

COMPUTERS AND APOLLO

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Assignment

November 25, 1970.

1.1 General

The last few days before a lunar mission launch probably have a larger utilisation of computers than any other phase of the mission. The many functions will be performed with increasing frequency and complexity, culminating in the vehicle liftoff from the pad.

ACE (short for Automatic Checkout Equipment) is a large bank of computers situated at Cape Kennedy. This equipment is running continuous checks on all spacecraft systems, monitoring the loading of propellants and parameter trends, and performing check routines with the CMC, LGC, and LVDC, which are the computers situated in the CSM, LM, and SIVB 3rd stage of the launch vehicle.

Some of ACE's results are sent via high speed lines to Mission Control Center (MCC) at Houston, where they are processed and formatted for display by the IBM 360 computers which form the RTCC (Realtime Telemetry and Command Complex).

The RTCC in turn is being used by the mission flight controllers to generate test digital command requests for transmission to the spacecraft via the Merritt Island tracking station situated at the Cape.

The rest of the tracking network (14 stations and one ship) is also being checked out by computers at MCC and Goddard Space Flight Center (GSFC) with a standard series of performance tests known as CADFISS (Computation and Data Flow Integrated Subsystems). These computers instruct the sites to perform tracking, telemetry processing, and command functions, monitor the outputs against pre-programmed standards, and inform the sites of the results.

The sites to MCC flow of high speed (40.8 kbs and 2.4 kbs) data and low speed 100 wpm teletype data, is switched, error protected, and routed via Univac computers situated at Pasadena California, London, Canberra, Goddard Space Flight Center, and Houston.

In conjunction with all this activity, the flight crew are probably having some final runs in the spacecraft simulators, controlled by computers. Other computers are assessing meteorological data from possible abort recovery zones, small range safety trajectory computers are being checked out. Still others are analysing solar flare activity data and numerous other tasks.

This type of activity continues throughout the mission with a slight overall reduction because the large checkout system at Cape Kennedy is shut down after lift-off. Shutting down ACE is offset to a certain extent by other off-line machines being brought into use. These machines in conjunction with specialised spacecraft simulators are used by the "backroom" spacecraft systems personnel to analyse spacecraft trends, simulate possible problems that may have developed and if necessary to check out new crew procedures to overcome the problems.

Three main groups of computers are associated with the flight of an Apollo spacecraft. These are -

- i) MSFN ground station computing systems
- ii) Mission control and communications processors
- iii) Spacecraft computer systems.

The first two groups will be covered later, but as the spacecraft computers probably contribute most to the overall mission success, the discussion will commence with a description of these devices.

2.1 Spacecraft Computers

Prior to liftoff and before all major spacecraft manoeuvres, the command module computer assists the crew by indicating the steps in various check lists and comparing resultant events and values with nominal conditions. During the liftoff sequence and insertion into earth orbit, the primary vehicle guidance along the reference trajectory, velocity, attitude, and engine commands are generated without external control by the launch vehicle computer in the third stage. This system is backed up by numerous possible ground commands including computer memory dumps and substitution of new data. During this powered phase and again during the translunar injection phase, the command module computer is providing trajectory monitor information to the crew displays, displaying times to critical events, and continuously calculating abort guidance data (commands, burn times, attitudes) for the service module engine or reaction control systems. The major source of input data for these calculations is the inertial monitoring unit which was aligned to the pad reference prior to liftoff.

Orbital navigation accuracy is confirmed and if necessary corrections made to the inertial platform reference during the two earth orbits prior to TLI.

After the TLI burn, controlled by the LVDC, the crew performs the transposition and docking manoeuvre. This is separation of the CSM from the launch vehicle third stage, a 180° pitch manoeuvre, docking with the LM and separation of the docked CSM and LM from the third stage. During this manoeuvre the command module computer is used to control attitude deadband limits, length of attitude thruster burn pulses and other functions in a combination of crew hand control commands and digital autopilot mode.

These three spacecraft computers are tied to the computer situated on the ground by a system of radio links.

2.2 Lunar Module

The LGC, or Lunar Module Guidance Computer is the heart of the guidance and navigation of the vehicle. This is illustrated in Figs. 1 and 2. This computer is linked by radio to the computer complex situated in a MSFN ground station and subsequently by land line and satellite to the Mission Control Center at Houston.

For the task of navigation in space, a system of inertial guidance and star tracking is utilised. The LGC and its software interpret the inputs from the latter devices to produce information to guide the vehicle along the intended trajectory.

The inertial guidance portion of the system employs accelerometers mounted on a gyroscopically stabilized gimbal-mounted platform. The inertial system senses acceleration and attitude changes instantaneously and provides incremental velocity and attitude information to the LM Guidance Computer for the generation of attitude change and thrust commands. The associated optical system used to take star or landmark sights serves the one purpose of providing data to establish an inertial reference.

The LGC contains in its memory the desired trajectory information to achieve the landing on the lunar surface and a subsequent rendezvous with the Command Module. The position in space of the vehicle at any instant is also calculated by the LGC using data from the onboard inertial system or from data obtained by the MSFN tracking stations and transmitted to the LGC. Any velocity or attitude changes to achieve a desired trajectory can thus be calculated by the LGC.

These velocity and attitude changes can be applied to the vehicle engines or to the RCS (Reaction Controls) completely automatically via the spacecraft control electronics interface. Fig. 2. The astronauts do, however, have the ability to intervene

in this process by using a computer I/O called a DSKY (Display and Keyboard)(Fig.3) to select a manual mode of control via the spacecraft translation controls. The DSKY also selects the other computer routines such as landing, cruise, tracking, and rendezvous and can also be used to load tracking data (stat vectors) voiced to the astronauts from a ground station.

