JOURNAL OF SPACECRAFT AND ROCKETS
Vol. 33, No. 1, January–February 1996

Thunderstorm III 4-Megahertz Burst-Mode Data Acquisition System

Steven D. Baker,* Michael C. Kelley,† and Timothy F. Wheeler‡
Cornell University, Ithaca, New York 14853

Experimental results from many platforms indicate strong coupling between lightning and the ionosphere and show the necessity of high-frequency sampling in future experiments. We describe the lightning-triggered, burst-mode data acquisition algorithm and circuit used in the NASA sounding rocket 36.111, which is scheduled for launch in 1995. Burst-mode acquisition increases the time resolution by almost two orders of magnitude over that of continuous sampling, but requires a smart controller to select important data. The increase in time resolution will yield sounding-rocket electromagnetic-wave data valid up to the plasma frequency for the first time in the lightning environment. The instrument samples the vector electric field and one component of the magnetic field at 4 MHz with 10-bit, resolution, yielding a burst rate of 320 Mbits/s. Burst-mode instruments use ground commands, precursors, or recorded preburst data to ensure the proper data are recorded.

Introduction

IN the early years of space research, the electromagnetic waves launched by lightning strokes were found to disperse in time and to create an audio-frequency radio wave, which whistled when converted to sound waves. These whistlers bounce between the Earth's hemispheres along magnetic field lines and are an important loss mechanism for the radiation belts. The study of whistlers has revealed much about the plasma around the earth, including the distribution of ionization in the ionosphere.[1] Research in the last two decades, including a number of curious ground-based, rocket, satellite, and Space Shuttle observations during severe storm conditions, showed that lightning may be an important source of ionospheric disturbance as well. At this time, known interactions between lightning and the ionospheric plasma are virtually unexplained by existing theories. In situ rocket and satellite measurements performed in the past have been hampered by telemetry bandwidth limitations, and hence, crucial information is absent. A summary of these experimental results is given.

The phenomenon of explosive spread F (an event in which the radar backscatter signal due to electron density irregularities from approximately 250 km increases to sizeable levels in tens of milliseconds and decays in hundreds of milliseconds) was first reported by Woodman and La Hoz.[2] The NASA rocket flight Thunder Hi (33.022) measured large-amplitude transient electric fields owing to lightning in the ionosphere above an active thunderstorm[3] with amplitudes sufficient to drive plasma instabilities in the F region of the ionosphere.[4] Woodman and Kudeki[5] subsequently conducted a radar experiment that showed explosive spread F is highly correlated with lightning activity.

A class of early/fast Trimpi events (a type of transient perturbation in the propagation of subionospheric vlf signals) was reported that cannot be explained by the whistler-based theory of resonant pitch-angle scattering and precipitation of radiation-belt particles. One theory is that plasma in the mesosphere is heated, resulting in a perturbation to the Earth–ionosphere waveguide, causing the Trimpi event.[6,7]

The Thunderstorm II sounding rocket (27.120) measured large (10–40 mV/m), long-duration (1 ms) electromagnetic (EM) pulses with electric-field components parallel to the Earth's magnetic field associated with virtually every lightning stroke from a small storm cell. These ELF electric and magnetic field signatures occurred at the leading edge of the high-frequency component of the lightning-induced pulse, as shown in Fig. 1. The subscripts refer to field components perpendicular and parallel to the Earth's magnetic field. As a whistler-mode wave with the frequency of the pulse could not have propagated to the rocket in the same amount of time as the high-frequency components, the authors theorized that the leading edge of an intense VLF packet (40–80 kHz) interacted locally with the ionospheric plasma to create the pulse.[8] Data from Thunderstorm II and Thunder Hi indicate lower hybrid emissions are enhanced when the whistler packet propagates through the plasma and seem to persist after the packet is gone.[3,8] ISIS-2 spacecraft data also show lightning-generated whistlers exciting lower hybrid waves.[9]

Space Shuttle observations showed a brightening of the sodium airglow layer directly above a lightning flash. Flashes occurring within a few seconds of this created no airglow, indicating the glow is not due to reflection.[10] This airglow might be related to the anomalous optical events (an anomalous optical event is an event with obvious clustering of optical impulses or continuous emissions with resulting durations of several hundred milliseconds) seen in the 27.120 flight[11] and the WIPP rocket campaign.[12]

