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FOUR YEARS OF OPERATIONS AND RESULTS WITH FORTÉ[1]

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Abstract

The FORTÉ (Fast Onboard Recording of Transient Events) satellite was launched on 29 August 1997 and has been in continuous operation since that time. FORTÉ was placed in a nearly circular, 825-km-altitude, 70 degrees inclination orbit by a Pegasus rocket funded by Air Force Space Test Program. The Department of Energy funded the FORTÉ satellite, which was designed and built at Los Alamos. FORTÉ's successful launch and engineered robustness were a result of several years of dedicated work by the joint Los Alamos National Laboratory/Sandia National Laboratory project team, led through mission definition, payload and satellite development, and launch by Dr. Stephen Knox. The project is now led by Dr. Abram Jacobson. FORTÉ carries a suite of instruments, an optical system and a rf system, for the study of lightning and anthropogenic signals. As a result of this effort, new understandings of lightning events have emerged as well as a more complete understanding of the relationship between optical and rf lightning events. This paper will provide an overview of the FORTÉ satellite and will discuss the on orbit performance of the subsystems.

Introduction

Lightning emissions range from ultra-low-frequency (ULF) through ultra-high-frequency (UHF) and also include the visible-light spectrum. Satellite-based observations of radio frequency (RF) and optical emissions from lightning have been occurring for over 30 years[1,2,3,4,5]. This same energy range is also of interest to the National Laboratories for detection of electro-magnetic pulse (EMP) from nuclear weapons detonations for test ban treaty-monitoring purposes.

Los Alamos National Laboratory and Sandia National Laboratories (SNL) have developed for space flight FORTÉ (Fast On-orbit Recording of Transient Events), an advanced radio frequency impulse detection and characterization experiment. The FORTÉ emphasis is on the measurement of impulsive electromagnetic pulses, primarily due to lightning, within a noise environment dominated by continuous wave carriers, such as TV and FM stations. Optical sensors augment the RF system in characterizing lightning events. A principal goal is to develop a comprehensive understanding of the correlation between the optical flash and the very high frequency emissions from lightning.

The FORTÉ satellite was launched on 29 August 1997 into a nearly 825-km circular, 70-degree inclination orbit by a Pegasus-XL rocket funded by Air Force Space Test Program from the Orbital L1011 airplane. This Department of Energy satellite serves as an engineering test-bed for advanced sensor technologies to be carried on the next generation of nuclear test ban treaty-monitoring satellites. The FORTÉ baseline design required minimum mission duration of one year, with the capability to operate for up to three years.

FORTÉ carries a suite of instruments for the study of lightning and anthropogenic signals. The optical payload, built by SNL, comprises (1) a fast-time-response photodiode detector (PDD) sampling an 80-degree field-of-view throughout the visible and near-IR and sampled every 15 microseconds, and (2) a 128 x 128 pixel CCD array imager (LLS) whose square image is inscribed in the PDD FOV, and whose input is the bright narrow-band-filtered line emission at 0.77 microns wavelength. The radio-frequency payload, built by Los Alamos, comprises (1) a multi-band-coincidence trigger with perpetual recording of power background in all 16 trigger subbands (each 1 MHz wide), (2) a wideband (300 Megasamples/sec) rf receiver operating in any of

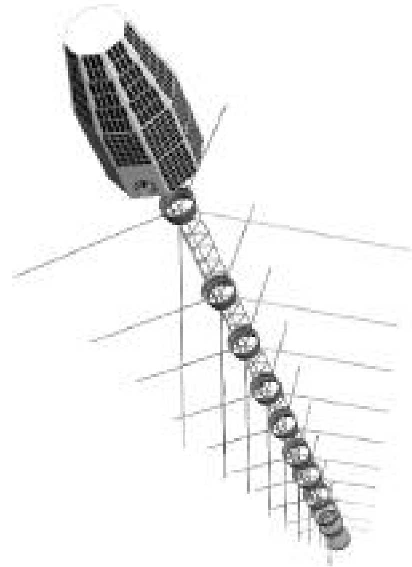

Figure1: Conceptual drawing showing the FORTÉ satellite and 35 ft rf antenna.

three positions within the VHF, and (3) a pair of medium-bandwidth (50 Megasamples/sec) simultaneous rf receivers also operating anywhere in the VHF. The rf payload derives its signals from either two mutually orthogonal monopoles mounted at the base of the satellite or multi-element, passive, moderate-gain log-periodic antennas on a 35-foot, nadir-directed deployed boom. There is ample memory on board for thousands of events to be stored and then downloaded. The downloading is done up to several times per day, at both SNL and the Los Alamos autonomous, remote groundstation at University of Alaska-Fairbanks. In the first 3.5 years of operation, over 4.3 million optical and RF events were detected by the sensors on FORTÉ. This paper provides an overview of the various satellite components and discusses the on-orbit performance of the subsystems in addition to lessons learned.

The Spacecraft System

The FORTÉ satellite is composed of both the spacecraft bus and the payload subsystems. The satellite itself is approximately 2 meters tall by 0.8 meters wide weighing 468 lbs. A nearly 12 meter long rf antenna mast is deployed from the bottom of the satellite in the nadir direction (Figure 1). The space frame was constructed to maximize the usable volume of the interior of the Pegasus shroud and thus provide the maximum area for solar panel installation. The satellite volume itself is mostly empty with the space frame supporting the body-mounted solar panels. The top portion of the satellite is slightly pencil shaped to provide maximum power in a noon illumination.

The FORTÉ satellite was designed and built at Los Alamos using in-house components as well as commercial, off-the-shelf products. Los Alamos served as the integrating organization with all assembly done at Los Alamos. All environmental testing was done at either Los Alamos or SNL test facilities. FORTÉ's successful launch and engineered on-orbit robustness are the result of several years of dedicated work by the joint Los Alamos National Laboratory/Sandia National Laboratory project team prior to launch during integration and testing.

Spacecraft Bus

The spacecraft bus is composed of the following: 1) command and data management system, 2) attitude control and determination system, 3) power system, 4) solid state recorder, 5) telemetry systems, 6) spacecraft event timing system and 7) space frame.

Command and Data Management System (CDMS)

The CDMS is the primary system for commanding and data handling for the FORTÉ spacecraft. The CDMS provides the communication interface to all the FORTÉ subsystems, and consists of four modules: 1) the spacecraft process controller (SCP) utilizing the Honeywell 1750A processor, 2) a Los Alamos designed Serial Communication Card (SCC), 3) a Data Acquisition Card (DAC) also designed by Los Alamos, and 4) a SNL-designed High Speed Formatter (HSF). The SCC, DAC and HSF modules communicate with the Honeywell 1750A processor using the Honeywell PBIO bus and other satellite instruments using a variety of custom and standard electrical interfaces. The spacecraft software was written in C with some assembly language routines for speed optimization. The SCC, DAC, and HSF were implemented using state machines and extensive use of ACTEL 1020A gate arrays. Total power consumption of the CDMS is 4.6 watts.

The heart of the spacecraft process controller (SPC) is a Honeywell VHSIC MIL-STD-1750A microprocessor, providing 1 MIPS of computing power and 64K words of programming space, half of which is used for code and half for data storage. The bootstrap basic processor code is hardwired in read only memory and has only very limited capability. The more extensive full flight code is uploaded into RAM. At the current time, the operational flight code is the original code that was uploaded just prior to launch with a couple of minor patches that have been made after launch.

The serial communication card (SCC) provides the interfaces to the FORTÉ Payload Controller (FPC), the Optical Lightning System (OLS), the Power Control Unit (PCU), the Global Positioning System Receiver (GPS), the Solid State Recorder (SSR), and the Command Receiver. The FPC, OLS, PCU, and GPS have 9600-baud serial ports, while the SSR and command receivers have custom serial links. The FPC is a Los Alamos designed instrument, while the OLS and PCU are SNL designed instruments. The GPS, SSR, and command receiver were obtained from the commercial sector.