The normal method used by Mission Control to talk to the LGC is by a digital radio link. Data in the form of stat vector updates and reference mats (initial IMV set up parameters) are sent to the computer. Data such as the contents of the LGC temporary store can be sent to the ground by a return link.

The LGC has also two further sources of data at its call; the Landing Radar and the Rendezvous Radar. The former radar system senses velocity and range relative to the lunar surface, while the rendezvous radar tracks the command module, giving look angle and inter-vehicle range.

2.3 LM Guidance Computer (LGC)

The LGC is a core memory, digital computer, with two types of memory - fixed (36864 words) and erasable (2048 words). The fixed memory permanently stores navigation tables, trajectory parameters, programs, and constants. The erasable memory stores intermediate information. It is capable of acting as both a system control computer and also as a general purpose computer where it is used to solve navigational problems.

Due to the number of different functions required of the LGC, the computer hardware is time-shared. This time-sharing is accomplished by assigning priorities to the various processing functions required of the LGC.

The first priority is given to data fed to the LGC from systems directly controlled by it. Angle inputs from the CDU are an example of this.

The second priority is assigned to both systems and program controlled processes such as control of the reaction control systems.

The third priority is program Controlled Processing. Most of the time the LGC's hardware is controlled by the program stored in its memory. A total of eight routines or 'jobs' can be progressed at one time. These 'jobs' are assigned priority numbers which determine the order in which they are processed.

The scheduling of jobs can also be controlled via the DSKY. Through the DSKY, the LGC keeps the astronaut informed of the operation of the guidance and control of the vehicle, requests the astronaut to perform various functions and allows him to enter commands or load data into the computer.

The mode of communication between the astronaut and the computer consists of the Verb and Noun, very much like a normal grammatical sentence. The Verb code indicates what action is to be taken (Operation), while the Noun code indicates to what this action is applied (Operand).

The LGC has the capability of displaying a verb to the astronaut, telling him that it was time he took some action such as feeding data into the computer.

2.4 LM Abort System

The LM vehicle contains a second general purpose computer, the Abort Guidance computer. This computer obtains data from a strapdown inertial guidance system and is used to back up the LGC, providing attitude and velocity to the vehicle if the prime computer fails. During normal operation the Primary Guidance and abort guidance are compared as a system cross check.

2.5 Command Module

The Command Module computing system is almost identical to that of the Lunar Module. The main difference is in the design of the computer software which has to carry out the somewhat different task of controlling the command module during its Earth re-entry phase.

The navigational system again uses an inertial reference which can be set up by a celestial reference. One extra navigational input is, however, provided to the Command Module computer. This is a measure of angular difference between two reference points which is provided by a sextant. One further extra set of parameters is input to the CMC - this is data from the Saturn IVB instrumentation unit and SVDC. This allows the SIVB and CSM to be controlled as a single unit.

3.1 MSFN Ground Station Computers.

The various on-site computers perform real-time functions concerned with telemetry, commands, antenna pointing and checkout of on-site equipment. Two large general purpose digital

computers perform the first two functions and two small ones perform the last two. Peripheral devices used consist of magnetic tape units, input/output consoles, high and low speed data units, analog to digital converters, with high speed printers and special telemetry processing equipment.

3.2 Telemetry and Command Computers

A separate computer is used for each of the functions of telemetry and command data processing. Fig. 4 shows the magnetic tape interfaces for these two computers. The various mission programs required to support these functions are written using a compiler and contained on magnetic tape. Using a bootstrap, a loader is read into core of the appropriate computer and the desired program then selected and read into core memory.

The program is then initialised with numerous parameter type-ins such as Remote Site identification and launch vehicle lift-off times. At the completion of this process the whole core is dumped onto a magnetic tape called the Recovery tape. Should the computer fault during mission support, this recovery tape is automatically read back into core and program execution commenced within a period of approximately 30 seconds. Had this facility not been available, then under a fault condition a complete reload from the systems tape plus initialisation would take approximately 10 minutes. Since the spacecraft in earth orbit can take a maximum of 9 minutes to pass from horizon to horizon, a fault under these conditions would be disastrous. Using the systems of recovery tapes, impact of these problems is minimised.

When a fault does occur, the contents of core are dumped out onto another tape called the fault tape prior to reading in the memory tape. Post-pass analysis of the fault tape may then possibly give some indication as to why the computer is faulty.

The telemetry software also uses a further magnetic tape containing the various formats which determine those telemetry parameters to be transmitted to Houston via high speed data. Different formats are used during the various mission phases. It is necessary to store these formats on magnetic tape because of the limited capacity (64K) of core memory.

The command software uses two additional magnetic tapes. The first is used to record all data uplinked to the spacecraft and the second to record all changes in input/output

channel activity. Both of these history tapes are required for non-realtime analysis.

3.3 Telemetry Data Flow

Realtime telemetry data is received from the command and service module (CSM), the lunar module (LM) and each astronaut when they are on the lunar surface (Fig. 5). Whilst in lunar orbit telemetry and voice data is recorded on-board when the vehicles are on the far side of the moon. When the vehicles reappear, this recorded data is then transmitted to ground stations in addition to real-time data. Under realistic mission conditions various telemetry data totalling to a maximum of 153.6 kbs is transmitted from the spacecraft. However, the maximum bit rate for transmission of data from remote sites to Houston is 4.8 kbs. It is the function of the telemetry software to select the required parameters and transmit them via HSD to Houston. All other data entering the telemetry computer goes into the "bit bucket".

