground station contacts were received at this high rate, over-abundant data would
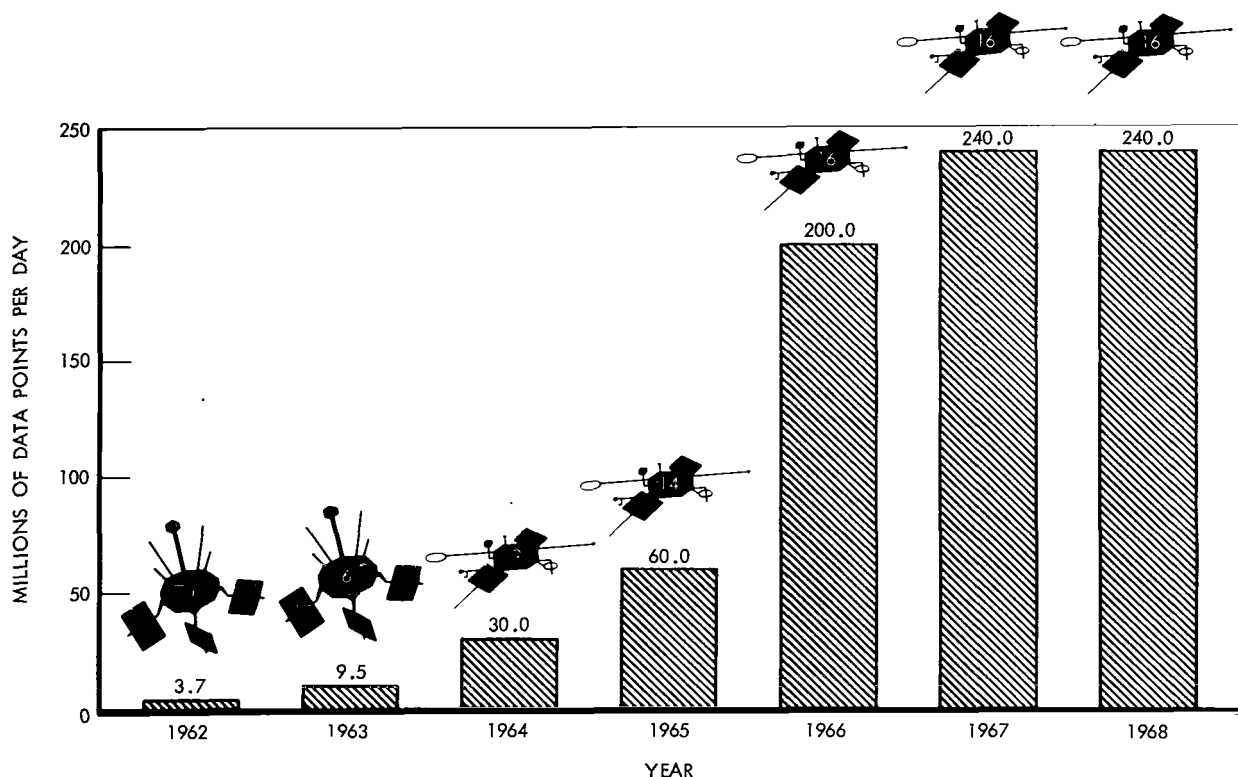

Figure 1-Trend of data output from earth satellites. The number shown inside each spacecraft indicates the number of launchings planned for that year.

2

be available. This fact was recognized early in the program and led to a restricted data gathering schedule and the inclusion of two other lower data rates (1,000 and 8,000 bits per second) for the satellite, thus producing an average of 90 million data points per day as shown in the third column of Table 1.

DESIGN CONSIDERATIONS

Before discussing the earth satellite data system now operated by GSFC, it will be useful to examine the factors that strongly influence the design of any satellite data system.

The first factor of design requires a continuous operation of the data acquisition system to assure complete coverage of the phenomena. The technique must be such as to permit quick scanning of the results so that the time interval of special interest can be identified and the data in these sections subjected to special analysis.

The second factor of design requires a signal conditioning system which will extract the signal out of the noise, reconstitute it, put it in digital form and perform a quality check to assure that spurious signals have not been accepted. The automatic means of accomplishing this is the heart of STARS (Satellite Telemetry Automatic Reduction System).

The third factor of design is also apparent in the general-purpose nature of STARS. The design must be in favor of adaptability to a variety of uses. This consideration has led to the choice of a PCM (Pulse Code Modulation) type of satellite telemetry system, using a binary coded digital system for data transmission for most of our satellites. This system may not be as efficient as some alternatives but is readily adaptable to a variety of uses, with special advantages for real-time readout.

