ON-BOARD PROCESSING FOR THE NOVA SPACECRAFT

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ABSTRACT

A major hardware change to the TRANSIT Navy Navigation Satellite System (NNSS) is underway. A new generation of satellites called NOVA are being built which have on-board a general purpose minicomputer, high precision clock, orbit adjustment system (OATS), and disturbance compensation system (DISCOS).

This paper describes the software and processing for the on-board computer. The software is a system of interrupt driven, real-time programs which perform various data management and control functions and allows great flexibility in the operation of the satellite. In addition to loading special programs and data and dumping specified regions of memory, data management includes loading and then retransmitting navigation message data and collection of both telemetry (TM) data and DISCOS thruster firing data. Through its interface with the spacecraft TM and command systems, the on-board computer also serves as a powerful control device, especially in the orbit adjust phase immediately after launch. It has already been demonstrated with a previous version of these satellites that this highly flexible software system can be quickly reconfigured after launch to recover from failures to other satellite hardware systems.

Also described in this paper are other satellite subsystems which interact with the flight computer and the system of ground support computers and software.

INTRODUCTION

The TRANSIT Navy Navigation Satellite System has been available for military use since 1963 and for public use since 1967, providing all-weather navigation to worldwide users. This system has been continuously updated and improved with no user changes required (1).

A major hardware change to the TRANSIT system is currently taking place with the placing of a new type of satellite into the constellation. These satellites were originally called TIP (Transit Improvement Program) satellites and were designed and bult by The Johns Hopkins University Applied Physics Laboratory. The satellites have on-board a high precision clock and a general purpose minicomputer which allows great flexibility in the operation of the satellite while requiring no changes to user equipment (2). Also, each satellite has a hydrazine-fueled Orbit Adjustment System (OATS) and a single axis Disturbance Compensation System (DISCOS). See Figure 1.

Two TIP satellites were launched. The operational version of the satellite is called NOVA and is being built by RCA. The first NOVA spacecraft was launched in May 1981. Nominally, the spacecraft are launched by SCOUT vehicles into near-polar, 180 by 400 nm (330 by 740 km) altitude parking orbits. The hydrazine fueled orbit adjust system is then used to change the orbit to circular at 600 nm (1110 km) altitude. At the same time the inclination is precisely trimmed to a selected value near 90° to control the nodal precession. An important part of this operation is to select optimum directions for thrusting to correct the altitude and inclination together and minimize the fuel requirements. Utilizing special orbit adjust-phase software, the flight computer is the main controller for the OATS operation.

Improvements in the orbit determination process and software for the TRANSIT system have been described in a previous paper (3). This paper is concerned with the software and processing for the on-board computer. This software is a system of interrupt driven, real-time programs which are resident after launch to perform data management and spacecraft control in orbit (4). The system is designed to support two phases of operation -- the post-launch phase and the operational phase.

During the post-launch phase which includes the OATS operations, gravity-gradient attitude capture, and spacecraft performance evaluations, the flight computer system:

1. maintains an internal clock on universal time (UTC),
2. stores and dumps requested telemetry (TM) data,
3. monitors and stores DISCOS thruster firing information,
4. monitors selected TM channels and performs control functions based on these readings,
5. performs spacecraft power management by duty-cycling certain electrical loads,
6. uses delayed command capability to support OATS firings, spin-axis slewing, and gravity-gradient attitude capture.

During the operational phase, the system performs the following functions in addition to 1-3 above:

1. loads and manages ephemeris information in storage, with eight days' worth stored continuously,
2. controls the navigation message transmission on the normal (50 bps) modulation.
3. manages the incrementally programmable synthesizer (IPS) hardware registers to provide high precision clock control,
4. performs automatic leap second clock adjustments when required to keep the satellite clock on UTC,
5. tests all ground commands for validity when the satellite is in the secure state, and
6. provides a recovery capability to restore spacecraft hardware registers which might have become garbled.

The software is complicated, and its operation involves a myriad of detail. Its complexity makes changes difficult. Its very presence complicates by an order-of-magnitude the ground software needed to manage the satellite. In return for this complexity, however, comes an unbelievable flexibility to redefine the mission after launch, correct unanticipated problems, and work around partial failures (5). Furthermore, the flexibility provided by the flight software adds no space or weight to the payload.