3.4 Command Data Flow

The high speed data interface between Houston and the command computer permits the Flight Controllers to have remote control of both the command and telemetry software as well as sending data to, and controlling functions onboard, the spacecraft (Fig. 5).

If the controllers wish to change the format being used in the telemetry software for processing data, their request is sent via HSD to the command software. The latter interprets it as a request for the telemetry software and hence the request gets transmitted from the command computer to the telemetry computer via an inter-computer input-output channel. If it is a valid request, the appropriate format is read from the magnetic tape into memory and processing commenced. If it is an invalid request then a message to that effect is inserted in the HSD stream to Houston.

Data to be uplinked to the spacecraft takes one of two forms. Either it is a command to perform a function (e.g. start recorder rolling, switch antenna), or it is new data for the on-board computer. The first type of commands are all pre-stored within the command software. If the Houston controllers require the spacecraft to perform one of these functions, their uplink request is sent via HSD to the command software. If it is a valid request, the software obtains the command from core memory, formats it and uplinks it to the spacecraft via the appropriate peripheral

device. If the spacecraft accepts and acts on the command, it sends a message to this effect within the telemetry data. This is detected by the command software which sends the message via the intercomputer channel to the telemetry software which in turn sends it to Houston via HSD.

If the spacecraft does not accept the command, the appropriate message in the telemetry data is again detected by the command software. The command will then continue to be transmitted under one of the following conditions, depending on whether it is a priority or non-priority command:

- i) continue to be uplinked until verification is obtained or until stopped from Houston;
- ii) the uplink repeated unless it has been transmitted more than a specific number of times.

Under either of these conditions, the result is sent to Houston via the telemetry computer.

Data for the spacecraft computer such as navigation update information is generated within the computers at Houston. The information is formatted and transmitted via HSD to the command computer. After validity checks have been carried out, the information is stored within memory and also written onto the recovery magnetic tape. The latter operation is performed in order that the information can be recovered should the computer fault before the data is uplinked to the spacecraft.

When the flight controllers desire to uplink this information to the spacecraft from the remote site, they transmit a request to uplink via HSD to the command software. If the request passes all validity checks, the command software formats the data and uplinks it to the spacecraft. On receipt, the spacecraft inserts the data into the downlinked telemetry data. The command software looks for this returned data and makes a bit by bit comparison check. The results of the comparison are sent via the intercomputer channel to the telemetry software and thence to Houston. If the comparison showed that an error existed, then the flight controller has the choice of either uplinking the data again, or of just uplinking that part which was in error.

3.5 Contingency Operations

Should the HSD circuits between Houston and the remote site fail, then control of the telemetry and command software is transferred to on-site personnel. The only Houston function that it is not possible to duplicate is the generation of

data for the onboard computer. In this case the backup teletype circuit is used for transmission of this information to the site. The on-site personnel control the software by push button matrices and information is presented to them by high speed printer.

3.6 Error Protection in Data Transmission

No attempt is made to correct for errors in transmission. Combined attempts to protect against, and check for errors, are made, with the methods used being dependent upon the transmission path. Polynomial error protection is used on the Houston/Remote Site and sub-bit encoding is the Remote Site/Spacecraft data link. In the method of sub-bit encoding, a pattern of five bits is uplinked for every one bit of data.

3.7 Antenna Pointing

A computer system of positioning the antenna is available in addition to the normal RF method of control (Fig. 6). Predicted positions are received via TTY at the MSFN sites. The computer interpolates between the data points and either presents the information in real time to the antenna position programmer, or it provides a paper tape containing the information for use by the latter. The antenna position programmer compares the actual angle of the antenna with the predicted values and inserts an appropriate error signal into the antenna servo control system. At the present time the capability to generate predicts on-site is only available for lunar view periods.

3.8 Automated Site Checkout/Simulation and Monitoring

At the present time a computer orientated system is being progressively installed which will ultimately have the following three capabilities:

- i) Automated checkout of a remote site's capability for mission support.
- ii) Generation of simulated data in order to train personnel in mission operational procedures.
- iii) Monitoring of on-site equipment operations during mission support time.

4.1 GSFC and MSC

At the opposite end of the chain of computers to the LM and CSM lies the Manned Spacecraft Center (MSC) situated at Houston. The controllers in the Mission Control Center at Houston originate the commands sent to the vehicles and also receive the

telemetry information from these same vehicles.

Data to and from the MSFN stations is, however, not sent directly to Houston, but routed via the Goddard Space Flight Center (GSFC) at Greenbelt, Maryland. This is illustrated in Fig. 7.

4.2 GSFC

Telemetry and tracking data from various MSFN stations arrives at GSFC at a 2.4 kb/sec rate by standard land line and is interfaced into the Univac 494 computer system via the Computer Line Terminal (CLT). The 494 machine is used to reformat this data into a 50 kb/s stream for transmission to MCC via wide band link. MSFN tracking data also arrives at the CLT via a teleprinter link and is also reformatted. Spacecraft commands and computer loads generated at Houston are sent to the MSFN stations via the GSFC Univac 494 computer system. The computer in this instance identifies the command routing indications and directs them to the appropriate station and hence to the spacecraft. This latter data arrives at GSFC over another 50 kb land line.

During an Apollo mission the Goddard Space Flight Center is used to check out the MSFN ground stations and also act as an emergency mission control center. A pair of IBM 360-75 computers are used for these tasks.