DE-2 investigators noticed a remarkable impulsive event registered in several detectors while the satellite was over Hurricane Debbie. The data indicate that ionospheric electrons were accelerated upward by a parallel electric field that lasted many milliseconds.[13]

Taken together, these observations give compelling evidence for an anomalous and powerful interaction between the ionosphere and the EM pulse from lightning. The primary emphasis of the NASA rocket Thunderstorm III (36.111) instrumentation is to study the nonlinear coupling phenomena wherein lightning-generated waves penetrate the ionosphere and stimulate phenomena such as plasma heating, parallel electric field generation, and the stimulation of other ionospheric irregularities.

Scientific Objectives

The Thunderstorm III instruments were designed to investigate the physics of the long-duration EM pulse, lightning pulse propagation, ionospheric transient effects, and anomalous optical effects. Specifically, these measurements will enable us to ascertain how the pulse propagates, whether it is related to 40–80-kHz nondispersed whistler frequencies, and the significance of the associated current pulse. The data will help us establish whether the EM pulse produces field-aligned electron beams or heats the plasma. We will study the variation in pulse characteristics with height and range from the sferic source, the details of high-frequency whistler propagation, and the strong amplitude variability of the whistler waves. The transient effect studies include 1) determining what fraction of

Received Feb. 22, 1995; revision received Aug. 31, 1995; accepted for publication Aug. 31, 1995.

*Doctoral Candidate, School of Electrical Engineering.
†Professor of Electrical Engineering, Space Plasma Physics Group.
‡Research Engineer; currently Research Engineer, Communications and Space Sciences Laboratory, Pennsylvania State University, University Park, PA 16802.

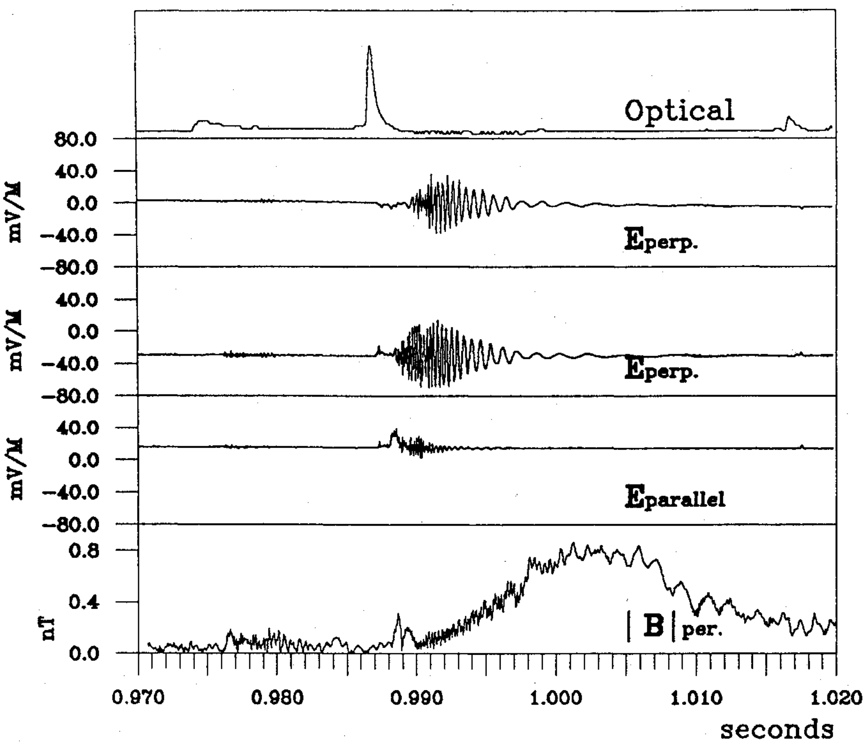

Fig. 1 Optical, electric, and magnetic field observations in the ionosphere associated with a lightning strike: time 5:53:54.97 to 55.02UT, altitude 294 km. Reprinted with permission of the American Geophysical Union.[8]

the lightning-injected charge is deposited in the ionosphere, 2) the total energy input to the ionosphere from lightning, 3) the conditions under which the lightning-induced whistler stimulates lower hybrid waves, and 4) if the horizontal electric field causes large-scale ionospheric motions to develop. Finally, we will determine the causes and source regions of anomalous optical effects and if they are related to high-altitude discharge or transient airglow.