These factors of design have also led to the use of a relatively large digital computer in the data processing system rather than smaller special purpose computers. The capacity of the computer not only gives the desired flexibility, but also a capability for expansion into the reduction and analysis part of the system, thus providing a potential for increased efficiency in the data analysis process. In order to exploit it, a very close collaboration has to be built up between the experimenter, the equipment designer and the programmer. Generally this is not feasible until actual data are available to the experimenter so that he can choose appropriate analytical techniques and computational processes. The large scale digital computer can cope with these analysis requirements as they develop.

As shown in Figure 2, the overall information gathering system is separated in four locations: the spacecraft, the data acquisition station, the central control station at GSFC, and the data processing area at GSFC. This system operates in two modes, the first of which is a real-time mode. The command portion of the system, the data transmission and the receiving portion are interconnected by radio or microwave links, and operate in somewhat of a closed loop fashion while the satellite is passing over the ground station. The data processing function is a completely separate operation and is the first step in putting the data into a form suitable for analysis by the experimenter.
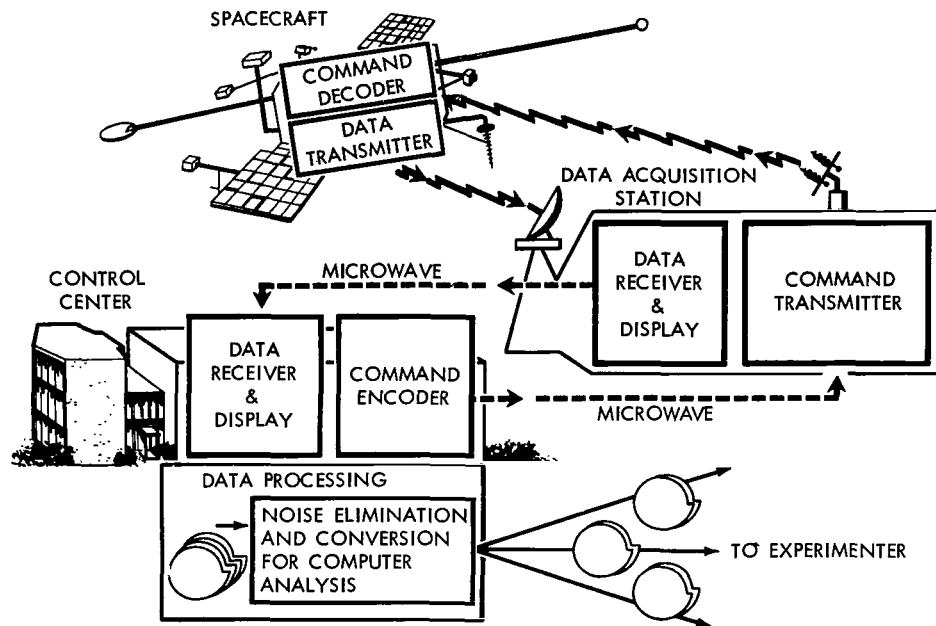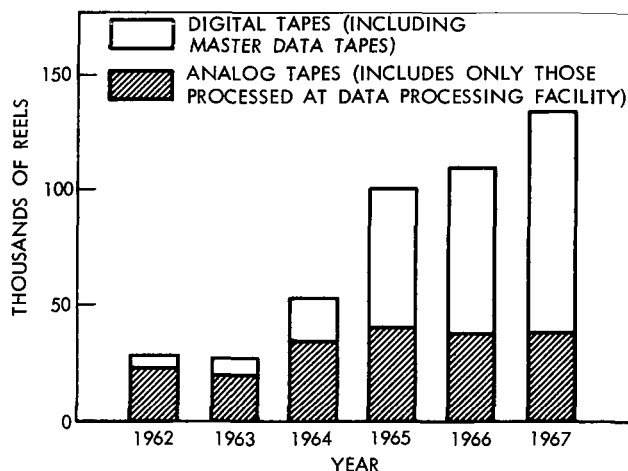
Figure 2-GSFC data system.

Figure 3-Tape usage by year.

Either during or after the real-time command mode of operation the major bulk of the telemetry data produced by the experiments is recorded at the ground station in a fairly routine manner along with ground timing and other pertinent information on seven-track analog magnetic tape recorders. The volume of tape expected as a result of this operation for the scientific missions only is shown in Figure 3. Included in the figure is the number of digital tapes produced as output from the data processing operations which will be described. TIROS and Communication satellites, are not included in the statistics.