4.3 Apollo Universal Command System

The Apollo command system with its starting point at Houston is designed with two main objectives in mind. Firstly, the communication of computer loads or memory updates to the spacecraft and the control of certain parameters in these vehicles. Secondly, the automatic communication of information or requests to the MSFN stations by direct intercomputer data flow (Fig. 7).

The basic tools of this process are contained in the Real Time Computer Complex at Houston. The system consists of four IBM 360-75 computers. For any single mission, two computers are assigned, one as prime and the other as an off-line spare. These computers are each extended to 4 mega bit storage and a single system is capable of running an Apollo mission.

All command information is initiated by the Flight Controllers at MCC utilizing the Real-Time Computer Complex (RTCC). This information may be command loads, Execute Command Requests (ECR), or Computer Execute Function (CEF). A command load is information generated for use by the spacecraft computers. An ECR

contains instructions sent to the MSFN station to direct the uplink of a command load or a command to change a spacecraft function (RTC). The CEF contains instructions sent to the remote site directing a certain function to be performed by the station command computers such as a printout of previous commands uplinked to the spacecraft.

4.3.1 Command Loads

The Computer Command Controller (CCC) is responsible for the generation of command loads from instruction from the Flight Controller. A manual entry is made to the RTCC system specifying the tracking stations to which it should be sent and the type of load. When the load has been compiled by the 360-75, it is displayed by the Cathode Ray tube display devices (Digital TV) on the CCC console and the Flight Controller console. If the Flight Controller approves the load, the CCC will transfer it to the Univac 494 computers associated with the Communication, Command, and Telemetry System (CCATS). From there it is shipped by wide band link to the 494 communicating processing computer at the Goddard Space Flight Center and subsequently to the appropriate ground station and spacecraft.

4.3.2 Execute Command Request/Computer Execute Functions

The above functions are generated by switches and pushbuttons on the various consoles in the Mission Operations Control Room (MOCR) situated at Mission Control Center and converted to digital words for inputting to the CCATS 494 computer system. The CCATS Command Software formats these words for transmission to GSFC via the 50 kb/s lines and hence to the ground stations and spacecraft. When these executes are received at the MSFN tracking stations, a validity check is made on them by the site computer system and a CAP VAL (Command Analysis Pattern) is sent back to the CCATS if the function is found to be correct. The computers in the spacecraft also generate a MAP (Message Acceptance Pulse) which is also returned to MCC when the command has been correctly decoded at the spacecraft, thus closing the command loop to and from the spacecraft.

4.4 Apollo Telemetry

4.4.1 During an Apollo mission the Lunar Module, Command Service Module and launch vehicle parameters are routed to MCC for use by the Flight Controllers and other mission support

staff. These parameters, after reformatting at the MSFN site by the 642B computers, are sent via two 2.4 kb/s audio lines to GSFC where they are terminated by the CLT (Fig. 3). The GSFC 494 computers reformat this data for routing to MCC via the 50 kb/s wide band lines.

4.4.2 CCATS Telemetry Processing

The CCATS 494 computer software is designed to process near realtime telemetry data received from the MSFN. The telemetry is decommutated and presented to the Telemetry Instrumentation Co-ordinator (TIC) who selects which source of data (i.e. from which MSFN site) is to be processed. A certain amount of parameter scaling and extraction of digital events is also performed by the CCATS system.

4.4.3 Data Processing by RTCC

Once per second blocks of telemetry data are transferred to the RTCC computer system (360-75). The RTCC telemetry processor performs limit sensing, scaling, and any special processing required. It also provides data to a selection of digital-to-television formats that can be selected by the flight controllers at the MCC consoles.

5.1 Tracking Data

Tracking data generated by the MSFN and Radar sites follows exactly the same path to the RTCC system as does telemetry data. The data processing in the 360-75 computer is, however, somewhat more complex. During unpowered flight, the ground stations only output one sample of tracking data per six seconds (one sample consists of all the information necessary to determine the spacecraft's position and velocity at a given time). This low sample rate is necessary - otherwise the RTCC complex would soon be swamped by excess data.

5.2 RTCC Processing

The RTCC contains data on the desired orbit of the spacecraft and also the actual path they are travelling. This path is updated from ground station tracking data.