The Data Acquisition Card (DAC) provides electrical interfaces to the Attitude Control and Determination System (ACDS). The ACDS consists of magnetometers whose outputs are analog voltages which require conversion by the DAC, 3 mutually orthogonal torque rods that are driven using a 28 Vdc digital signal, and the scanwheel horizon sensor which is a dedicated 88 bit serial stream that contains the attitude information. The DAC also provides voltage monitors and temperature sensors located at various satellite locations, deployment signals for the boom antenna, and a feedback network for determining if the boom is deploying in a nominal fashion.

The High Speed Formatter (HSF) provides data from the payload subsystems to the S-band transmitter as commanded. The HSF also provides UHF beacon real time state-of-health data.

Attitude Control and Determination System (ACDS)

FORTÉ is a momentum-biased, gravity-gradient stabilized spacecraft. Active stabilization is achieved by reading sensors (magnetometers and Earth horizon sensor), applying attitude control algorithms resident in the spacecraft processor, then driving actuators (magnetic field coils and single pitch axis momentum wheel) at a 1 Hz rate[6]. The attitude control and determination system (ACDS) hardware, control algorithms, and simulator were produced by Ithaco Inc.

The ACDS is composed of three main components: 1) the scanwheel, 2) magnetometers, and 3) magnetic torque rods. The primary sensor is the Ithaco Scanwheel® that is used to provide both rotational inertia that helps to stabilize the satellite in roll and yaw, as well as modify pitch. In addition, the scan wheel has a horizon sensor which, due to the rotation of the wheel, sweeps out a 270 degree partial cone centered on the nadir direction with an 8 degree opening angle looking out the side of the spacecraft at an angle of 45 degree from nadir. The horizon sensor is used to accurately determine the position of the Earth's CO_2 emission layer at the horizon relative to the spacecraft's attitude in order to determine the satellite's pitch and roll attitude information.

The three two-axis Ithaco magnetometers mounted parallel to the spacecraft axis are used to measure the Earth's magnetic field flux along two different axes. Each magnetometer is situated parallel to one of the primary axes, so that the B-field along each axis is measured by both a primary and redundant magnetometer. These readings then generate a three dimensional vector indicating the direction (and magnitude) of the Earth's magnetic field at that point. The magnetometers are primarily used to determine the rate of change of the magnetic field vector relative to the satellite orientation, and the amount of torque required by the Ithaco torque rods to efficiently modify the attitude of the spacecraft appropriately.

There are different modes in which the ACDS operates. Acquisition, or B-dot mode, was in effect immediately after the satellite was released from the launch vehicle. In this mode the scan wheel does spin at a constant speed, but relatively slowly (400-500 rpm). This helps stabilize the spin vector axis of the satellite, but does nothing to slow the delta pitch, or tumbling of the satellite. In B-dot mode, the satellite effectively tumbled twice per orbit. Normal mode, which provides nadir-pointing control of the vehicle, has been used for the rest of the mission. In normal mode, the scan wheel is spun up to approximately 1000 rpm to provide extra stiffness. The rf boom antenna also provides additional gravity gradient stability for the vehicle.

Power System

The FORTÉ power system is composed of 1) solar panels, 2) NiCd batteries, and 3) the power control unit (PCU) and charging system developed by SNL.

The solar cells from Applied Solar Energy are silicon based with a predicted efficiency of 12%. Upon delivery, it was determined that the efficiency was closer to 14%. The body-mounted solar panels provide a daily average of 55 Watts with a peak of 325 Watts of power.

The batteries were obtained from Deskin Research. The two 7.5 amp hour NiCd battery packs use SAF NiCd cells. The batteries are typically discharged only 20% of maximum during a day/night period. No reconditioning of the batteries has been necessary to date.

SNL built the PCU, whose main function is to manage the current from the solar arrays and efficiently charge the batteries utilizing microprocessor technology. In addition, the PCU can control the switched loads to the payload subsystems and provides autonomous load shedding according to a programmable table of load shedding thresholds for each switched load. The PCU also provides fault protection for the case of the PCU power supply being over temperature, the spacecraft bus being undervoltage or the spacecraft current being over a maximum safe value. The PCU can independently control each battery charge state via eight different charge states and the voltage-temperature (V-T) trickle charge criteria curve with over 30 separate curves. Although only minimal sets of these flexibilities are currently in use, it is envisioned that as the satellite ages, the different charge states and various V-T curves will be required.

The PCU has two main modes of operation with regard to system battery charging: Constant Current Mode (CCM) and Peak Power Tracking Mode (PPT). The PPT mode is the primary mode used when there is inadequate power from the Solar Arrays to support the Mission profile. PPT mode is a way to maximize the solar array power through autonomous operation. Calculated PPT performance indicates that there is improved battery charging performance of 3-15% over the CCM mode for many. The PPT selected battery is swapped once per week to assure uniform battery usage.

The PCU does an approximate calculation to keep track of the amount of energy available in the batteries. The energy calculation is a calculation for a composite battery based upon current in and current out of the batteries.

Solid State Recorder (SSR)

The FORTÉ state-of-health data is stored on the flight solid state recorder, a Gulton AN81751, with error detection and correction. The 16 MB recorder continuously records the state-of-health (SOH) data from over 1000 data points every 1-16 seconds depending upon the telemetry data point tasking by the SPC. Up to 27 hours of SOH can be recorded before the recorder wraps back on itself.

Telemetry Systems

The FORTÉ satellite communications system is composed of three communications links: 1) a UHF (1/4 wave monopole) transmitter which broadcasts realtime SOH which is used during the satellite contact to verify the realtime health of the system and commanding, 2) a S-Band (bifilar helix) transmitter to transmit either the high speed science data or the stored state-of-health data, and 3) a VHF (1/4 wave monopole) receiver at 2048 bps for the command uplink. Both the UHF and S-band transmitters are located on the bottom (nadir pointed) of the spacecraft while the VHF receiver is located about midway up the side of the satellite, located so as to be visible to the ground in most anomalous orientations of the spacecraft. The UHF transmitter can broadcast at either 256 or 1024 bps, but only the 1024 bps mode has been used since launch. The S-band transmitter also has a variable downlink rate from 16Kbs to 2Mbs in 8 steps in case of link margin problems. However, only the 2Mbs mode has been used.

The UHF transmitter was turned on at separation from the rocket and remained on continually for the first several weeks after which it was turned on only when it was over either the UAF or the SNL groundstations. UHF on/off timed commands are sent to the spacecraft twice per week to autonomously turn on the transmitter when it is in view of the groundstations.

Spacecraft Event Timing

Precise time stamps for each rf event are required in order to correlate the rf events, which can occur anywhere in the field of view of the antenna, with located events from ground truth experiments such as the National Lightning Detection Network (NLDN). FORTÉ timing can be accomplished one of two ways. The spacecraft has an 8 MHz clock from which a one Hz clock tick can be distributed to the individual payloads. The spacecraft clock is also responsible for keeping the Mission Elapsed Time (MET), which slowly drifts due to the clock precision. FORTÉ also flies a GPS receiver, which can also be used to provide precise 1 Hz clock ticks synchronized with Universal Time to the payloads. Since the spacecraft distributes only a one Hz tick, individual clocks in each of the payload boxes subdivide the 1 second ticks as needed to provide precise subsystem timing.

The GPS receiver is a Motorola Viceroy, which has been modified to remove the redundant RS-422 port in order to reduce power requirements. The Viceroy is a 12 channel, dual antenna receiver which uses the L1 broadcast frequency from GPS. The two antennas sit on the top deck pointed anti-nadir and are mounted at an approximate 30 degree angle from the horizontal. A 9600 baud serial link connects to the CMDS for time message distribution. The receiver is designed to achieve position and time solution accuracies of ± 100 meters and 1 microsecond. The GPS receiver is used only for precise timing and is not used for precise knowledge of the FORTÉ satellite position for each impulsive event. The GPS receiver also provides a precise 1 Hz pulse coincident with the UT second, which is distributed to the various payloads, as well as a serial date/time/position/velocity message to establish absolute UT on board. Every 64 seconds, this complete message is embedded into the SOH data stream and stored in the SOH data on the SSR.