The next section focuses on the 4-MHz burst memory developed to give high-resolution EM-wave information, which will improve our understanding of the underlying physical processes of the lightning–ionospheric interactions previously described. The instrument uses a burst-mode data acquisition system that is triggered by an optical sensor. The scheme will increase the time resolution of the measurements by almost two orders of magnitude over continuous sampling. To our knowledge, this experiment will obtain electric- and magnetic-wave data up to the plasma frequency for the first time in the lightning environment.

Instrument Description

To capture high-frequency data (20 kHz to 2 MHz), we digitize the vector electric field and one component of the magnetic field (to differentiate between an EM and an electrostatic wave, we need at least one component of the magnetic field) with 10-bit accuracy at a rate of 4 MHz. This sampling rate will give valid data for frequencies up to the nighttime plasma frequency at most heights and above the electron gyro frequency at all heights. To aid correlation with continuous lower-frequency data (200 Hz to 20 kHz) on other telemetry (TM) channels, a 20-bit time tag with 160-μs accuracy is written to the buffer synchronously with the data. A 20-bit frame synch completes the 80-bit frame. Present ground-based recording technology of NASA imposes a maximum 4-Mbit/s TM rate. The frame rate, and hence the data word rate per sensor, is 50 kHz. This 50-kHz TM rate implies a maximum duty cycle of only 1.25% and shows the necessity of building a smart data acquisition system, since a random sampling of data is not likely to produce useful information. Furthermore, to study the transient effects associated with the leading edge of the lightning-induced EM pulse, we must provide a separate fast digitizer triggered by the event itself. We can use the visible light pulse to provide the trigger function, since the intervening plasma slows down the EM pulse of interest. In remainder of this section we describe the design criteria and implementation scheme we chose. Details concerning electric and magnetic field measurements in space may be found in elsewhere, e.g., Ref. 14.

Design Criteria and Implementation

The memory size and configuration were chosen to maximize the number of lightning events sent to telemetry. Two separate banks of memory are used, so buffered data are always available for the TM link. One bank is available for writing data from the sensors at 4 MHz, while the other is being read by the TM interface at 50 kHz. The download time for a full memory must be short compared to flight time and should be on the order of the interval between lightning flashes. At the same time, the memory must be large enough to accumulate data from several closely spaced events, as the median time[15] between strokes in a flash (a lightning flash is composed of one or more distinct strokes, which appear almost continuous to the eye) is about 50 ms. It is desirable to take snapshots of data during more than one stroke in a given lightning flash, because the physics of the secondary strokes is likely to be different from the first, since an ionization channel already exists and since secondary strokes usually involve less current. It is known that some of the ionospheric effects under investigation (such as the ELF EM pulse) can occur on each stroke,[8] but it is unknown whether some threshold must be met for other phenomena to occur.

The length of each snapshot was kept as small as possible while still guaranteeing a frequency overlap between the burst and continuous channels. The typical time delay between an optical flash and the time when the whistler frequency is below the upper cutoff frequency of the continuous channels is about 4 ms. The memories were chosen to be 512 K $\times$ 80 bits, allowing sixteen 8.192-ms data snapshots to be stored in a given memory. The time to download one memory is then $80 \times 16 \times 8.192$ ms $\approx$ 10.49 s. During this time, the other memory is available for writing lightning-event data. If the second memory is completely filled while the first is being downloaded, then data collection ceases until the first is emptied.

As it is possible that no lightning strokes will occur to fill one memory while the other is being emptied, or that the optical sensor will fail, a backup mode nicknamed quick-fill was instituted.

Immediately after a memory has been emptied, it is completely filled at a 4-MHz rate with the current data on the analog-to-digital converter outputs, regardless of the state of the optical pulse sensor. Upon completion of quick-fill, the memory is available for writing event data. Event data will be written over quick-fill if and only if the optics detect lightning in the following 10.35 s.