GENERAL DESIGN

Telemetry data processing is accomplished in two stages as shown in Figures 4 and 5. The first stage, basically a continuation of the data acquisition of the ground stations, consists of converting serial analog telemetry data into digital form for use in a computer, as well as quality checking, editing, incorporating ground time and orbit information, and decommutating the telemetry data to yield individual experimenter tapes.
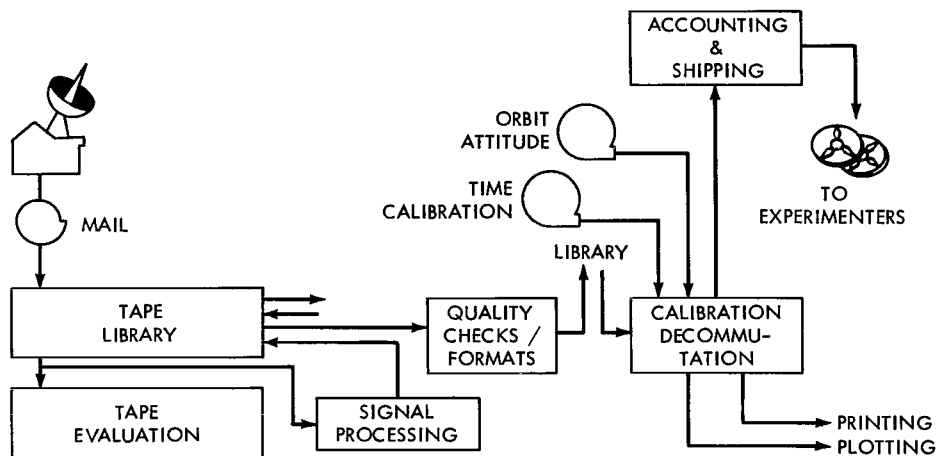
4

Figure 4-Data processing operation flow.

The second stage is the responsibility of the experimenters themselves. In general it makes use of automated methods, such as computer operation, to reduce the experiment data to their most meaningful form.

The figures illustrate the several major operational steps: tape evaluation, signal processing, quality control, and decommutation or separation of the data into experimenter tapes. Upon receipt of these tapes the experimenters then perform a quality control check, calibration and conversion of the data, reduction of the data, and final analysis. The STARS project is part of an overall plan to develop an optimum system for handling and processing this telemetry data. The objectives of the project are being accomplished in three phases:
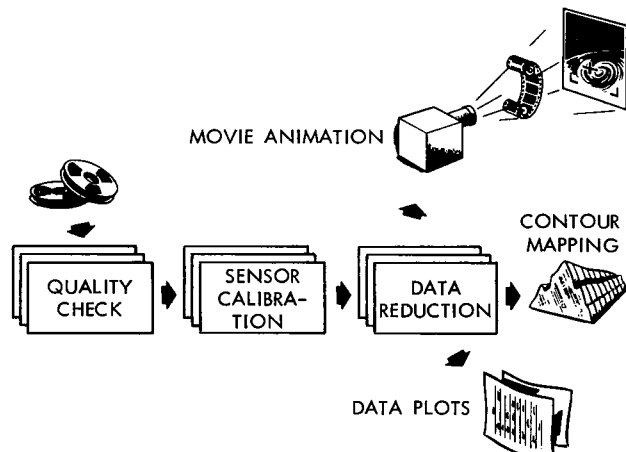

Figure 5-Experimenter data reduction.

1. The near-term objective was to provide telemetry data processing lines to meet the then-impending data processing requirements.

2. The intermediate objectives are to increase the efficiency and economy of operation of the data processing equipment, enhance its capability, and shorten the time from acquisition to delivery of processed data to experimenters.

3. The long-range objectives are to develop techniques and equipment to process scientific data completely, and provide the results to experimenters in the most meaningful form in the shortest possible time.

5

STARS PHASE I—NEAR-TERM OBJECTIVES

The tape which is produced at the ground stations and air-shipped to GSFC, is the major raw material used at the centralized data processing facility. Upon receipt of the tapes, they are logged into the Analog Tape Library and prepared for disbursement to the tape evaluation and STARS signal processing lines. Selected tapes from the most recent shipment from each ground station are rated on the tape evaluation lines. Information derived from this step is used to evaluate and improve ground station performance. In the near future we plan to perform most of this evaluation at the ground stations, using similar equipment. Any duplication of tapes which may be required is also performed on these lines.

