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Combined Release and Radiation Effects Satellite (CRRES): Spacecraft and Mission

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The CRRES mission is a joint NASA and U.S. Department of Defense undertaking to study the near-Earth space environment and the effects of the Earth's radiation environment on state-of-the-art microelectronic components. To perform these studies, CRRES was launched with a complex array of scientific payloads. These included 24 chemical canisters which were released during the first 13 months of the mission at various altitudes over ground observation sites and diagnostic facilities. The CRRES system was launched on July 25, 1990, from Cape Canaveral Air Force Station on an Atlas I expendable launch vehicle into a low-inclination geosynchronous transfer orbit. The specified mission duration was 1 year with a goal of 3 years. The satellite subsystems support the instrument payloads by providing them with electrical power, command and data handling, and thermal control. This review briefly describes the CRRES observatory and mission, and provides an introduction to the CRRES instrumentation technical notes contained within this issue.

Introduction

THE CRRES system was launched on July 25, 1990, on the first commercial Atlas I, from Space Launch Complex 36B at Cape Canaveral Air Force Station (CCAFS). It is commanded and controlled from the United States Air Force Consolidated Space Test Center (CSTC) at the Onizuka Air Force Base in Sunnyvale, Callifornia. The spacecraft (Fig. 1) was originally built for launch by the Space Shuttle, but was modified for launch on the Atlas I vehicle after the Challenger accident. These modifications included the removal of a large orbit transfer stage and removal of one-half of the original chemical canister payload. The orbiter cradle was replaced with a payload adapter to mate with the Centaur upper stage of the Atlas I. The solar panels were relocated to fit into the 14-ft diam Atlas I fairing.

This review discusses the CRRES mission and spacecraft. It is divided into two main sections: a mission overview and a spacecraft description. The mission overview defines the mission objectives and briefly discusses each of the primary CRRES mission phases. Perturbations to the CRRES orbit, within the context of the CRRES mission design, are also discussed. Detailed discussions of the CRRES mission, objectives, and scientific observations made thus far are provided in separate articles in this issue.

The salient design and operational features and the performance of the principal subsystems are presented in the spacecraft description. Although the individual science payloads are not discussed in detail in this paper, a list of the payloads, their location on the spacecraft, their look directions, and boom-deployment angles are provided for reference. For detailed discussions of the science payloads refer to the instrumentation technical notes contained within this issue.

Mission Overview

The initial CRRES orbit[1] was 350 × 33,584 km with an inclination of 18.1 deg (Fig. 2). The initial apogee altitude was approximately 2000 km lower than the targeted geosynchronous altitude of 35,786 km. Following orbit insertion and just prior to separation from the Centaur, the CRRES was oriented with its spin axis lying in the ecliptic plane and pointed 12 deg ahead of the Sun's apparent motion and spun up by the Centaur to its nominal initial spin rate of 2.2 ± 0.2 rpm.

CRRES was acquired by the Air Force Satellite Control network (AFSCN) Indian Ocean Tracking Station approximately 40 min after launch. Initialization and checkout of the vehicle subsystems and instrument payloads, including boom deployments, was accomplished on schedule, within 30 days after launch. Prior to deployment of the long wire booms and the Astromast boom, the vehicle was spun up to 20 rpm; these booms required the centrifugal force of the higher spin rate for their deployment. After the booms were fully deployed the vehicle was spun down to its nominal spin rate of 2.0 rpm, using a sequence of phased spin-down maneuvers.[2] Separating the spin-down pulses by one-half of a boom swing period cancelled the side-to-side motion of the booms, significantly reducing the minimum time required between successive maneuvers.

Normal on-orbit operations began immediately after initialization and checkout was completed. Nominally the majority of the science instruments remain powered and active except during long occultation periods during which duty cycling of selected instruments is required. Normal spacecraft operations include maintaining the spin axis between 5 and 15 deg from the Sun; autonomous battery charge control by an onboard power control unit; and both passive and active thermal control for maintaining the spacecraft temperatures within their specified limits.

The specified mission duration was 1 year with a goal of 3 years. During this time the CRRES will travel through the severe radiation environment of the Earth's inner and outer radiation belts. There are three primary mission objectives: 1) to study the effects of the natural radiation environment on microelectronic components and on high-efficiency gallium arsenide solar cells and to map this environment, 2) to conduct low-altitude satellite studies of ionospheric irregularities (LASSII), and 3) to conduct a series of chemical release experiments in the ionosphere and magnetosphere. To accomplish these objectives CRRES was launched with a complex array of scientific payloads. These included 24 chemical canisters which were ejected from the satellite, releasing clouds of metal vapor. Three separate chemical release campaigns were conducted during the first 13 months of the mission. The first 3 years of the mission are under the management of the Air Force Space Systems Division. After that CRRES will be transferred to NASA where it is planned to join the constellation of spacecraft in the Global Geospace Science program.