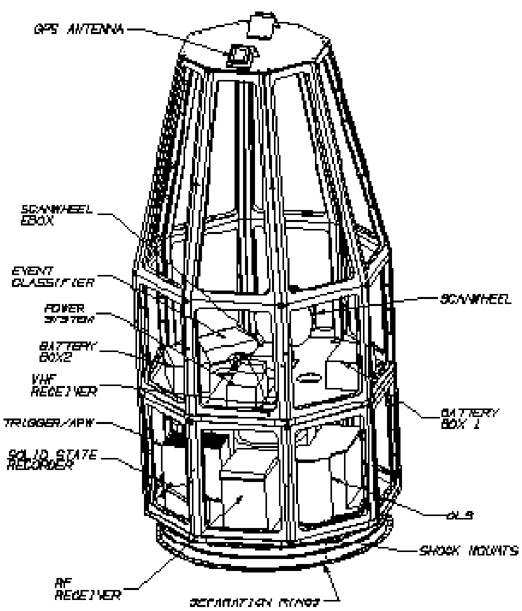

Figure 2: Cut-away line drawing showing the FORTÉ space frame and interior layout

Space Frame

Traditionally, spacecraft structures are nominally made from aluminum primarily due to low cost. This results in a significant amount of the total satellite weight budget being contained in the structure. Los Alamos, in partnership with Composite Optics Incorporated (COI), developed a lightweight, all-graphite composite spacecraft structure. Incorporating advanced materials and unique manufacturing techniques, this structure enables a higher fraction of useful payload to be placed in orbit. The FORTÉ experiment provides the test bed and space validation[7,8] for this structure and for other key aspects of these technologies that will be used in other space programs.

Because the cost of developing and employing molded fabrication techniques is high, an approach developed at COI, called SNAPSAT™, was adopted. The basic spacecraft configuration was dictated by the Pegasus-XL. The octagonal cross-section of the spacecraft lends itself to using a modular construction. The spacecraft primary structure, as shown in Figure 2, is composed of 6 major structural components, 3 structural trusses, 3 instrument decks and 24 solar array substrate panels. Because all payload components needed to be electrically grounded and because of the requirement of the spacecraft to have a rf shield to isolate the interior components from the antenna, the surfaces of most of the modular pieces were copper plated.

The final weight of the space frame was 130 pounds, with weight savings of approximately 100 pounds over a comparable aluminum structure.

Payload Subsystems

There are two primary payloads on the FORTÉ satellite: the rf subsystem including 2 types of antennas, three radio receivers and trigger boxes, and the optical subsystem including both the imaging CCD and the wide field-of-view fast photodiode. There are also two engineering, developmental subsystems onboard both used with the RF system: the adaptive pre-whitening filter and the event classifier.

RF Antennas

The most prominent feature of the FORTÉ satellite is the primary VHF antenna, which is approximately 35 feet long, with the largest transverse elements in the antennas being about 17 feet long There are two independent, log periodic array (LPA) antennas in this structure, mounted on the bottom of the spacecraft, arranged in a turnstile configuration. The antennas have a common support structure, but are electrically isolated, making them sensitive to the orthogonal linear polarizations. The frequency range for these antennas is 20-300 MHz. The primary antennas were a partnership between Los Alamos and AstroAerospace with Los Alamos responsible for the antenna design and AstroAerospace responsible for the boom design and functionality.

The FORTÉ satellite also has a set of secondary antennas that are active monopoles less than a meter in length mounted on the bottom of the vehicle oriented orthogonal to the nadir direction and orthogonal to each other. The secondary antennas were used for the first two months on orbit. The primary antenna assembly was deployed from the spacecraft on orbit on October 29, 1997. The antennas have a gain of approximately 10 dBV and the footprint on the earth has a diameter of 900 km.

RF Receivers (TATR & HUMR)

Part of the FORTÉ program is to demonstrate the ability to collect VHF data, but equally important is the ability to characterize the data. Two receivers were flown which were optimized for resolution, using twelve bit digitizers and a bandwidth of 22 MHz, which are referred to as TATRs (Twenty MHz and Twelve bit Receiver)[9]. These are identical superheterodyne receivers with bandwidths of 22 MHz, separately tunable across the 30-300 MHz band. The first component of each receiver is a mixer stage, which takes the signal from the antenna and up- converts it to a higher frequency. The mixer frequency is tuned to center the up-converted signal at the desired point, and the high frequency signal is passed through a fixed frequency, 22 MHz wide bandpass filter. The band-limited signal is then down converted to baseband by a second mixer and processed by a 12-bit high-speed digitizer operating at 50 megasamples/sec. Converting all signals to baseband allows the digitizer to operate at a constant sample rate regardless of the signal band chosen, giving a uniform oversampling for all bands. Finally, the digitized data is passed to the payload mass memory for storage.

The second type of radio receiver operates with a 90 MHz bandwidth, at the cost of having only 5 or 6 effective bit resolution. This is the HUMR (Hundred Megahertz Receiver). This is also a superheterodyne receiver, which is tunable across the 30-300 MHz band in 3 steps. The HUMR has a single-stage mixer similar to the TATRs, which is used except when it is tuned to the extreme low end of its range where leak through of the mixer oscillator is a serious problem. At the extreme low end, the HUMR bypasses the mixer stage altogether and simply feeds the baseband signal straight from the antenna into the final antialiasing filter. In either case, the bandlimited signal is digitized by an 8-bit digitizer operating at 300 megasamples/sec.

The receivers are connected to the antennas via a switching network allowing any of 3 receivers to be connected to either of the antennas, resulting in 27 possible antenna/receiver combinations.

Each receiver is continually taking data when it is turned on, with the data written to a circular buffer. The data from each receiver is discarded unless recording is initiated by a signal from one of the trigger boxes, described below. Each data set consists of pretrigger and posttrigger samples, with the total number of samples and the ratio of pretrigger to posttrigger samples programmable.
Because the mission objective is to detect impulsive sources, with signals that are compared to ionospheric delay times, the duration of the signal that needs to be recorded is controlled by the degree of dispersion introduced by the ionosphere and the bandwidth of the receiver. FORTÉ has a variety of record lengths optimized for different experimental goals.

Trigger Boxes

Each TATR has a trigger box feeding off the second stage mixer output. The primary function of these boxes is to provide the signal for the RF receivers to record data, but they may also be used to get an estimate of the average noise power in the band to which the TATR is tuned.

Each trigger box has eight 1MHz bandpass filters, evenly spaced across the 22 MHz bandwidth. The signal levels in each of the eight channels can be monitored continuously. The running average signal level is needed to determine the baseline for threshold triggering and also provides an estimate of the RF background.

A trigger signal can be generated by several means, the choice of which is predetermined from the ground. The trigger box has access to the spacecraft clock and in the simplest mode can be set to generate triggers at predetermined times. Triggers can also be generated autonomously using programmable criteria based on the threshold levels in each channel and coincidences between channels, allowing for dispersive time delays. Finally, the TATR trigger box can be set to accept and pass on a trigger generated from the PDD optical sensor.

Adaptive Pre-Whitening Filter (APW)

The adaptive pre-whitening filter (APW) is a developmental device designed and engineered by SNL which can be switched into the HUMR signal stream directly after the mixer stage. This filter consists of a set of 128 analog delay lines whose outputs are summed with digitally defined weights. The weights are chosen so as to suppress undesired features in the signal, such as narrow-band carriers. This device has its own logic to adaptively determine the optimal set of weights in a given noise environment. The APW can be inserted into the HUMR signal producing an output spectrum that has the bright carriers suppressed. It can also not be inserted into the signal, but still provide a trigger for the rf system. If it is used as the trigger source, it can be programmed to determine a running average of the power in a band with a set window time and then look for signals exceeding a configurable threshold above the average. Typically, it is used with a 2s moving average updating once each second. The FPC controls this trigger threshold setting algorithm.