All tapes are stored in the library until enough are accumulated for processing in chronological order of transmission from the spacecraft. They are then scheduled for the signal processing lines.

The PCM front end extracts the signal out of the noise and reconstructs it in a clean form; synchronizes with the data stream; identifies unique frame synchronous words; and formats the data into--for the case of OGO--128 word frames with nine bits per word. It also provides signals for interrogating the time decoder. The STARS I time decoder, utilizing signals recorded on three tracks of the station tape, reconstructs and presents a best estimate of time at which the data were received at the recording station in days, hours, minutes, and seconds, plus other identifying information.

The same techniques have been adapted for use on the other telemetry systems, one of which is the PFM (Pulse Frequency Modulation) system used on the smaller Explorer satellites. This system produces a frequency analog of the sensor output, rather than the two-level square wave signal produced by the PCM telemetry.

The final output from either of these processes, along with time and other identifying information, is recorded on the output tape in the manner shown in Figure 6.
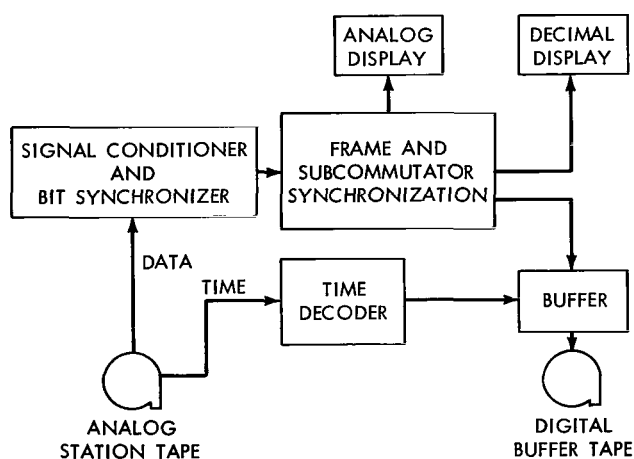
The next step in the STARS I data processing system consists essentially of a large-scale digital computer used to quality-check and format the data from the digitized tape produced by the previous step. The tape is examined for bad or missing data points, time is checked, error indicators are analysed and a new tape is made and now termed the master-data tape. This tape, along with an orbital tape which records the satellite position and orientation and other correlative information at any given time, is kept on permanent file for reference at the National Space Sciences Data Center at GSFC.

Figure 6—STARS I, signal processor.

The master-data tapes are then stored until enough are accumulated for further processing in chronological order. The final data processing step is to strip out or decommutate the data of interest to a given experimenter from the master-data tapes. These are recorded on a new set of experimenter-tapes an along with a separate tape, which correlates time with orbital position and altitude, provide the experimenter with all of his data in a form suitable for input to most digital computers. Depending on the experimenter's wishes, a calibration can be applied to the data in this step. In this case the data are presented to the experimenter in terms of the engineering units appropriate to the physical quantities originally detected by the experimenter's sensor.

STARS PHASE II—INTERMEDIATE OBJECTIVES

Examination of the previous flow diagram and the timing involved indicates that a major production bottleneck usually results from the long turn-around time between quality control and any reprocessing needed as a result of STARS I malfunctions or poor signal-to-noise ratios. This led to the merging of the two into a one-step operation to improve the turn-around time.

The introduction of the STARS II lines into the GSFC processing operations early in 1966 will bring two major changes. One is the performance of signal processing and quality checking in a single integrated system. The other is the use of a fully automatic system, with computer-controlled setup and operation. These changes should bring about the following improvements.