To create a complete spectrum of an event, the burst-mode data must be concatenated with the continuous lower-frequency data. Data (even continuous) that are sent on different TM links have undesirable nonphysical phase shifts and must be aligned by correlating the signals. The correlation process is more difficult for intermittent, stored data; however, tagging the burst data with a time stamp as they are digitized aids the process. Ideally, the time tag would be accurate at least to NASA's 1-ms time resolution and not overflow during the flight. The time tag used in the system described here has 160-μs accuracy, and the timer period is approximately 2.8 min. The time tag also provides a useful way to separate events and determine whether data are from a quick-fill or an event. Discontinuities in the time tag indicate the beginning of a new event, and a decrease in the time tag (other than overflows) indicates the end of event data.

Circuit Description

Figure 2 shows a block diagram of the system controller, which contains circuits to 1) address the read and write memories, 2) generate the pulse-code modulation (PCM) frame clock, 3) control the mode of the write-memory address counter, 4) set the length of the data snapshot, 5) generate event triggers, 6) track the number of events stored in each memory, and 7) optimally set the read–write status of the memories.

The address counter is clocked at the data digitization rate of 4 MHz to generate memory write addresses while the PCM address counter is clocked at the 50-kHz frame rate of the PCM encoder to generate memory read addresses. The 50-kHz clock is derived from the 4-MHz system clock using a divide-by-80 circuit. The address-counter state (quick-fill, event writing, or disabled) is set as a function of the signals 8ms15, AC19, and AC20. During a quick-fill the address counter counts through the memory's entire address range (0_H to $7FFFF_H$) while an event trigger causes an 8.192-ms data snapshot to be written. The snapshot length is set by the 16-bit 8msCtr, and event triggers are created by the UWPulse circuit if the conditions of the next paragraph are met when the UW input line is asserted by the optical sensor.

An event trigger occurs on assertion of the UW input only if 1) the system has completed taking data from the previous trigger, 2) the write memory is not in a quick-fill state, 3) the optical trigger has pulsed to the unasserted state since the previous trigger, and 4) the write memory is not full of event data. The first two restrictions ensure that all events are the same length, as a variable snapshot length would make it difficult to distinguish between the end of one event and the start of the next. The third restriction prevents the memory from being filled by one overlong anomalous optical event where the UW input remains asserted for hundreds of milliseconds.

The Swap circuit tracks the number of events in each memory and swaps the read–write status of the two memories via the Qt control line to maximize the number of events telemetered using this algorithm: If the read memory has been completely dumped or if all of the events in the read memory have been dumped and the write memory contains at least one event, then swap the logical positions of the memories.

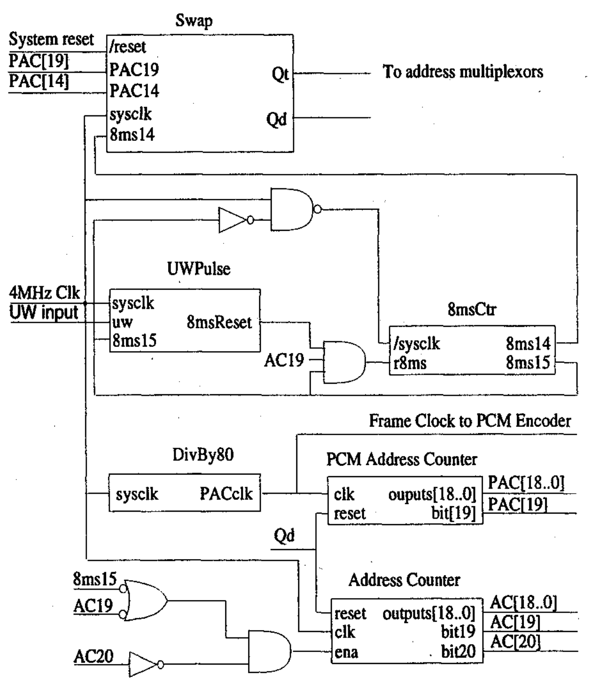

Fig. 2 Block diagram of controller for burst memory system.