THE FLIGHT COMPUTER AND ITS INTERFACES

The NOVA flight computer is a general purpose minicomputer with specialized Input/Output (I/O) logic to service various spacecraft functions in real-time. The computer consists of two redundant CPU's complete with I/O logic and two magnetic core memories. Either memory or both may be used with either of the redundant CPU's. Each memory provides programmable storage of 16,384 words of 16 bits each. There is also a 64-word hard-wired, Read-Only Memory (ROM) containing a special loader for restarting the software.

The NOVA computer was designed for assembly language programming. The memory cycle time for the computer is 4.8 μs, with the time for an ADD operation being 9.6 μs. The NOVA interrupt system is a hard-wired priority system containing 32 inputs. The 24 highest priority interrupts are labeled external and the last eight are internal. As implied by their name, external interrupts are driven by systems external to and independent of the computer. The eight internal interrupts are controlled by the software and are used for high-speed linkage to various subroutines. These interrupts can also be masked and enabled via software.

All computer input data are transmitted via RF link. The satellite can receive digital data at a rate of 10 bps or 1000 bps. The slow rate can feed the computer or the command system, while the 1000 bps data can only be used by the flight computer. There are a number of ways, direct and indirect, in which computer outputs can be realized. Direct outputs occur when data from memory are transmitted by the RF downlink channel to the ground. Indirect outputs are inferred when another satellite subsystem changes in response to a directive from the flight computer. The most useful direct output occurs in the computer dump mode. Upon command, the telemetry system transmits continuous flight computer data (via TM modulation). This mode requires a dump program in the computer to relay the contents of memory to the TM system at the proper rate.

The flight computer software interacts through special hardware interfaces with other subsystems to give the computer far-reaching powers in controlling and monitoring the satellite. The computer derives most of its power to perform control functions by virtue of its direct interface to the spacecraft telemetry and command systems. The NOVA hardware includes a telemetry system whose function is to gather, process and format spacecraft data for transmission to the ground in a serial bit stream. The TM system is digital, with 8 bits per channel, 172 channels per frame, and a 4.2 s frame rate. The TM interface allows the computer to exchange data with the TM system under direct software control. To receive TM data, the software requests via the interface one of the 172 TM addresses. When this address occurs within the normal cycling of a TM frame (every 4.2 s), the computer is interrupted and receives the data for storage or processing. Generally, data stored in the flight computer memory is later returned to the TM system in the form of a memory dump transmission.

The NOVA command subsystem contains digital (10 bps) logic to perform the remote execution of relay commands, pulse commands, digital data commands and slow (10 bps) loading of the computer memories. Through the command interface, the flight computer has direct access to the front end of the command system. Any command can be issued by the flight software by serially transmitting the command bits through the interface at the required 10 bps rate. The length of a relay command bit string requires 2.3 s for complete transmission. Any command can be executed with a programmed time delay by allowing the computer to issue the command. This “delayed command” capability results from loading the information for the delayed commands into the computer memory to be processed at a programmed time.

The main implications of the I/O interfaces described above are that the computer is limited to a data sampling rate of 4.2 s for any given TM channel, and the maximum command rate is one every 2.4 s. These constraints are quite important in some of the control functions implemented during the orbit adjust phase of the satellite mission (5).

GROUND SUPPORT SYSTEM

The NOVA operational ground support system is illustrated in Figure 2. The software for this system includes at least five major programs and uses four different computers. The backbone of the system is the ground station PDP-11/40, operating through a front end PDP-8. This system is used to control all real-time satellite operations, and is also used for data formatting, real-time conversions and display, and miscellaneous utilities.

A program to be injected into the NOVA flight computer begins as source code which contains the program written in the flight computer assembly language. The source code is input to the IBM-3033 computer and processed by an assembler program called ARTIC. The output of ARTIC is the machine code on a magnetic tape along with a printed listing of both the input assembly language instructions and the corresponding machine code. The program tape is then stored on a disk file in the PDP-11 by the TIPLIB program. This disk file library contains the latest versions of all the flight computer software, including operational and diagnostic programs.