Event Classifier (EC)

The final component of the RF system is the event classifier. This is a signal processing computer that takes the output of the three receivers and performs various signal processing functions in an attempt to classify the signals into distinct categories[10]. Because the optimal algorithms for doing the discrimination were not determined prior to launch, this device has the capability to be programmed. The event classifier is a specialized DSP device utilizing the Texas Instruments TMS 320C30 chip. Unfortunately, due to launch constraints, the EC was never fully operational at launch and was turned on for testing only one time after launch.

Optical Lightning Detectors (OLS)

FORTÉ carries an optical detection system, the optical lightning system (OLS), consisting of two parts. The first part is an imaging CCD camera designed to look at lightning, the lightning location subsystem (LLS). The LLS optics consists of an f/1.6 tele-centric, multi-element focusing lens assembly with a 3.2 mm aperture and a 5.3 mm focal length. The CCD array is 512 x 512 with 16:1 binning on the chip to ultimately provide 128 x 128 pixels. The processor stores event amplitude, event location and frame time. The camera looks at the 777.4 nm oxygen line, using a 10 Å wide filter. The field of view of the camera is 80 degree, with a resolution of 10 km. The associated electronics is capable of triggering on transient optical events having pulse widths shorter than a few milliseconds. The LLS can be run in either full frame mode or bright pixel only mode to conserve memory requirements.

The LLS camera has a framing rate of 420 s^{-1}, which is approximately the same as the flash rate in intense thunderstorms. Because of the relatively slow framing rate and the way in which the data is generated, this system is self-triggering and runs independently of the other detectors on board FORTÉ.

In order to detect lightning against the sunlit earth and to reduce data storage and transmission requirements the LLS keeps a running average of the past eight frames and records only those pixels in a new frame which vary by more than a certain amount from those in the average of the previous frames. Lightning flashes do not illuminate more than ten pixels in any one frame.

The second part of the OLS is a fast photodiode detector (PDD). The PDD is a broadband (0.4 - 1.1 μm) silicon photodiode detector that collects amplitude versus time waveforms of lightning transients. The instrument has an 80 degree field-of-view that translates into a footprint of about 1200-km diameter for an 825-km altitude orbit. The instrument is typically configured to produce 1.92 ms records with 15 ms time resolution. The PDD is typically amplitude-threshold triggered, with a noise-riding threshold, and with a requirement that the signal exceed the amplitude threshold for five consecutive samples before a trigger occurs. This protocol eliminates false triggers due to energetic particles. However, the instrument can also be slaved to the VHF receivers whereby a trigger is forced whenever a VHF signal is received or whenever a trigger signal is received from the LLS.
The PDD provides 12-bit sampling with a piece-wise linear dynamic range covering four orders of magnitude and a sensitivity of better than 10^{-5} W m^{-2}. Several background compensation modes allow the instrument to be operated both at night and at a reduced sensitivity in the day. There is also a minimum inter-trigger delay of about 4.4 ms which results in a ~2.5 ms minimum dead time between successive records. The trigger times of both the VHF and PDD records are GPS-time-stamped to a 1 μs precision.

The OLS has 2 MB of local memory, which is sufficient to store all the data for up to 12 hours, depending upon the threshold chosen and the activity of the thunderstorms. This data is held in OLS memory until commanded to be downlinked.

FORTÉ Mass Memory and Controller (FPC)

FORTÉ has a large number of instruments, most of which can be operated in several modes, making it a complex payload to operate. This complexity is managed by an onboard computer, the FORTÉ payload controller (FPC). The heart of the FPC is a Honeywell VHSIC MIL-STD-1750A microprocessor, the same processor used by the SPC, providing 1 MIPS of computing power. The FPC controls all of the FORTÉ instruments and also provides the interface to the spacecraft using the 64K words of available programming space, half of which is used for code and half for data storage. Unlike the SPC, however, the FPC also has an EEPROM divided into 64K x 4 banks of reprogramming space, one bank for each version of FPC code. The FPC EEPROM banks have each been reprogrammed at least once each since launch.

FORTÉ is equipped with a 160 Mbyte SRAM mass memory. The RF experiments are able to write to this memory, which is partitioned in various ways depending upon the experiments being conducted. The RF receivers have high data rates and require direct access to memory via a DMA controller. The FPC also has access to the memory after data is collected to provide input for the event classifier.

Ground Systems and Satellite Operations

Tracking Ground Stations

The FORTÉ satellite is currently utilizing two different ground stations. The primary FORTÉ groundstation is located at SNL. The major components of the SNL groundstation are: 1) a 15 foot dish on a auto-track pedestal for high speed S-band data downlink, 2) quad-UHF (realtime state of health) and VHF (commanding) antennas mounted on a separate computer driven pedestal, and 3) control room containing transmitter, receiver, and groundstation computers. The SNL groundstation is used to monitor the realtime SOH UHF frequency and verify commanding during a contact, to uplink spacecraft commands and downlink the stored SOH and science data.

A second, 100% autonomous groundstation is located on the top of the engineering building on the University of Alaska-Fairbanks (UAF) campus. The UAF site was chosen as a good match to the satellite orbit (the maximum data that can be downlinked results when a groundstation is placed about 10 degrees less than the inclination of the orbit) and because it would provide satellite state-of-health data 90 minutes after launch and 12 hours before the first SNL satellite contact. This groundstation is capable of making 7-8 satellite contacts per day, each of which has a duration greater than 13 minutes (the time required to downlink both the OLS and RF science data), which is to be compared to only 2 contacts per day possible at SNL of durations greater than 13 minutes. Thus, the UAF groundstation provides for a low cost, factor of 4 increase in the amount of science data the satellite is able to collect and transmit to the ground. And because the contacts are spread over 12-14 hours, it greatly simplifies the operations planning required to provide uniform coverage of the Earth.

The UAF groundstation is composed of a 2.24m (originally 1.8m) S-band tracking dish with co-mounted UHF and VHF single helix arrays, a single workstation and a small equipment rack with transmitter and receiver. There is also an internet camera displaying the important parts of the equipment rack for troubleshooting from afar. The UAF tracking dish is mounted on a 20 foot tower on the roof of the Engineering building exposed to the elements. The tracking dish only has trouble tracking when temperatures dip below -45 degrees Fahrenheit.

Initially, UAF was only used to monitor SOH data broadcast on the UHF frequency and successfully received the first on-orbit telemetry. Five months after launch, S-band science data was being routinely and autonomously downlinked on a daily basis to UAF. At the current time, up to 1.2 GB/day is downlinked daily.

Satellite Operations

The success of LANL satellite projects can be attributed to a small, highly motivated, and highly integrated team for both the ALEXIS and FORTÉ projects. This philosophy has been used not only early during concept, design, fabrication, integration and test preflight, but also for the operations team. This philosophy is best exemplified by the early use of the groundstation as the ground test interface, and by the early involvement of the mission operations team during the ground test flow.

FORTÉ satellite operations work on a system of distributed responsibility. LANL is responsible for flight operations and mission planning and scheduling plus all aspects of the remote groundstation in Alaska, while SNL is responsible for realtime flight operations including spacecraft commanding and SOH quick look, plus all aspects of the primary groundstation.

The flight operations concept is to use a tightly knit collaboration between science teams; operations team and groundstation controllers utilizing a strong reliance on automation and web access. The science and operations teams are located at Los Alamos, while the primary groundstation controller team is located at SNL. This small, highly integrated team enables rapid response for effective corrective action whenever the experiments need to have configuration changes to optimize data quality or response to off-nominal situation.

All data from either groundstation are autonomously transferred back to LANL either immediately for SNL or after normal working hours over the internet for UAF. Once the data are received at LANL, automated processing jobs split, archive and make the data available to the scientists for study initially on the 85 GB local cache. The data are also archived on the LANL terabyte storage system and can be retrieved to the local cache upon demand.