Comparison to Previous Instruments

The decrease in power requirements and increase in memory density during the last decade have made burst memory architectures more common on satellite and rocket payloads. Examples are the electric field probe experiments on the ISEE,[16] CRRES,[17] and FREJA[18] satellites and the TOPAZ III (40.001), CRIT I (35.014), CRIT II (35.019), and Soliton (36.071) sounding rockets, and the transient gamma-ray spectrometer on the WIND spacecraft.[19]

The WIND instrument has a cumulative burst rate on the order of 2.4 kbits/s, and FREJA's burst rate is 64 Mbits/s. While these are substantially lower than the T-III burst rate of 320 Mbits/s, normalizing to TM bandwidth (376 bits/s for WIND, 8192 bits/s for Freja and 4 Mbits/s for T-III)[19,18] gives an interesting perspective. The ratios of the normalized burst rates for WIND, T-III, and FREJA are approximately 1:10:1000. The extremely high ratio for FREJA is usually only feasible or necessary for satellites.

The methods employed to acquire burst data are also of interest, as they vary with the phenomena being studied. The burst memory for the Soliton rocket was designed to capture data from a heated region of the ionosphere where the energy from a powerful ground-based HF transmitter was being absorbed. An 8-MByte first-in, first-out memory (FIFO) was written to continuously until the rocket TM data showed the spacecraft had just exited the heated volume. A ground command then froze the FIFO and initiated the slow TM playback. Although somewhat nerve-wracking, the system worked, with 70% of the memory having data from within the heated volume.

The CRIT experiments carried shaped-charge barium releases and required high-resolution data only for a short period after each release. A radio signal triggered the barium release on a subpayload bearing the shaped charge, and the burst-data acquisition began immediately afterward. Similarly, the Thunderstorm III instrument takes high-resolution data of the plasma waves induced by lightning for a short time after each stroke, and the burst mode begins immediately after the optical signal from the lightning is received. The optical signal serves as a event trigger because the plasma waves travel at less than the speed of light.

Other instruments mentioned use the signal itself to trigger the burst mode along with various algorithms to ensure that the data from the beginning of the event are captured. While waiting for an event, the gamma-ray spectrometer on WIND records preburst data and begins burst-mode processing after the count rate exceeds a threshold. FREJA and TOPAZ III actually take continuous data and decide which snapshot of data to keep a posteriori by comparing the energies of the snapshots. Two memories are used—one is for writing the current data, and the other holds the snapshot with the most power up to that time. The data set that has the most power is saved, and the other is overwritten by the next data snapshot. After a set time, the best snapshot is downloaded, and the process repeats.

Conclusions

Remote and in situ measurements give compelling evidence that EM pulses created by lightning affect ionospheric dynamics. No current theory explains this coupling. Although the available data lack high-frequency information, they indicate high-frequency waves are important. The burst memory designed for the Thunderstorm III rocket allows us to collect EM waveform data with a time resolution above the electron gyrofrequency and often above the plasma frequency. Obtaining continuous waveform data at these frequencies is not feasible using available TM.

When looking for special events, a burst memory architecture is a useful method to circumvent the TM bandwidth problem rocket and satellite instruments face. The instrument may use a precursor to trigger the burst memory or be triggered by the data themselves. When triggering off the data, one must devise a method to ensure that data from the beginning of the event are captured. One must also provide some method to correlate burst data with continuous data on other TM links.

Acknowledgments

This instrument was sponsored by NASA under Contract NAG5-5009. The optical sensor was provided by the University of Washington Geophysics group. We appreciate use of the MaxPlus II software donated to Cornell University by Altera Corporation.

Note in Proof

The Thunderstorm III rocket was launched on Sept. 2, 1995, at 1:13 a.m. GMT, and the burst-mode data acquisition system worked perfectly.

References

[1]Helliwell, R. A., *Whistlers and Related Ionospheric Phenomena*, Stanford Univ. Press, Stanford, CA, 1965.

[2]Woodman, R. F., and La Hoz, C., "Radar Observations of F Region Equatorial Irregularities," *Journal of Geophysical Research*, Vol. 81, No. 31, 1976, pp. 5447–5466.

[3]Kelley, M. C., Siefring, C. L., Pfaff, R. F., Kintner, P. M., Larsen, M., Green, R., Holzworth, R. H., Hale, L. C., Mitchell, J. D., and LeVine, D., "Electrical Measurements in the Atmosphere and Ionosphere over an Active Thunderstorm: 1. Campaign Overview and Initial Ionospheric results," *Journal of Geophysical Research*, Vol. 90, No. A10, 1985, pp. 9815–9823.