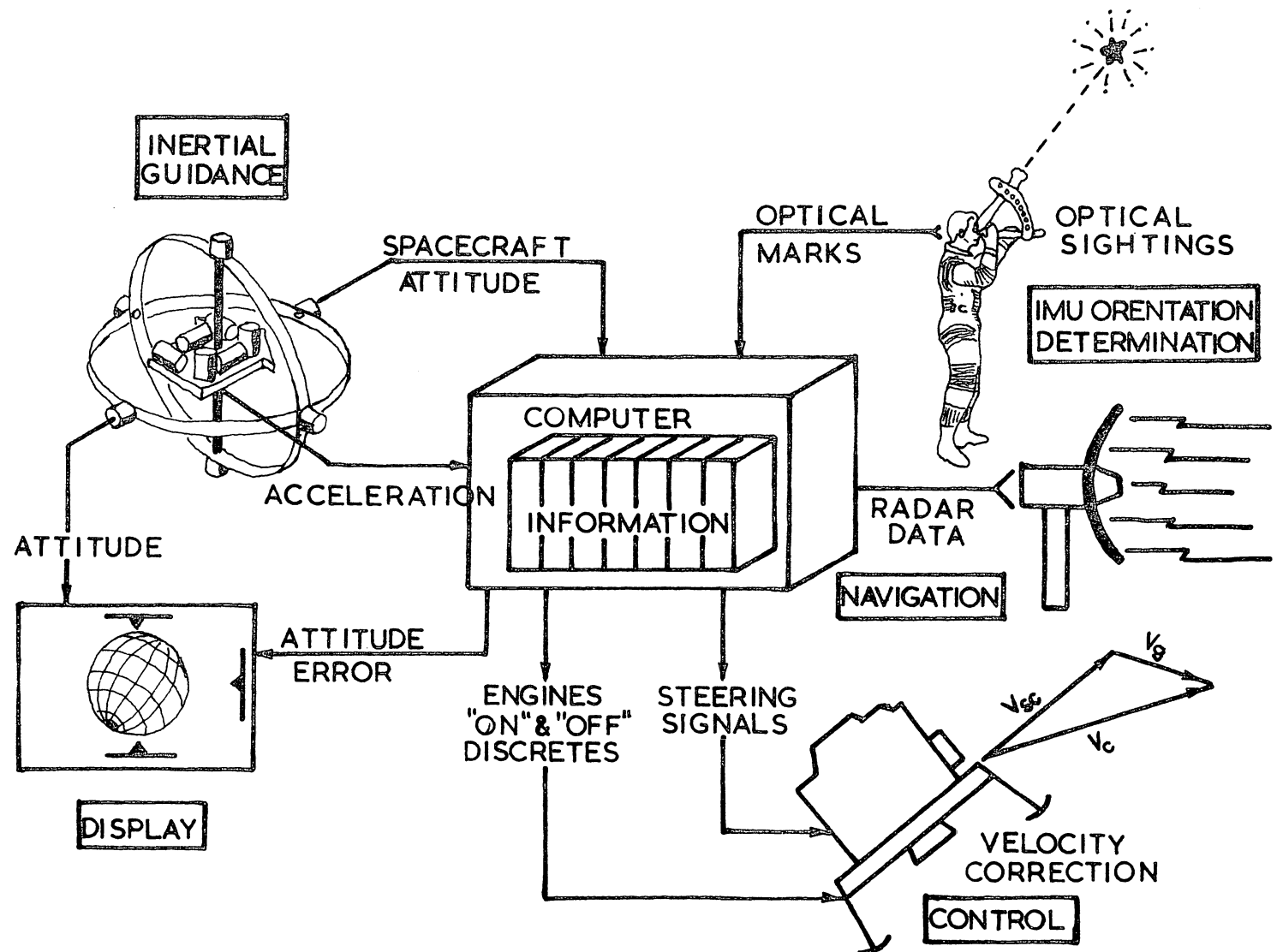
A batch of eighty samples of tracking data is reviewed by Data Select who will then process this data by removing error points and making various corrections. A predicted path will then be calculated from this new data and compared with the

previously computed path held in the RTCC. If the new data is likely to refine the previous data, the new data will be used to update the actual flight path.

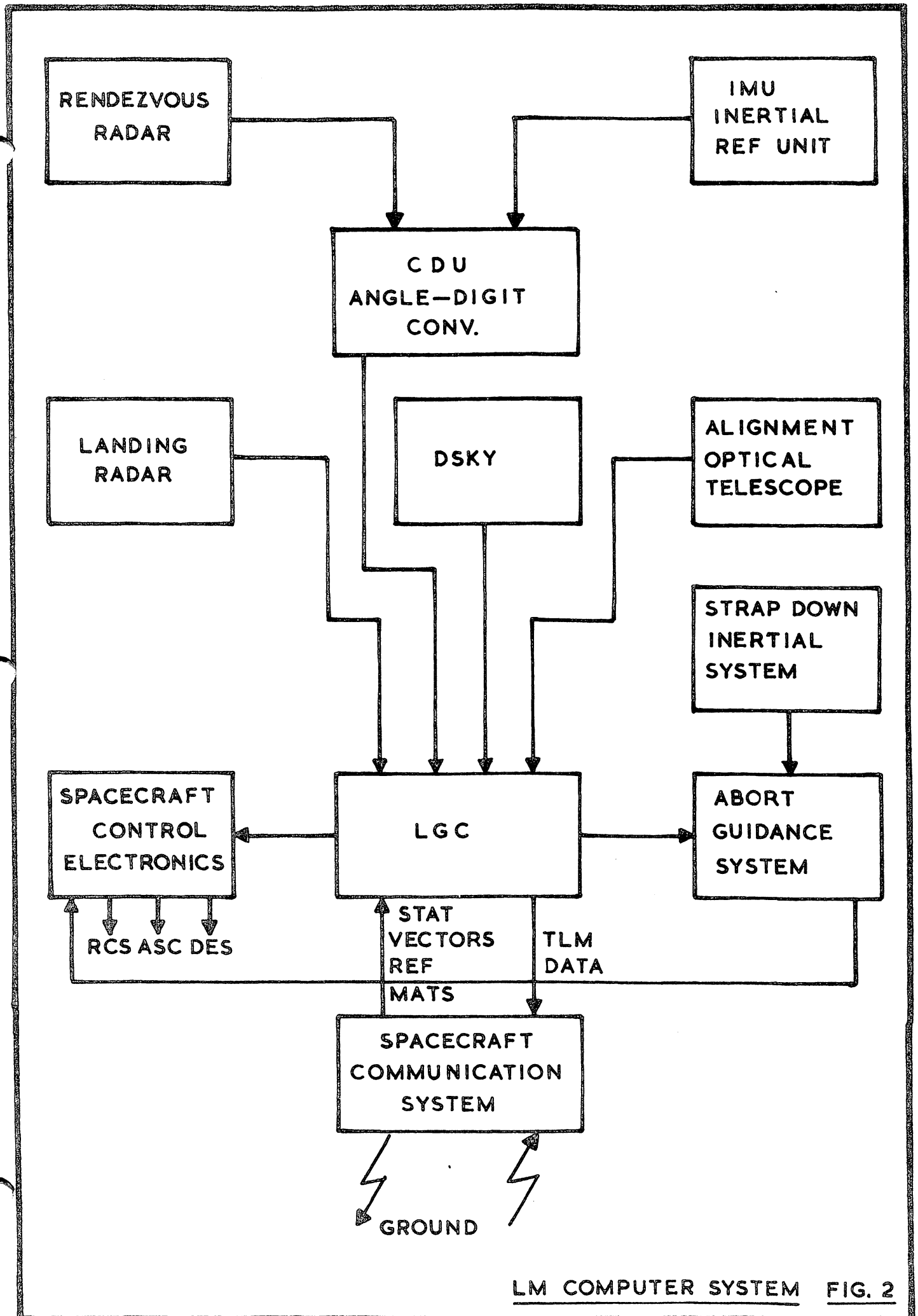
When a path correction is required to be made to the spacecraft, the Dynamics Controller will compare the actual flight path against the required path and use the RTCC to calculate the correction in the form of a spacecraft vector and velocity change. The change can be automatically sent to the computer in the spacecraft to be acted upon at the specified instant.