The satellite operations team strives to maximize data acquisition through effective management of resources. The FORTÉ resources that require management are: 1) power, 2) data memory, 3) downlink time, and 4) uplink command queue. Careful planning is also required for maintenance of temperatures for the S-band transmitter and the experiment boxes within safe limits. To aid in long term planning a series of flight rules have been developed, based upon the post-flight experience. These rules define when to change the battery charge states, when experiments can be turned on, duration of data acquisition per orbit, and how full the DAS memory can be as a function of S-band transmitter temperature. In total, about a dozen rules are required for safe operation of the FORTÉ satellite.

Satellite operation responsibilities are distributed between two organizations located in two different parts of New Mexico. Coordination between the SNL and LANL teams is done both via e-mail and an extensive web site. The web site serves as the source of all operational information and can be readily accessed by everyone on the team. The web site contains a detailed set of documentation on how the various boxes work, cable layout drawings, environmental test results, integration photos, calendars of events both past and future, access times for the several dozen ground targets that are used, procedures for nominal and off-nominal operations and operations plans that detail everything that is required to be done on each SNL contact. In addition to e-mail and the web site, a cell phone and pager are used by the on-call LANL operations team member to answer any questions the SNL operators might have in real time.

The FORTÉ operations team meets weekly with the RF science team to define the guidelines for operations and to plan the upcoming week's activities. Both the RF and OLS science teams utilize the web-based target access lists to create detailed input planning requests to the operations team. These inputs are then merged via a PERL widget tool into the detailed web-based plans for each of SNL contact. This same tool automatically generates all of the rf command files for uplink. These web pages, which detail the commands to send and general information, alerts and cautions, are downloaded by the SNL operators for execution and also serve as an on-line archive of satellite operations activities.

Current Mission Status

After nearly 4 years of on-orbit operations, FORTÉ continues to be an extremely reliable satellite, which has encountered only a few real problems since launch. In this next section, we will discuss the on-orbit status of the satellite components.

S/C & FPC Processors:

Both the spacecraft and flight processing (SPC & FPC) microprocessor units have worked flawlessly to-date. Minor changes to FPC software have been made during several FPC code uploads. No problems were encountered during the uploads, indicating the EEPROM has not experienced any major radiation damage. Only a minor patch for a state-of-health bug has been made to the SPC software since launch.

A minor problem with corruption of the broadcast time messages between spacecraft and FPC has been observed on two separate occasions, and the problem appears to be temperature dependent. This causes FPC bad command errors on orbits when the scan wheel side of the spacecraft faces the sun for 100% sunlight orbits.

No double bit errors have been observed since launch in either the SPC or the FPC memory. No memory has been lost to-date in any of the on board memory or from any of the subsystems.

Attitude Control & Determination System

The ACDS system goes through a slow "rotisserie" cycle as the orbit precesses with temperature extremes between –10→+64 degree C, but with average daily fluctuations of only a few degrees. The only minor ACDS problem that has been encountered is that the scan wheel system appears to be affected by penetrating particles. This results in an erroneous Sun/Moon-in-the-field-of-view flag being set. The majority of these erroneous events occur in the South Atlantic Anomaly (SAA) and in the auroral regions. For the most part, the software safeguards implemented prior to launch have successfully protected the satellite from unnecessary pitch and rolls.

The status relative to the three distinct phases of the mission is described below:

--Initial acquisition
The ACDS correctly oriented the spacecraft in a two revolution (in pitch) per orbit tumble within hours of separation using the Bdot mode. The transition to normal nadir-pointing mode was accomplished a few days later. The ACDS performed well with the only excitement coming when the upset bounds were set too tight during this initial testing phase. Increased noise due to the Sun/Moon-in-the-field-of-view flag being set resulted in the pitch data exceeding the upset bounds. As a result the s/c pitched 360 degrees twice before the bounds could be relaxed. These two events occurred in the northern auroral zone over northern Russia when neither the Sun nor Moon was visible to the scan wheel.

--Antenna deployment
The deployment of the primary antenna was expected to generate significant disturbance torques, and there was a concern that the ACDS system might not be able to maintain control authority over the spacecraft attitude. Many simulation runs were executed to determine which initial state of the ACDS would provide the most dynamic range to combat the disturbances. The antenna deployed flawlessly and the torques were significantly less than expected. Therefore the ACDS system was not significantly stressed during deployment.

--Post deployment (nominal mission)
With the antenna deployed, gravity gradient has added to the stability of the spacecraft. Short duration scanwheel upsets, found primarily in the SAA, have been successfully removed via the threshold bounds filter. Several times a year, the sun appears right at the Earth's limb, and thus changes the "apparent" size of the Earth as viewed by the scanwheel sensor. Although this results in minor satellite pitch motion, this behavior was expected and software safeguards have been adequate to control this situation.

GPS:

The GPS performance has been good, with the following anomalies noted:

1. Just prior to launch, the vendor issued a warning that the unit would upset and require power cycling if allowed to track more than nine GPS satellites at a time (it is a 12-channel receiver). This problem was seen soon after launch, and was worked around by adjusting the sky inclusion angle that masks a variable subset of the constellation from view.

2. Difficulty in cold start, constellation acquisition has been encountered. This is now understood, and it was related to translation of 2-line element sets to GPS format. This was a problem in initial acquisition and after upsets in December 1997 and again in March 1998, but significant work has since been done to refine and cross check the process.

3. An increase in constellation size spanning December 1997 to February 1998 upset the receiver in a way related to (1) above. This resulted in a frequent drop of the 1 Hz tick. The solution was to use a receiver feature that allows ignoring specified GPS vehicles, reducing the propagation compute burden in the receiver.

4. On two occasions, bad time broadcasts at the Saturday/Sunday midnight GPS week start were observed, upsetting the timed commands queue in the payloads. The vendor later confirmed this anomaly. The problem is avoided by a weekly command, which suspends time broadcasts for a few seconds around the problem time.

Neither Y2K nor GPS-week rollover problems were encountered. There also has been no need to turn the GPS heaters on since launch.

Power:

The power generation system is operating as designed with no problems. No processor upsets have occurred. Battery charging states are changed several times throughout the dawn-dusk→noon-midnight orbit period for optimal battery charging. The batteries are nominally pulled down to no more than 80% of capacity in order to increase their longevity. This is accomplished by keeping the orbit-averaged current usage to less than about 3.5 Amps. The temperatures of the batteries vary from –10 → + 28 degree C for the different orbits, with an average temperature near 0 degree C.

S-Band Data Downlink:

For the most part, the S-band downlink has been working well. A minor problem, however, occurs when the S-band temperature is at 8 degrees C. Somewhere near 8 degree C, a drop-out occurs during downlink resulting in a 2 second gap in the data while the receiver reacquires the signal. To minimize the impact of this dropout, we usually transmit fill pattern for 30-120 seconds (S-band transmitter heats up at a rate of 3 degree per minute) before any data is transmitted.

SSR:

No problems with the SSR have been observed since launch.

RF System:

The RF primary experiment has been working as designed. The initial rf data derived its signal from the secondary antennas, the short-monopole active antennas close to the satellite body. Those two months of preliminary data were much noisier than after 28 October 1997, due to the particular pre-amps into which the active antennas were fed. A problem with the #2 secondary antenna system was noted after launch which was attributed to too close a proximity to the UHF transmitter, making it non-functional.

The eight-channel triggering scheme has worked extremely well to reject signals like manmade carriers and radars, triggering only on broadband signals. For normal operations prior to December 1999, both the TATR's and Triggers were on all of the time. However, during 100% sunlight orbit periods, TRIG-B was turned off to minimize excessive temperatures. TATR-B data could still be collected when TRIG-B was off by using TRIG-A.

One position of the TATR-B antenna switch failed on 11/10/97 as the satellite was coming out of a 100% sunlight orbit period allowing TATR-B to be attached only to one remaining antenna.