1. Decreased amount of reprocessing, through on-line control.

2. Elimination of the digital tape between signal processing and quality checking and attendant logistic handling.

3. Greater flexibility through the use of an on-line computer.

4. Reduced turn-around time.

5. Increased ease of maintenance through program-controlled checkout.

The STARS II system, as shown in Figure 7, combines a CDC 3200 general purpose computer with special signal-processing equipment. Three systems will be available, two for processing
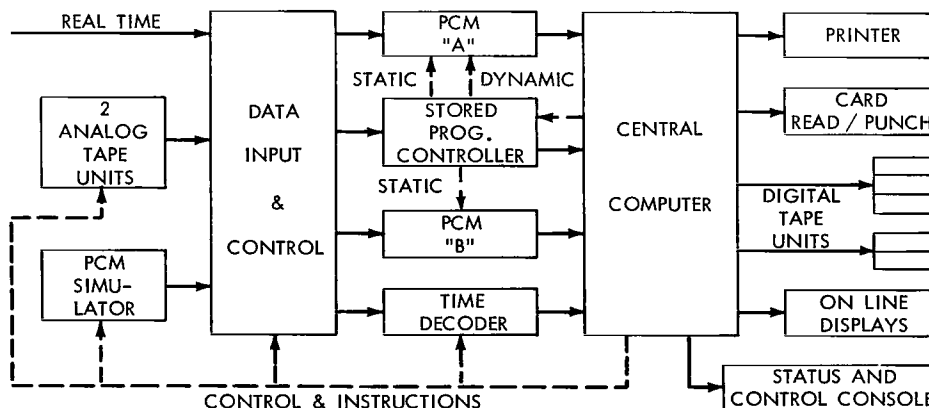

Figure 7—The STARS II system.

PCM data and one for PFM data. For PCM, the system consists of the following elements: input subsystem, two PCM subsystems, time code subsystem and status, control and display subsystems.

The normal data input to the system will be from an analog tape recorded at a tracking station. Data from a real-time link can also be accepted. A third source of data input is the stored program simulator, an integral part of the system. In the case of recorded data, the analog tape can be played into the system at up to thirty-two times the recorded speed. Since the satellite transmission rates are fixed, this speedup capability reduces the processing time proportionally. Data from low-rate satellites can also be processed with a large gain in efficiency.

The input control unit provides automatic selection of the data source, as well as both speed and track selection of the analog tape playback units.

The two PCM subsystems consist of two signal conditioners, two group synchronizers, one stored program controller, and one limit checking unit. By communicating with the central computer through individual input-output channels, provision is made for processing two telemetry channels simultaneously, the intent being to process two from a single satellite. For example, two OAO data links are received on separate carriers.

For maximum recovery of data, both point-sampling and integrate-and-dump detectors are provided in the signal conditioners. Ambiguity detection for split phase codes and automatic polarity inversion capability were also provided. For greater reliability in processing data from single channel satellites, the two bit synchronizers are switchable between the two PCM subsystems.

A three-mode frame synchronization strategy with search, verify, and lock is used. Data transfer to the computer may be started in either the verify or the lock mode to maximize data recovery. If the computer is started in verify mode, the information may be saved in the computer for use in case the PCM subsystem proceeds into lock mode. There is also automatic correction for multiple bit slippage for higher data recovery.

A bit-stream mode of data input is provided to handle formats that are beyond the PCM subsystem capability. In this mode the reconditioned bits are transferred to the computer regardless of word, frame, and subframe synchronization. Frame synchronization and formatting are accomplished in the computer. Although this is not an efficient mode of operation in certain cases, such as the burst-frame operation, it is the only known method of reliably recovering the data.

The control information for the PCM stored-program controller, consisting of static and dynamic instruction can be loaded from the computer. A static instruction is used once for each processing run for the automatic setup of such items as bit rate, data acquisition strategy and format parameters. Dynamic instructions are those used at least once for every telemetry word, for variable word length control, data routing to displays, subframe synchronization and limit checking. In addition, the PCM channel can be programmed to perform limit checking and flagging on every data point.

The time-code subsystem is functionally similar to that of STARS I. It was adapted to the fully automatic system by providing computer setup of the speedup factor, input signal selection,

and strategy for the best estimate of time. It also provided automatic reinversion of the input signal to achieve maximum time resolution. Time readouts can be provided on request from both PCM subsystems.

The status and control subsystem provides the interface with the CDC 3200 computer for communication with the PCM subsystem and PCM simulator; automatic setup of the time decoder, analog tape units, display subsystem, and data input control; and feedback of status information from all of these subsystems to the computer. Status information from the PCM and time-code subsystems includes indication of data and time quality. The computer printer will be used for on-line display of this quality information. In addition, the display subsystem can plot raw PCM data from the PCM subsystem, or processed data from the computer on a multichannel oscillograph recorder. The remaining displays for system operation are provided on a centralized telemetry console. The telemetry console also contains manual overrides for all automatic setups. For overall system control, an executive routine in the CDC 3200 computer will provide full system setup which includes loading of the PCM and simulator-stored program controllers. The executive routine will also control job sequencing, accounting, and calculation of statistics concerning system performance.