The PDP-11 program that selects the flight computer programs from the library and formats them for transmission to the satellite is called TIPLOAD. The input to TIPLOAD is a card deck which defines the programs to be selected from the disk file library. This data from the library is then merged with other flight operation inputs and formatted for transmission to the spacecraft. The output of TIPLOAD is a disk file (LDM file) in the PDP-11. The data on this file is arranged into segments called “modules” which can later be individually transmitted to the spacecraft.

The navigation message data begins with the INJC program which is run on the IBM-3033 after the orbit programs have generated the predicted satellite ephemeris. The INJC output is a set of NAV message modules for injection by the TIPCOM program. Each of the message modules contains the navigation parameters for nominally a half-day of message. At the injection station, a PDP-11 disk file (INJD) is created from the INJC output and generally, there will be 16 modules or eight days worth of messages on this file.

During a satellite pass the LDM or INJD file data is transmitted to the TIP spacecraft under control of the TIPCOM program, which also resides in the PDP-11. In addition to transmitting data up to the flight computer, TIPCOM also receives and records downlink loading feedback flags from the flight computer. All real-time communications are handled through TIPCOM. In addition, TIPCOM converts and displays on CRT much of the normal TM data in real-time.

For the post-launch operations there is additional special attitude determination software which resides in the IBM-3033. These programs process TM data (both real-time and flight computer stored) and compute spacecraft attitude and spin-axis slewing maneuvers (6), (7). The output is a set of delayed commands which are then transmitted to the flight computer to accomplish the slewing maneuver.

The overall ground system is complicated but flexible. It gives the user the ability to modify the flight software after launch, as well as to manage the system in orbit in ways that were not anticipated when the software was developed (5).

FLIGHT COMPUTER SOFTWARE

The main flight computer software is a set of basic programs called SYS which are resident in memory at all times. SYS contains

1. loading programs which can handle data at 10 bps or 1000 bps. A large portion of the fast loader software is dedicated to managing the loading of navigation message data;
2. a program which sends loading status flags back to the ground station computer via the 325 bps TM downlink. These flags indicate whether or not each batch of data was injected correctly (without parity errors);
3. a memory dump program which can read out areas of memory on either a 325 bps or 1300 bps downlink;
4. a status routine which sends 80 bits of computer status information to the TM system each frame;
5. a timekeeping routine that keeps a high precision universal time clock. The basic software clock increment is referred to as a "tock" and is precisely 120/6103 s;
6. a Time-Queue program which controls the chronological sequencing of computer events such as delayed commands.

In addition to SYS, there are other special programs which are loaded by SYS when needed. Some of those programs are:

1. Navigation Message Program (NAVPRO)

NAVPRO is the main operational flight computer program and outputs the standard 50 bps TRANSIT Navigation Message containing the satellite's ephemeris data. To the user, the NOVA Navigation Message will look like that of the current operational satellites. In addition to the ephemeris data, every two minutes NAVPRO outputs timing words needed to give clock epoch to the ground. NAVPRO also handles the setting of the software UTC clock and synchronizing the broadcast message with the clock.

NAVPRO operates on a list of eighteen half-day modules of ephemeris data which fills most of the flight computer memory. NAVPRO automatically switches from one module to the next making the switchover look to the user like a navigation message injection. Should NAVPRO run out of valid message data, it will put out a “dummy” message which cycles every two minutes.

2. Delayed Command Program (DCPRO)

“Delayed command” refers to a relay or data command which is sent by the flight computer directly to the satellite command system at some pre-specified time. The delayed commands are prepared by special card inputs to the TIPLOAD Processing Program. DCPRO may also be used to send commands upon the occurrence of certain events. This is done in conjunction with a family of programs described below called TMON. TMON initiates delayed commands whenever the data in certain telemetry words matches pre-specified criteria.

Some of the more significant uses of DCPRO include arming and firing of the OATS, magnetically slewing the spacecraft spin axis, duty cycling spacecraft subsystems for power management, etc.

3. Telemetry Storage Program (TMPRO)

TMPRO is used to sample and store real-time telemetry data in the flight computer. The program expects as inputs a list of TM channels to be stored and the rate at which each is to be stored. TMPRO allows each TM channel to be sampled at its own rate, hence all channels need not be sampled during the same frame. The program remains operating in the flight computer until the specified storage area fills up. The program automatically stops storing data at this point. Once the program has completely executed, a memory dump procedure transfers the stored data from the flight computer to the ground station.