[4]Kelley, M. C., Farley, D. T., Kudeki, E., and Siefring, C. L., "A Model for Equatorial Explosive Spread F," *Geophysical Research Letters*, Vol. 11, No. 12, 1984, pp. 1168–1171.

[5]Woodman, R. F., and Kudeki, E., "A Causal Relationship Between Lightning and Explosive Spread F," *Geophysical Research Letters*, Vol. 11, No. 12, 1984, pp. 1165–1167.

[6]Inan, U. S., Shafer, D. C., Yip, W. Y., and Orville, R. E., "Subionospheric VLF Signatures of Nighttime D-Region Perturbations in the Vicinity of Lightning Discharges," *Journal of Geophysical Research*, Vol. 93, No. B2, 1988, pp. 11,455–11,477.

[7]Inan, U. S., "VLF Heating of the Lower Thermosphere by Lightning," *Geophysical Research Letters*, Vol. 17, No. 6, 1990, pp. 729–732.

[8]Kelley, M. C., Ding, J. G., and Holzworth, R. H., "Intense Ionospheric Electric and Magnetic Field Pulses Generated by Lightning," *Geophysical Research Letters*, Vol. 17, No. 12, 1990, pp. 2221–2224.

[9]Bell, T. F., Helliwell, R. A., Inan, U. S., and Lauben, D. S., "The Heating of Suprathermal Ions Above Thunderstorm Cells," *Geophysical Research Letters*, Vol. 20, No. 18, 1993, pp. 1991–1994.

[10]Boeck, W. L., Vaughan, O. H., and Blakeslee, R. J., "Low Level Light TV Images of Terrestrial Lightning as Viewed from Space," *Eos, Transactions, American Geophysical Union*, Vol. 72, No. 17, 1991, p. 171.

[11]Holzworth, R. H., private communication, Univ. of Washington, Seattle, WA, 1993.

[12]Li, Y. Q., Holzworth, R. H., Hu, H., McCarthy, M., Massey, R. D., Kintner, P. M., Rodrigues, J. V., Inan, U. S., and Armstrong, W. C., "Anomalous Optical Events Detected by Rocket-Borne Sensor in the WIPP Campaign," *Journal of Geophysical Research*, Vol. 96, No. A2, 1991, p. 1315.

[13]Burke, W. J., Aggson, T. L., Maynard, N. C., Hoegy, W. R., Hoffman, R. A., Candy, R. M., Liebrecht, C., and Rodgers, E., "Effects of a Lightning Discharge Detected by the DE 2 Satellite over Hurricane Debbie," *Journal of Geophysical Research*, Vol. 97, No. A5, 1992, pp. 6359–6367.

[14]Kelley, M. C., *The Earth's Ionosphere*, Academic, San Diego, CA, 1989, pp. 425–458.

[15]Malan, D. J., *Physics of Lightning*, English Universities Press, 1963, p. 18.

[16]Mozer, F. S., Torbert, R. B., Fahleson, U. V., Falthammar, C. G., Gonfalone, A., and Pedersen, A., "Measurement of Quasi-Static and Low-Frequency Electric Fields with Spherical Double Probes on the ISEE-1 Spacecraft," *IEEE Transactions on Geoscience Electronics*, Vol. GE-16, No. 3, 1978, pp. 258–261.

[17]Wygant, J. R., Harvey, P. R., Pankow, D., and Mozer, F. S., "CRRES Electric Field/Langmuir Probe Instrument," *Journal of Spacecraft and Rockets*, Vol. 29, No. 4, 1992, pp. 601–604.

[18]André, M. (ed.), *The Freja Scientific Satellite*, 2nd ed., Swedish Inst. of Space Physics, Kiruna, Sweden, 1992, p. 107.

[19]Owens, A., Baker, R., Cline, T. L., Gehrels, N., Jermakian, J., Nolan, T., Ramaty, R., Smith, G., Stilwell, D. E., Teegarden, B. J., Trombka, J., Yaver, H., Cork, C., Landis, D. A., Luke, P. N., Madden, N. W., Malone, D., Pehl, R. H., Hurley, K., Mathias, S., and Post, A. H., Jr., "The Transient Gamma-Ray Spectrometer," *IEEE Transactions on Nuclear Science*, Vol. 38, No. 2, 1991, pp. 559–567.

E. A. Thornton
Associate Editor