DATA REDUCTION AND ANALYSIS

At this point data reduction and analysis passes under the control of the individual experimenter. The processes involved are functions of individual need and the computing and plotting equipment available. However, in almost every case, the steps depicted in Figure 5 will be performed. The last step, visualizing the data, plays a most important role in the assimilation and understanding of the large mass of data.

The important point is that the final experimenter tapes produced by the previously described processes are in a format adaptable to large-scale digital computers. It is thus readily feasible to make full use of these computers and a variety of automatic plotting and display devices. The effectiveness with which this equipment is adapted to the individual need of the experimenter generally depends on a close collaboration between the experimenter, the equipment designer, and the computer programmer.

A study of numerous satellites suggests that from the viewpoint of data analysis the experiments may be broadly divided into five major classes:

1. Flux detectors with analog outputs which comprise all single-direction, nonscanning experiments with analog outputs, such as proton, electron, ion, and cosmic ray flux measurements.

2. Vector field sensors which includes all triaxial nonscanning experiments with analog outputs, such as measurements of the geomagnetic field vector.

3. Scanners which cover all experiments that concern an area such as the sun, a star, or the earth.

4. Counters, which represent all digital, counter-type experiments, such as Geiger counters and x-ray detectors.

5. Special, which contains all experiments not included in the previous four classes and those basically different among themselves.

A survey of data analysis programs presently used or being written for future experiments resulted in a list of characteristic operations for each experiment class and the number of computer instructions needed to execute them. Program size estimates were made for every operation and totaled for each experiment class. By weighing the number of instructions for each class according to the relative number of data points in the particular class, an estimate of 382 instructions per data point was obtained. Combining this with totals for quality checking and decommutation gave a total of 488 instructions per data point. The expected 2×10^8 data points per day, which does not include operational satellites such as TIROS, produce an estimate of about 10^{11} instructions per day. The size of the workload can be visualized if it is expressed in 40-hour shifts of IBM 7090 computing per week. There results a weekly workload of twenty such shifts, not including any setup time, reprocessing, or debugging. Although this sounds like a tremendous computer workload, it should be kept in mind that it is presently distributed among approximately 100 national and international experimenters, most of whom have access to their own computer facilities. The above analysis of workload led to consideration of a more efficient and centralized data analysis facility, as the next objectives for data processing.

LONG RANGE OBJECTIVES

Major advances have been made in the signal processing area. Now the overall system from spacecraft to experimenters will be considered. The problem breaks down into two methods of attack:

1. Physical reduction of data volume.

2. New methods for handling huge masses of data.

The data collection rate within the satellite can be kept to a minimum and this goal may be achieved in several ways. One is to vary the data rate in discrete steps. High rates would only be used in regions of special interest or when special phenomena are expected. During periods of no interest the satellite could be turned off. The sampling rate of each experiment can also be minimized by varying the channel assignments to the experiments within the fixed overall data rate. For example, OGO has one format which assigns no channels to experiments but all to spacecraft "housekeeping" data. This format is used during the launch phase when the experiments have not yet been stabilized and the spacecraft performance is of primary interest.

Another method of reducing the ultimate data volume is data compression. This can be performed on board the satellite, at the acquisition station, or during the data processing and reduction. One such approach is to design the experimental apparatus so that only useful information and therefore fewer data points are generated. A technique used at GSFC is on-board curve fitting to the data and transmission of only the parameters which describe the curve. One way to overcome

redundancy in data is to transmit only when a significant change occurs. Compression can be performed by keeping the output of multiplexed experiments at a reduced constant value.

In lieu of performing compression on board the spacecraft, it could be performed on the ground immediately after reception. This approach has the obvious major advantage of no weight and power limitation. The disadvantage is that many stations would have to be so equipped and each compressor would have to be quite complex in order to handle all satellites.

The workload in the later processing stages can be reduced by early elimination of superfluous and erroneous data from further processing during the quality control and editing operations. In addition, each experimenter can perform quality checks and further reduce the data volume by eliminating redundant data, the criteria being based on characteristics of the experiment. The total workload can be reduced even more by analyzing only parts of the data selected through gross scanning of all the data by a program or by the experimenter.

For those cases where compression is not feasible, new methods must be developed to make large volumes of data easily accessible to the experimenters. The experimenter should be able to assimilate quickly the gross features of his data and focus on the most interesting areas, which can then be analyzed in detail.

Some progress has been made in this direction at GSFC by planning for acquisition of a high-volume on-line data storage and retrieval system. It is hoped that this will culminate in the ability to access any of the data contained on the equivalent of 10,000 reels of digital tape in a matter of seconds. GSFC is also planning for the acquisition of high-speed mass memories, on-line, which can store up to one million data points.