4. Telemetry Monitoring Programs (TMON)

TMON is a family of programs which monitor certain telemetry words and send delayed commands based on the TM data. For example, one program senses the OATS fuel temperature and turns a heater on and off by delayed command. In addition, the battery voltage is monitored and power draining spacecraft subsystems are turned off should the voltage drop below an input threshold. Other programs from the TMON family such as SPINUP and THRUST have been most useful for the special post-launch operations. A more detailed description of their use is given in Reference 5. WHLCON controls the momentum wheel speed by sensing it via the TM system and sending delayed commands to turn power on and off to the wheel. This allows the wheel to be brought up to speed slowly enough to avoid tumbling the spacecraft. Any of the TMON programs can be used in a TM storage mode only. Unlike TMPRO, however, TMON does not shut off and cease its monitoring function once its storage area is filled.

5. Periodic Program (CYCLE)

CYCLE is a program which causes the Time-Queue actions to repeat with a specified period. This program is most useful during the orbit-adjust operations when the times of many of the delayed commands are a function of the orbit geometry and hence are periodic.

6. Alter Program (ALTPRO)

ALTPRO is a program which alters flight computer memory locations as a function of time. The memory locations, their new contents, and the corresponding times are all specified by the user. This feature of changing the program logic dynamically while the flight software is actively running turns out to be both powerful and useful in the orbit-adjust operations.

7. VCO Mode Program (VCOPRO)

VCOPRO stops the TM commutator on a specified channel and allows TM data for that channel to be received and recorded continuously by the ground station.

8. DISCOS Data Storage Programs

Each NOVA satellite will contain a single-axis Disturbance Compensation System which consists of a sensor portion and two teflon thrusters. A constant speed momentum wheel provides spacecraft yaw stability which assists in keeping the DISCOS system nominally aligned with the “along-track” direction. The purpose of the DISCOS device is to counteract the along-track components of drag and solar radiation pressure forces and thus make long-term orbit prediction more accurate. With drag removed, the ephemeris precision becomes limited primarily by the geopotential model errors.

The flight computer, through its external interrupt system, is able to sense the DISCOS thruster firings and hence record data useful for performance analyses. Two DISCOS data storage programs are available. One, called DSPRO, simply stores the total number of fore and aft thruster firings. The second program is more complex and is called DRAG. DRAG stores the difference between aft and fore thruster firings during an input (nominally 1 minute) interval. In the satellite’s operational phase, the navigation message data requires most of the available memory. For DRAG to operate continuously for long periods (days) it stores its data over used navigation data. Then before the next navigation message injection, DRAG is terminated and its data dumped to the ground station.

CLOCK CONTROL FOR THE NOVA SATELLITE

The new navigation satellites contain hardware that greatly increases the potential precision of the real-time satellite clock. The IPS allows precise "steerage" control over the satellite 5 MHz output. The IPS system is used to maintain a high-precision clock by observing the satellite epoch on the ground and injecting IPS control parameters for clock steerage.

One of the important functions of the flight computer software is to "manage" the IPS system in real-time in orbit. The two main tasks of the IPS control program are:

1. It increments (or decrements) the IPS A-Register at a programmed rate to compensate for oscillator aging drift.
2. It continuously moves the IPS A-Register up and down on a 2.5 s cycle to give the effect of a fractional A value, and improve the hardware resolution by about two orders-of-magnitude.

REAL-TIME SPACECRAFT CONTROL VIA THE FLIGHT COMPUTER

The flight computer has proven its value in performing real-time control functions that have been indispensable in past operations (5). Some of the demonstrated control capabilities used thus far include:

1. Spacecraft power management.
2. Temperature control of the hydrazine system.
3. Spacecraft spin-up and nutation control using the magnetic system.
4. Controlled spacecraft tumble and de-tumble.
5. Real-time management of the IPS system.
6. Controlled firings of the hydrazine thruster.
7. Spin-axis slewing for directional control of thruster firings.
8. On-board UTC clock management.
9. Controlled gravity-gradient capture.
10. Validation of ground-transmitted commands.
11. Stopping the TM commutator on a specified channel for continuous TM readout.
12. Bringing the momentum wheel up to full speed slowly enough to avoid tumbling the spacecraft.