6.1 Conclusions

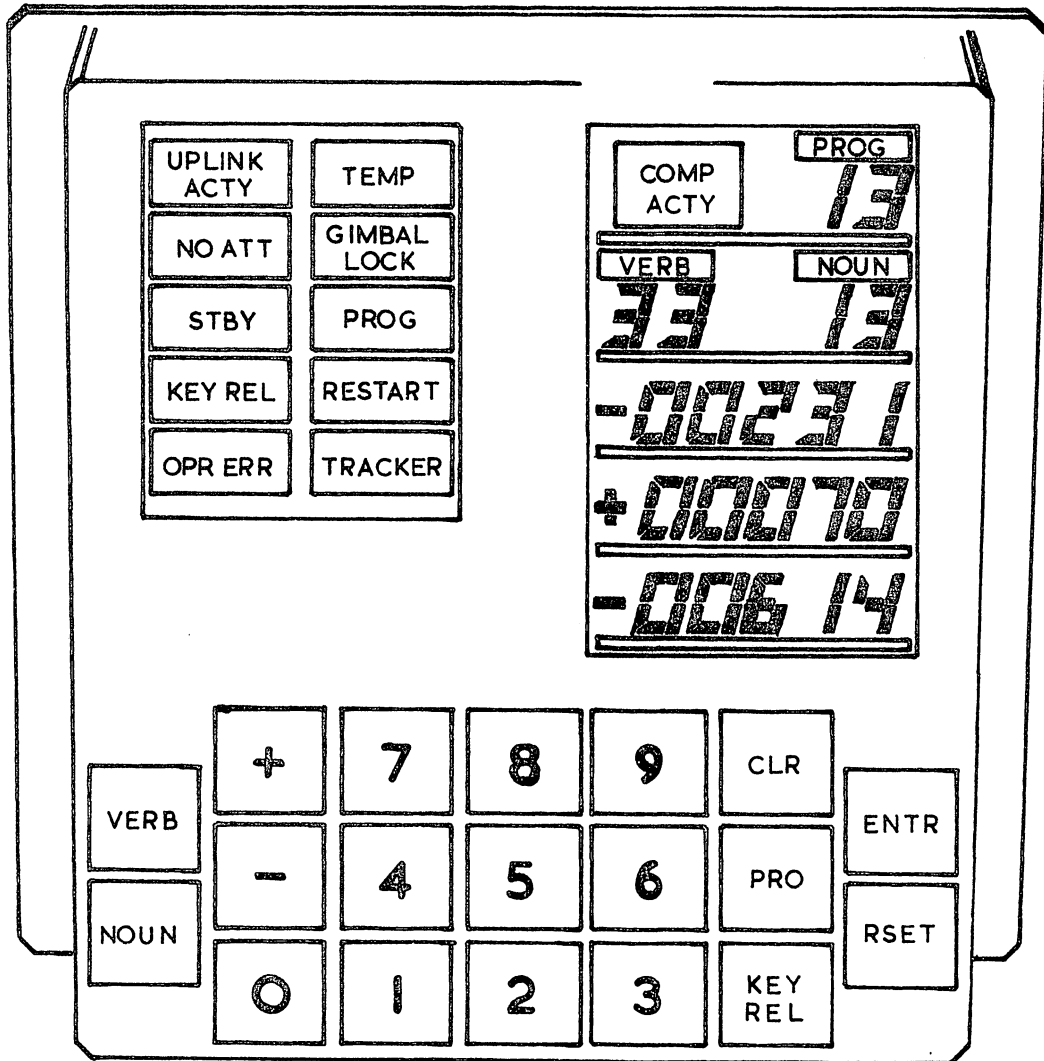
The object of this discussion has been to show that without the modern high speed digital computer, the Apollo project would have been impossible. Not only would the launch vehicle be impossible to check out without computers, due to its complexity, but, if launched, could never be directed along a planned flight path.