The nominal working mode for the rf experiment early in the mission was to have one TATR tuned to a center frequency of 38 MHz and the other tuned to a center frequency of 130 MHz, thus covering a wider range of the VHF spectrum. On 26 September 1998, however, the voltage controlled oscillator (VCO) for TATR-A failed. TATR-A could only then be used if cross-strapped to the TATR-B Local Oscillator (LO). In this manner, both TATR's could be tuned to the same center frequency but could look for polarization differences between the 2 orthogonal antennas. On 10 December 1999, the VCO or the LO for TATR-B failed, leaving only the HUMR radio working.

Up until this point, only a few exploratory HUMR experiments had been made, to support the testing of the APW. The HUMR by itself does not have the sophisticated triggering scheme that the TATR's had and can trigger based only on instantaneous signal power from the entire analog bandwidth. To increase the efficiency of the HUMR data collection, we now use the APW filtered HUMR data as the trigger source during daylight and the OLS as the trigger source when in darkness. The APW has been programmed with 5 different narrow filter settings that can be used to filter the HUMR signal before reaching the HUMR trigger. A narrow filter between 36-39 MHz is typically used for low band HUMR data collection. This filter setting works essentially anywhere in the world with the exception of North Europe and the northern part of North America, where there are 35.5 MHz radars that are especially active during winter, whose power can leak into the filter band.

In late November 1998, it was noted that some of the TATR data had an unusual feature, an apparent flipped reflection of the original signal that was dubbed "crossed swords". This "crossed sword" contamination of the data occurred randomly, initially just a few percent of the time but eventually increasing up to 20% of the time. The origin of the problem was not determined, but the characteristic of the problem was similar to a shifted data buffer. In fact, using this model, the original data could be recovered with minimal processing using an algorithm developed by Mike Bredeman of SNL. After the TATR failures, this same feature was also noted in about 50% of the HUMR data. By chance, it was discovered in March 2000 that the automatic gain control (AGC), which is a software-only controller, appeared to be the culprit. It is not understood why software would cause a shift in the data, but since AGC use was discontinued, the data has been 100% free of this anomaly.

Because of timing differences between the OLS and the rf system, OLS-triggered rf event records need to be 4-8 ms in duration instead of 500 µs, which had typically been used in the past. These larger record lengths take up considerably more space in memory, but have provided more complete data for cross comparison between the optical and rf signatures of lightning.

Final calibration of the RF antenna is in work with both the absolute calibration and detailed mapping of the lobe pattern being determined. The Los Alamos Portable Pulser (LAPP) is being used for this exercise. Several times a week, the pulser gets off 5-8 shots per pass for this purpose.

DAS Memory:

The 163 MB of RAM in the DAS stores the digitized waveform data (160 MB) and a per-event log of configuration, timing, and addressing information (3 MB). This memory is susceptible to upsets from the space environment. Upsets in the large waveform data section are tolerated as noise in the data. The event log memory, which can't tolerate errors, uses a triplicated scheme to derive a 1 MB best-of-three voted data space, where each bit is voted at read time.

Recent studies of upsets over time have established rates of roughly eight single-bit upsets per megabyte per day. The errors are evenly distributed in time, location, and set/reset status. Test samples have found no failure of the voting scheme to correct upsets in the event log banks, thus demonstrating a simplified but robust single-event error correction method. Detailed memory testing is done during each 100% illumination period while the rf system is off due to heating constraints.

OLS:

OLS has had a very good overall performance record since launch. Both LLS and PDD have been operating at >85% of the time. Occasionally, the LLS power supply has failed to turn on upon command. Turn-on problems were experienced in the thermal chamber when the box was cold and with a low bus voltage condition but it has not been verified that this is the current cause. This condition has so far been cleared on subsequent turn-on commanding. PDD does not seem to have this turn-on problem.

The LLS is sensitive to penetrating particles and creates a lot of false triggers whenever it is in regions, like the SAA, where there are copious penetrating particles. Thus, the LLS is not operated in the SAA, in order to conserve memory space for valid events.

APW:

The APW is working well. Initially, a few problems were encountered with convergence, but a change in the set-up parameters made the convergence stable. The amount of attenuation achieved is better than anticipated. The minimum advertised was 14 dB, but up to 18-20 db or better has been realized. A problem with interactions between the APW and high-speed formatter (HSF) appears to be temperature-dependent. Some shifts in bits during transfer have been observed on rare occasions. It is possible to retrieve the data post-flight.

On 31 May 1999, the APW adaptive functionality failed. It can, however, still be used as a pre-programmed filter. It has been extensively used for the HUMR data collected after the TATR-B failure

SNL Groundstation:

The SNL groundstation has worked well with the exception of a few minor hardware problems. Problems that have been encountered are typical hardware failures and include the following: receiver power supply failed, drive motor failure, shorted cable in one of the two tracking systems, bit sync module problem which caused SSR dump problems, loss of feed amplifier and loose cable in S-band system resulting in low signal strength. During times when the SNL groundstation is down for repairs, all data (stored SOH and science) is downlinked to the UAF groundstation.

Occasionally, there has been observed a 12-second periodic dropout of the S-band downlink, which has not been resolved.

There have been several instances of RF interference at the groundstation. One type of UHF interference event was tracked to an adjacent laboratory in the groundstation building where the LANL/SNL multispectral thermal imager (MTI) satellite transmitter (DOE uses the same frequencies for both satellites) was being tested during FORTÉ contacts. A second UHF interference event was tracked to weather balloon transmitters in Area 3 at SNL. S-band interference events have been tracked to a laboratory in an adjacent building.

Alaska Groundstation:

The Alaska groundstation was originally conceived to be used to monitor the SOH of the FORTÉ satellite immediately after launch. This proved invaluable for the first couple of days after launch 1) when the satellite was in B-dot mode and the UHF antenna was not optimally oriented towards the SNL groundstation and 2) because the UHF SOH signal is much weaker than predicted on certain passes as viewed from SNL, (this has been attributed to the original antenna pattern being modified once mated to the satellite). Thus, the Alaska groundstation has become a semi-standard window into the SOH data for the SNL operators since 2 of the 4 potential contacts per day overlap with Alaska opportunities.

In December 1997, the Alaska groundstation was upgraded to receive S-band downlink of the science data. The original 6-foot dish was capable of locking onto the S-band signal at 1 degree above the horizon providing up to 8 contact opportunities per day when science data could be downlinked. In June, 1999 the 6-foot dish was replaced with a 2.24 m dish increasing the tracking link margin in the event that the MTI satellite opted to use UAF for science data downlink.

Once on the ground, the data is compressed and then transferred to LANL at midnight when the Internet traffic is less. All seems to be functioning well - on a fairly typical day (July 1, 1998), we moved 440,434,731 bytes of zipped data (~1GByte uncompressed) to LANL. This operation is totally unattended. Blind-data dump commands are uploaded in advance to the satellite, the groundstation tracks the satellite autonomously, and scripts both transfer the data to LANL and maintain space on the disk system.

Because it is not possible to take data and downlink data at the same time, the Alaska groundstation has enabled data collects over the continental US (CONUS) on every pass. The CONUS data is being correlated with groundbased lightening position/time data purchased between 4/1/98-10/1/98 and 5/1/99-10/31/99 to expand the scientific potential of the data by diverting the data download from SNL to UAF.

Three problems have been noted for operations at Fairbanks:

1.) S-Band Jamming Incident: A strong signal interfered with our S-Band for ~2 days June 9-11th, 1998. The strength of the signal made it impossible to lock onto the FORTÉ s-band signal in about half of the horizon making contacts. The signal has not been observed to reappear.

2.) UHF Receive Problems: Most UHF problems have been traced to the failure of a Radio Shack UHF TV amplifier part that was used to boost the signal UHF signal. After 3 years of use and multiple replacements, the Radio Shack amplifier was finally replaced with a narrow band, commercial amplifier.

3) S-band Receive Problems: Occasional major dropouts at the ground station were observed on the last pass of a suite of Fairbanks accesses several times per year. This was finally traced to bad calibration of the tracking pedestal.