No doubt other control functions not yet anticipated may become necessary. The built-in flexibility of the ground and flight software will allow them to be easily implemented as they arise.

ACKNOWLEDGMENT

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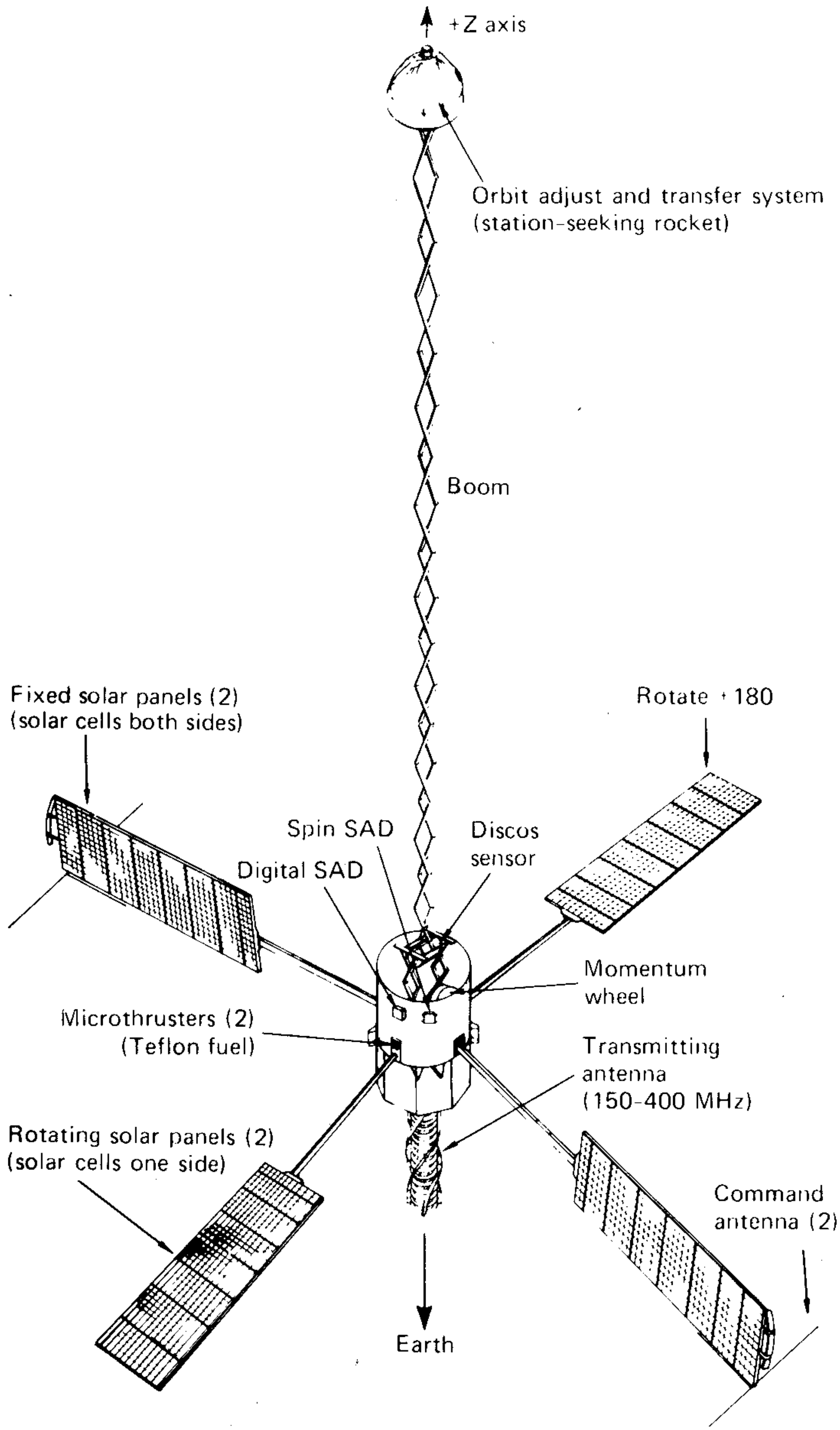

Fig. 1 Orbital configuration of TIP.