PGNCS REQUIREMENTS FIG. 1



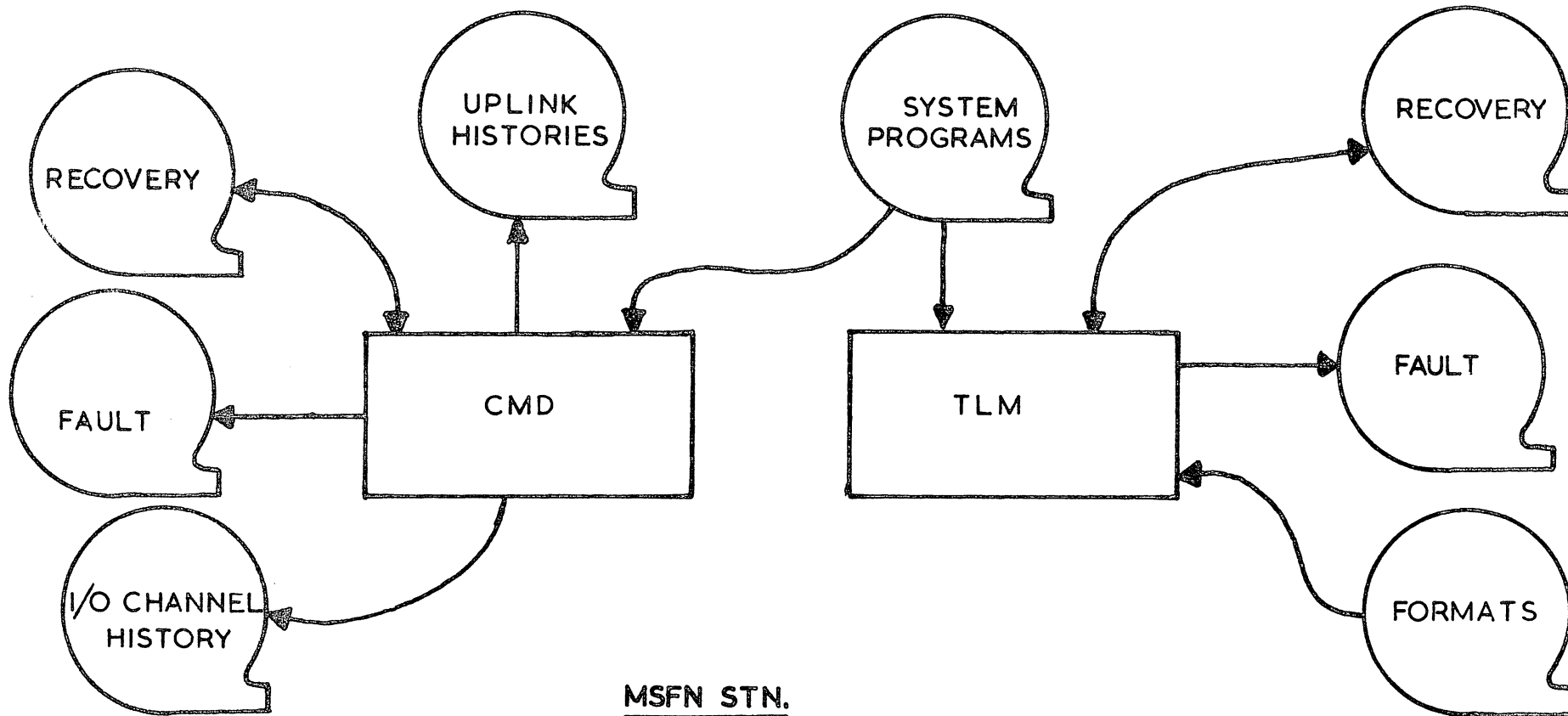
LM COMPUTER SYSTEM FIG. 2



DISPLAY & KEYBOARD

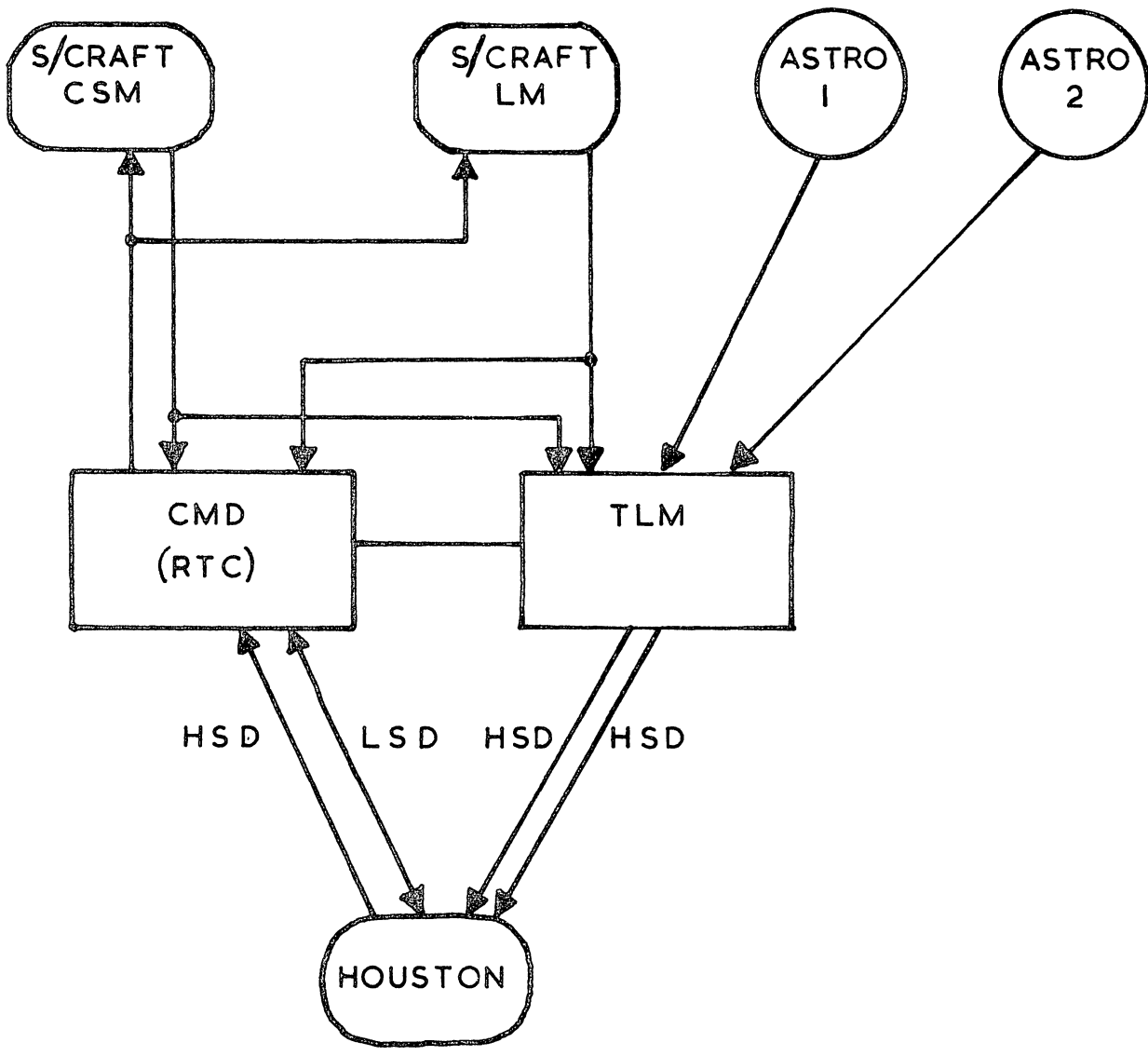
(DSKY)