Mission Operations

The above mentioned ops concept has worked extremely well for the FORTÉ project, with automation playing a key role. The operations team is composed of operators at SNL, and long range planners, scientific coordinator, data quality analysts, web plan manager and a dedicated programmer working on additional automation at LANL. The SNL level of effort has been a constant 2 full time equivalent (FTE) shared between ≈10 people for all years since launch. The Los Alamos level of effort started at about 4 FTE shared between 7 people and has decreased currently to 2.5 FTE shared between 4 people. Initially, 4 contacts per day were made with the satellite. Currently, only 2 or 3 contacts per day are made during normal operations and 1 contact per day during 100% illumination periods when operations are minimized due to thermal constraints.

Automation plays the key role in maintaining a small operations team while increasing the level of complexity in the data collection but reliably managing the satellite. Some of the automated tasks are, automated groundstation operation at UAF, automated data transfer between facilities, automated data archive and retrieval, automated data splitting and processing after a satellite contact. There is also a plethora of background jobs that are constantly checking all production computers for liveliness, checking to make sure all command files have been created in time for uplink, and checking for errors in the web based plans. Digital pager messages are also distributed with some of these alerts and messages. A common pitfall for most small, aggressive projects is the absolute reliance on a few key personnel. While this was initially a problem with FORTÉ, the additional automation and documentation that has been added over the past several years has lessened this potential critical situation.

Major Science Discoveries

In addition to being a highly successful engineering demonstration, FORTÉ has made several significant scientific discoveries.

One of the most interesting discoveries made by the Blackbeard experiment on the ALEXIS satellite, which was the predecessor to the FORTÉ satellite, is the identification of “trans-ionospheric pulse pairs”, or TIPPs[11,12]. The name was due to the occurrence of two separated pulses, each a few microseconds long, separated by tens of microseconds. These emissions’ instantaneous power was at least tenfold greater than that of VHF signatures ordinarily accompanying lightning. Unfortunately, Blackbeard was only allocated 16 MB of the ALEXIS 78 MB memory and could not retrigger so consequently was only able to collect a few events per day at best, too little data to fully characterize TIPPs.

The observation by Blackbeard of TIPPs instigated a lively discussion as to the origin of the second pulse. In each hypothesis, a tropospheric lightning process emits a prompt VHF along a direct ray to the satellite that correlates with the first pulse of the pulse pair (Figure 3).

The high-altitude-discharge (HAD) hypothesis[13] is based on the well-demonstrated fact that a relativistic upward discharge (eventually closing in the ionosphere) can be expected above thundercloud electrostatic transients in achievable storm electrification conditions. The HAD paradigm for TIPPs explains the second pulse in a pulse pair as follows: There are really two breakdown regions, one near or in the cloud (radiating the first signal), and the second in the mesosphere, where, although the electric stress E is lower, the ratio E/P becomes large again due to exponential decrease of p versus altitude. This second breakdown region is expected to radiate VHF, causing the second pulse delayed in time due to the propagation time. This time delay would be minimum for the satellite at the zenith and maximum for the satellite at the horizon.

The alternative, ground-reflection (GR) model[12,14,15] maintains that the second pulse in a pulse pair comes simply from VHF reflection off the Earth’s solid or water surface. This hypothesis is equally successful at reproducing the range of inter-pulse lags observed. The GR paradigm predicts that as the satellite approaches zenith, relative to the emitter, the lag increases to maximize at twice the emission height divided by the speed of light, and that the lag approaches zero as the satellite approaches the horizon as seen from the emitter. Thus the two explanations for the origin of the second pulse give qualitatively opposite predictions on the dependence of inter-pulse lag on satellite zenith angle (relative to the first-pulse emitter). Unfortunately, stand-alone pulse-separation measurements do not permit the zenith angle, or even trends in the zenith angle, to be unambiguously resolved. Thus, the Blackbeard data could not definitively resolve the HAD/GR paradigm choice.

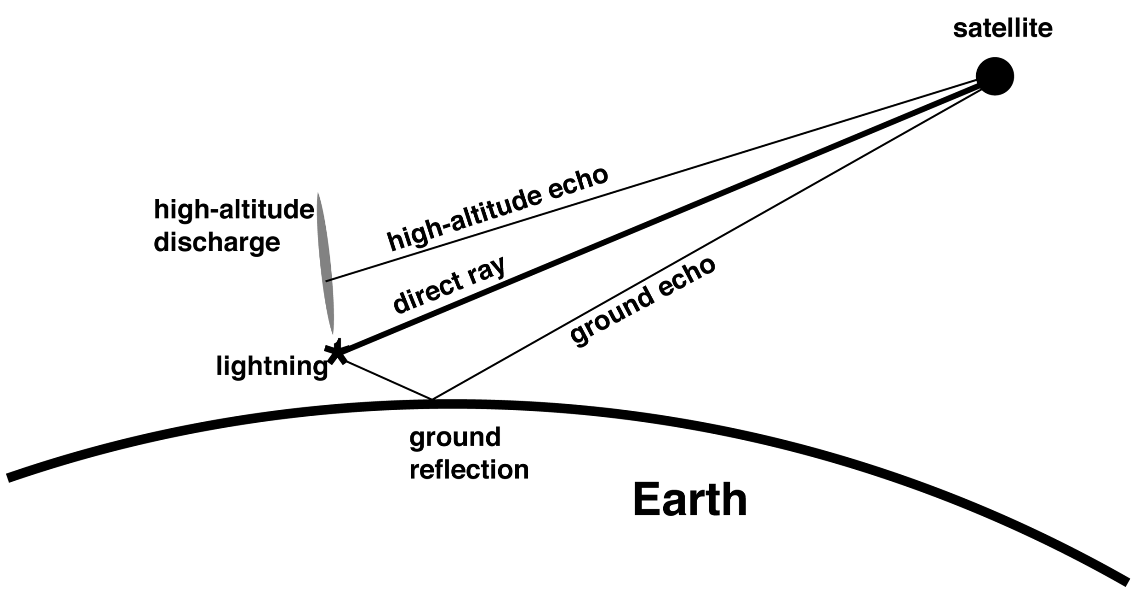

Figure3: Schematic drawing of the two TIPP origin hypotheses. The High-altitude–discharge (HAD) model predicts that the second pulse is from a secondary discharge in the mesosphere while the ground-reflection (GR) model predicts that the second pulse is a ground reflection.

The ability of FORTÉ to acquire copious records and to determine the slant TEC from each record allows us to throw new light on the origin of the second pulse in TIPPs. What FORTÉ was able to observe due to the ability to retrigger rapidly, paired with large memory storage is that several severe storms, not only had TIPPs associated with them, but TIPPs essentially continuously recurred from nearly the same location in the storm during the time of the FORTÉ overfly. This data shows a clear anti-correlation between the slant TEC value and the interpulse separation as FORTÉ changes view angle to the storm favoring the GR model[16].

By using other information (e.g., geolocation of flashes by very low frequency sferic receiver arrays) to determine the latitude and longitude of the VHF emitter responsible for a FORTÉ event, it is possible to infer the altitude of the emitter, from the intra-TIPP pulse lag. An extensive study of FORTÉ TIPP data[17] has demonstrated a land/water height difference as well as a latitude relationship that is consistent with atmospheric structure differences between equatorial regions and higher latitudes. The heights of the emitting regions ranges nominally from 6-12 km above the surface of the Earth, but in unusual mesoscale, convective complex storms such as those spawned in 1999 by the spring fires in Mexico, the height ranged from 15-20 km above the surface of the Earth.