As an example of the use of such a capability, work is being performed at the Goddard Institute for Space Studies on the analysis of TIROS radiometer data in connection with determining the heat balance of the earth (References 1 and 2). On board each satellite are flown five radiometer detectors, two of which sense radiation in the visible spectrum of wave lengths, the other three sense radiation in the 6 to 30 micron region. The outputs from these radiometers are sampled sequentially by a 5-channel commutator and are transmitted in analog form to the ground. They are then recorded and later digitized for computer entry. Approximately 400,000 sets of five-channel readings are obtained per day. For each set, the position, time and attitude information are computed and recorded along with the data on digital tape. The data are then calibrated and converted to absolute units, in this case, degrees Kelvin, and made available for analysis on an IBM 7094 computer. In the analysis program the data are segregated into 5° x 5° areas on the earth's surface. Three months of data are then averaged to obtain the heat energy balance of the earth, between the latitudes 60° north and 60° south. The resultant incoming and outgoing energy is plotted as a per day value for the time period June 1963 through August 1963, as shown in Figures 8 and 9 respectively. They represent the analyzed result of 200 million data points.

The acquisition of large on-line mass storage devices will both improve and speed up the processing of information exemplified by the above. In addition, on-line color plotting equipment would provide an improved presentation, better matching man's psychological image of temperature. As
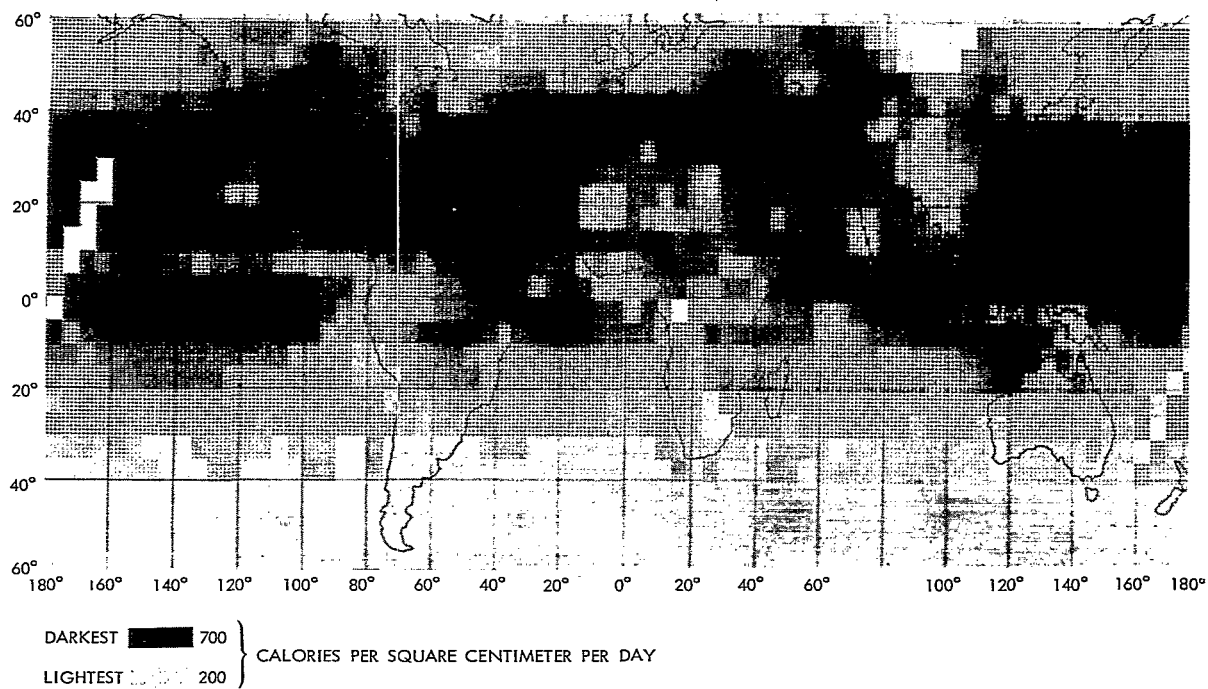
DARKEST ████ 700 ⎫
⎬ CALORIES PER SQUARE CENTIMETER PER DAY
LIGHTEST ⬚⬚⬚ 200 ⎭

Figure 8—Incoming radiation to earth atmosphere, June 1963 through August 1963, from TIROS VII radiation data.