FIG. 3



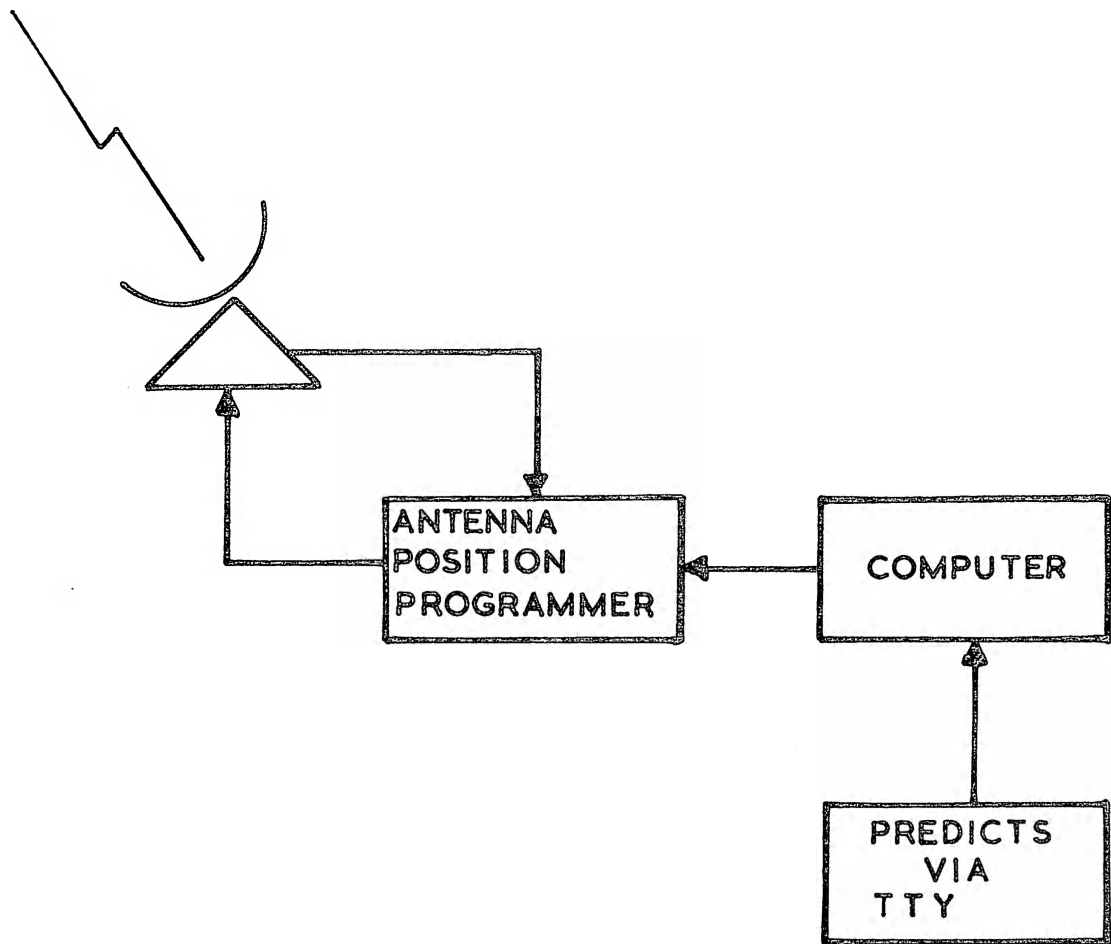
MSFN STN.
MAGNETIC TAPE INTERFACES

FIG. 4.



MSFN STN. DATA FLOW

FIG. 5



ANTENNA POINTING COMPUTER

FIG. 6