TIPPs in recurrent-emission storms by themselves provide both intra-TIPP lag and slant-TEC curves (as a function of satellite position), a relationship which provides the basis for autonomous geolocation of the emitters located in regions for which there is no ground truth. This technique was used to help differentiate between multiple storms simultaneously monitored by FORTÉ. Storms from different geolocations within a satellite footprint will often have TEC values that are different enough such that they form distinguishable curved clusters in plots of TEC vs. time. The values of TEC for the located satellite data used with a simple model of the ionosphere, and National Lightning Detection Network (NLDN) data to helps to identify TEC clusters that can be assumed to originate from relatively compact, and unambiguous, geolocations[16,18]. For the time period of April through September of 1998 sixty-five groups of satellite data records were geolocated. These groups represent a total of 6892 data records. Of this total, 761 had previously been assigned geolocations using timing coincidences with NLDN-located events. Thus, when information on the ionospheric TEC traversed was added to the time coincidence requirement, 6131 additional VHF signals were assigned.

The NLDN is a ground-based array of sensors in the continental United States (CONUS) observing the low-frequency (LF) and very-low-frequency (VLF) radiation from large-scale vertical currents. Prior to the launch of FORTÉ in 1997, essentially no work had been done on the statistical correlations between (a) ground-based LF/VLF and (b) spaced-based VHF remote sensing of lightning. During April – September 1998, FORTÉ was tasked with taking maximum triggered VHF data over and near the CONUS, and NLDN data was specially post-processed in a loosened-criterion mode providing enhanced detection range beyond the CONUS. The time history of reported events from the two systems was compared, and event pairs (each pair containing one event from FORTÉ, the other from NLDN) that were candidate correlations (closer than 200 ms from each other) were scrutinized to determine if there was a statistically meaningful timing relationship[17]. This study produced a statistically significant correlation, consisting of a prompt coincidence between a subset of NLDN events and a subset of FORTÉ events. This coincidence is most likely to occur for intracloud, and less likely to occur for cloud-to-ground discharges. The prompt coincidences mostly are within ±50 μs, after correction for the propagation of the VHF signal to FORTÉ from the NLDN-geolocated discharge. The NLDN-furnished geolocation of the prompt-coincident FORTÉ-observed VHF pulses allows the pulses to be better interpreted. In particular, it is possible to deduce, from the lag of the VHF ground-reflection echo, the height of the VHF emission region in the storm.

After the failure of the first vco, the data that was acquired was all single-frequency polarization data that provides a unique data set for study. The orthogonally oriented, linearly polarized FORTÉ log-periodic antennas, together with the corresponding phase-locked radio receivers, allow for an investigation of the complete polarization properties for a received signal. For each signal, a complete set of Stokes parameters are computed in a 2-dimensional time-frequency domain, that in turn can be further examined to obtain the degree of polarization, the tilt and the axis ratio of the polarization ellipse, and the sense of the E-vector rotation. With the impulsive nature of the LAPP transmitted pulses, polarization has been determined for each of the two temporally-split ionospheric radio modes, the ordinary and extraordinary modes. Together with the considerations of the FORTÉ antenna pattern, each mode was determined to be nearly circular polarized at the lower end of VHF, agreeing with the theoretical prediction[19]. With the given response patterns of the FORTÉ antennas, the original circular polarization will appear as an elliptical polarization.

This same LAPP data set was also used to study the effect of ionospheric Faraday rotation. With the broadband signal, the total cycles of Faraday rotations between a pair of frequencies can be accurately and unambiguously determined. With the known locations of the satellite and the LAPP, the slant TEC can be computed for each of the LAPP pulses. The added capability that these two areas of study have provided is potential independent location of the event. Impulsive broadband VHF source near the surface of the Earth, such as those produced by lightning discharges, can be located with the polarization observations. Faraday rotation can also be used to locate a repeated radio source[19].

Correlation studies between optical and rf events were one of the main mission objectives. The LLS is used whenever possible to obtain location information with the PDD providing the time history of the lightning event for comparison with the rf event time profile[20,21]. A detailed comparison between the FORTÉ-observed VHF and optical emissions from lightning transients has proven this technique to be a powerful tool that can be used to study both thunderstorm and lightning processes on a global basis. The preliminary results of this study[22] indicate that the VHF/optical correlations can be used to (1) effectively identify and distinguish between CG and IC pulses, including stepped and dart leaders, attachment processes, and return strokes, and (2) estimate a mean scattering delay for the in-cloud portion of CG-emitted light (138 ms).

Individual RF and optical pulses from lightning observed with the FORTÉ satellite have been compared and the observed rf/optical coincidence depends upon the type of discharge[23]. More than 80% of ground strokes showed obvious, associated optical and rf signals; only ˘ 50% of in-cloud events showed similar rf/optical correspondence. The peak rf and optical power in related pairs of pulses correlate over several orders of magnitude, although the relation is broad, due presumably to losses of the optical light by scattering in clouds. Ground strokes are among the strongest events seen, in both optical light and rf, while impulsive, in-cloud events are among the weakest. While the rf signals from ground strokes clearly coincide with simple optical signals, the intracloud lightning often shows nearly continuous, complicated rf and optical emissions which do not cleanly correlate with one another.

For initial, negative return strokes, low-level light is often observed preceding the main optical pulse, corresponding to the optical counterpart of the leader activity Also, we sometimes see structure in the optical leader, in which the light waxes near the leader onset, wanes, and then reasserts just before the return stroke. There is also the suggestion of discrete leader steps, approximately 4 ms before the attachment, which gradually blur into continuous leader emission. Initial negative return strokes are very commonly followed immediately (within 50-300 µs) by some form of cloud discharge, usually a doublet of Ni events. There are a few cases (4%) where the optical counterpart to a 1st - RS is double-peaked, with the optical peaks spaced by ≈700 µs. The rf pulses of IC activity tend to occur in the context of extended, multi-peaked optical emission, rather than to be associated with specific peaks of light.

Using the rf discharge as the time fiducial, we found that for ground strokes there appears to be a small delay between emission of the rf and optical signals, $<\Delta t_{CG}> = 59$ µs. For in-cloud events, however, the optical signal onset often precedes the peak of the rf, $<\Delta t_{Ic}> = -33$ µs. This implies that the light must have been emitted earlier than, or coincident with, the onset of the rf signal.

Optical light from leader activity was commonly seen, and rather than monotonically increasing like the rf leader, the optical leader often decreases mid-way through and increases again near the time of the return stroke. While the rf and optical light from return strokes typically appear as strong and unambiguous bursts, the rf pulses of IC activity tend to occur within the context of extended, multi-peaked optical emission.

Using rf TIPPs, the heights of several in-cloud events can be estimated. The height distribution ranges from 6-13 km, and falls off sharply at higher altitudes for rf/optical correlated events, which is a bit lower than has been observed from groundbased sferic arrays.

As an extension of this work for the future, Los Alamos is proposing to use a FORTÉ-like sensor on a constellation of satellites to provide global lightning and severe storm monitoring[24]. Los Alamos is currently developing V-sensor, which is to be a follow on programmatic rf detector similar to FORTÉ, for use in test band treaty monitoring. V-Sensor is scheduled to be flown on the GPS Block IIF satellites. In addition to its programmatic mission, V-Sensor would also do automated lightning classification and do location analysis, based on the FORTÉ results, and will automatically downlink the results to 2-3 groundstations located around the world. V-Sensor data would be used to forecast severe storms, improve warnings for aviation and ground personnel, provide global electrical circuit data for modeling, and increase the knowledge of global climatology and meteorology.

Summary

The FORTÉ project was initiated as an on-orbit test bed for a future programmatic instrument. It has proven to be a very robust and reliable satellite now one year past the design end-of-life and still going strong. If ALEXIS, also a Los Alamos mission that had a design end-of-life of 3 years and is still operational after 8+ years, is any indication of how long FORTÉ might survive, then we are planning on many more productive years from FORTÉ.

In addition to providing the test experiment for the programmatic mission, FORTÉ has provided new understandings of lightning events as well as a more complete understanding of the relationship between optical and rf lightning events. A future civil mission proposed for the programmatic V-Sensor experiment is to provide global lightning and severe storm monitoring information which would be continuously downlinked from the GPS Block IIF satellites.

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