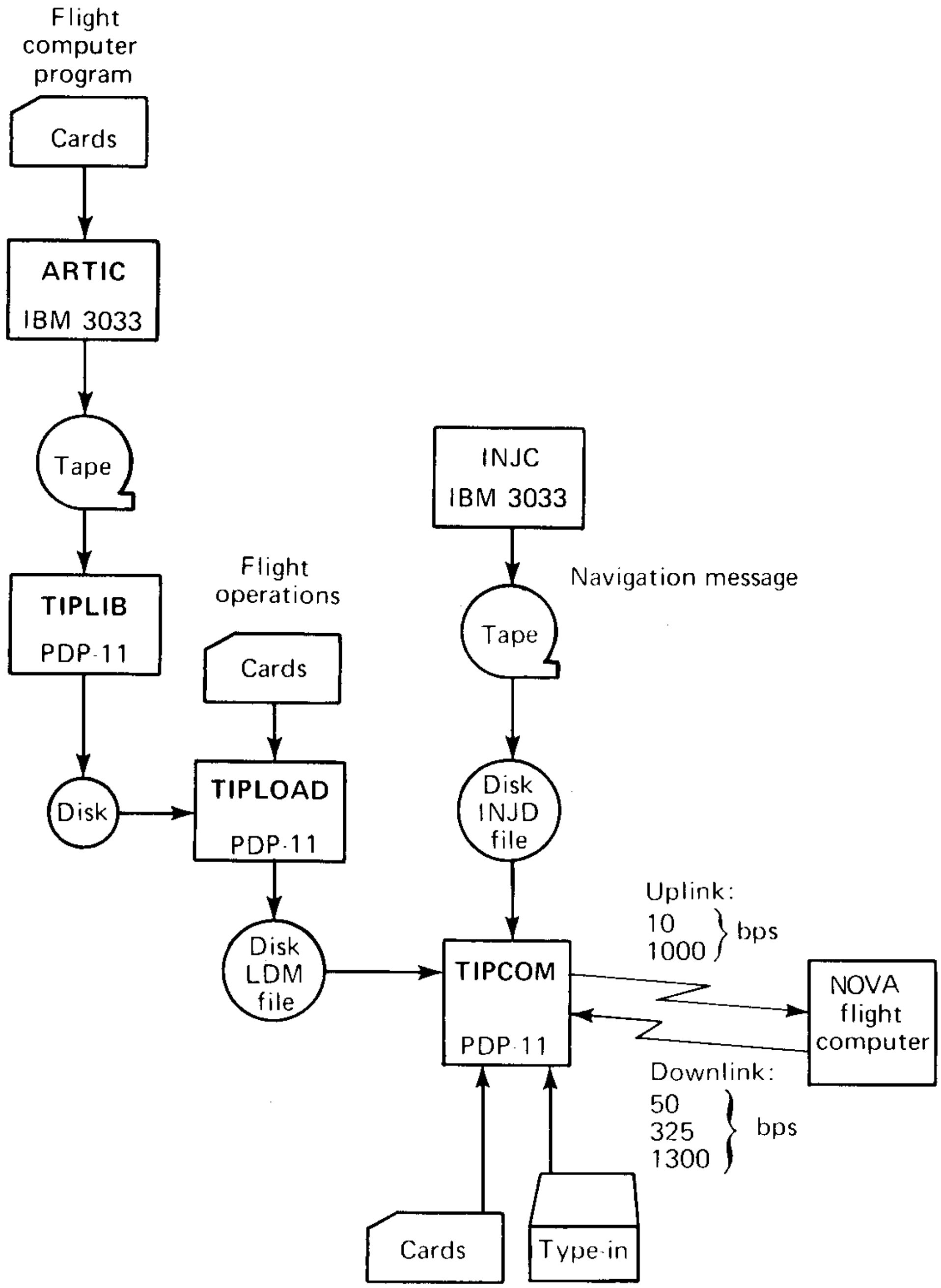

Fig. 2 NOVA ground support system.