DARKEST ▦▦▦ 700 ⎫
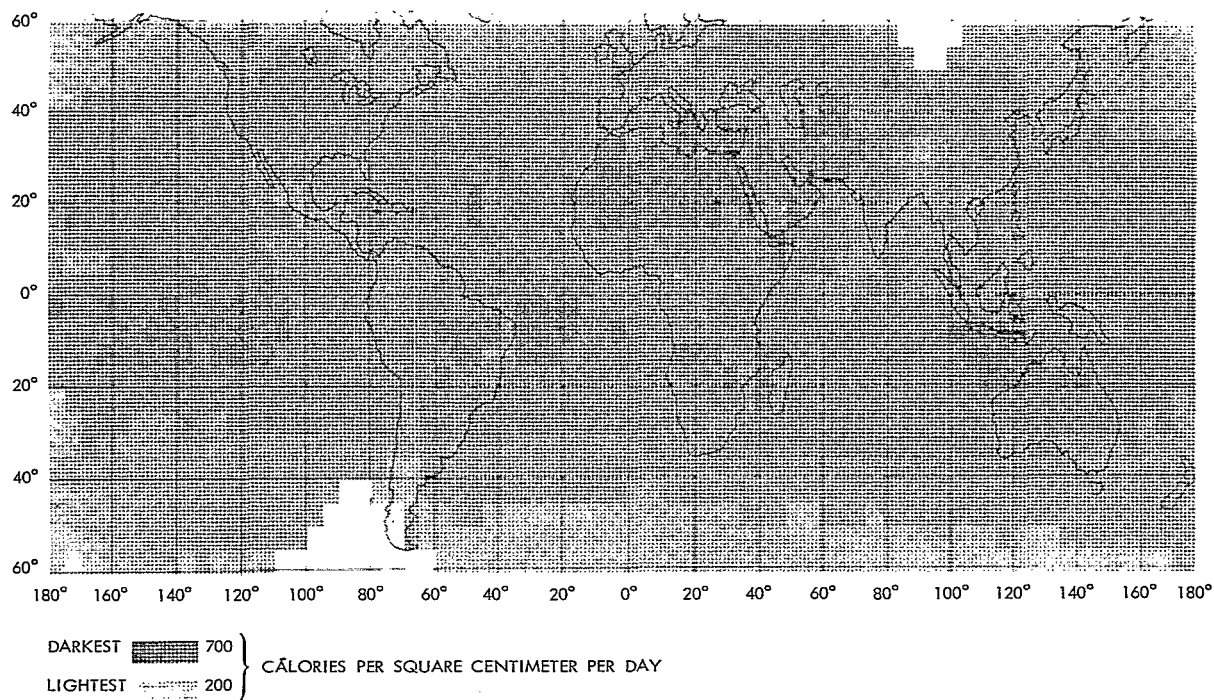⎬ CALORIES PER SQUARE CENTIMETER PER DAY
LIGHTEST ⬚⬚⬚ 200 ⎭

Figure 9—Outgoing radiation to earth atmosphere, June 1963 through August 1963, from TIROS VII radiation data.

we move into the era where more continual coverage of this energy flow becomes feasible by means of satellites, the above figures produced on a daily basis in motion picture form will allow an observer to watch the dynamics of energy exchange.

Another example is the plotting of magnetic field vectors as arrows on planar cuts through a reference coordinate system. Thus the magnitude and direction of the measured quantity are both apparent, and abrupt discontinuities or changes are easily seen.

Another example is automated motion pictures derived from satellite position and attitude information depicting the attitude and motions of a satellite while in orbit. This has already been performed for the OGO satellite by use of a microfilm plotter.

A more advanced step in data accessibility can be made by on-line display and communication with the experimenters. Each experimenter would be supplied with an inquiry and display console. The advantage of such a terminal would be random access to a large amount of data with very short access time, thus allowing the experimenter to rapidly scan the data and, for areas of interest call for more detailed processing.

CONCLUSIONS

In summary, we have a threephase effort in progress:

1. Production processing of the current workload.
2. Development of improved fully automatic systems for impending workloads.
3. An active program of study and analysis of how to improve the entire art of data reduction and display.

The objectives of the STARS Phase I system have been achieved providing equipment to handle the current data volume. The STARS Phase II systems are near completion, and represent improved, fully automatic equipment for telemetry data processing. Beyond the data processing covered in the STARS system, there remains a challenging area for improvement of data reduction and display techniques.

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—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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