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Department of Defense (DOD) Studies of the Radiation Environment

The primary focus of these studies is on the natural radiation environment and the effects of this environment on microelectronic components.[4] CRRES is traveling through the inner and outer radiation belts of the Earth, exposing state-of-the-art microelectronic components to this radiation environment to establish their capabilities for use in future space missions. Also, the radiation belts are being accurately mapped so that a direct correlation can be made between the exposure and microelectronics performance. More than 40 instruments are operating to support these studies. These include an experimental new generation of high-efficiency solar panels and instruments which are investigating the effects of solar flares and cosmic rays on the Earth's magnetosphere and radiation belts.

NASA Chemical Release Experiments

The CRRES payload complement included 24 chemical canisters, 16 large and eight small, which were released during the first 13 months of the CRRES mission at altitudes varying from near apogee to near perigee over ground observation sites and diagnostic facilities.[5] These releases formed large clouds of metal vapor, about 100 km in diameter, which interacted with the ionospheric and magnetospheric plasma and the Earth's magnetic field. These releases were studied with optical, radar, and plasma wave and particle instruments from the ground, aircraft, and CRRES. The three chemical release campaigns were 1) low-altitude releases (near perigee) over the South Pacific in September of 1990, 2) high-altitude releases (from 6000 to about 33,500 km) over North America in January and February of 1991, and 3) low-altitude releases over the Caribbean in July and August of 1991.

The third chemical release campaign required six releases to be performed predawn during Moon-down conditions over the Caribbean. To accomplish this, the orbit apogee was raised by 1450 km using two of the attitude control thrusters. This was accomplished in June of 1991 with a series of appropriately timed burns near perigee. The new orbit repeated the location of perigee near the same longitude every 3 days. Lighting conditions were changing slightly during the campaign, so to compensate, an orbit was selected that started

Table 1 Instrument sensor look angles and boom deployment angles

Instrument[a]	Location	Phi, deg[b]	Theta, −90 deg[c]
AFGL-701-13-1BZ	Magnetometer Boom	270.18	2.13
AFGL-701-13-1BX	Magnetometer Boom	180.02	0.11
AFGL-701-2	Compartment 8	0.0	0.0
AFGL-701-3	Compartment 8	0.0	0.0
AFGL-701-4	Compartment 4	225.0	0.0
AFGL-701-5A	Compartment 4	145.0	0.0
AFGL-701-5B	Compartment 4	180.0	0.0
AFGL-701-5B-10	Compartment 4	−184.5	63.6
AFGL-701-5B-20	Compartment 4	−184.5	62.4
AFGL-701-5B-30	Compartment 4	−184.5	50.1
AFGL-701-5B-40	Compartment 4	−184.5	39.7
AFGL-701-5B-50	Compartment 4	−184.5	30.0
AFGL-701-5B-80	Compartment 4	−184.5	21.1
AFGL-701-5B-90	Compartment 4	−184.5	12.4
AFGL-701-5B-100	Compartment 4	−184.5	1.2
AFGL-701-5B-110	Compartment 4	−184.5	−11.4
AFGL-701-5B-120	Compartment 4	−184.5	−21.4
AFGL-701-5B-23	Compartment 4	−184.5	−55.6
AFGL-701-5B-46	Compartment 4	−184.5	39.0
AFGL-701-5B-83	Compartment 4	−184.5	9.3
AFGL-701-5B-106	Compartment 4	−184.5	6.4
AFGL-701-6	Compartment 8	0.04	0.20
AFGL-701-7A	Compartment 4	180.0	0.0
AFGL-701-7B	Compartment 4	180.0	0.0
AFGL-701-8	Compartment 4	135.0	0.0
AFGL-701-9	Compartment 4	135.0	0.0
AFGL-701-11A	Compartment 4	180.0	0.0
AFGL-701-11B	Compartment 4	180.0	0.0
AFGL-701-11C	Compartment 4	180.0	0.0
ONR-307-3-1	Bottom deck	134.85	−9.89
ONR-307-3-2	Bottom deck	134.85	−9.89
ONR-307-3-3	Bottom deck	134.85	−9.89
ONR-307-8-1	Bottom deck	225.0	−45.0
ONR-307-8-2	Bottom deck	225.0	−15.0
ONR-307-8-3	Bottom deck	135.0	0.0
ONR-604	Compartment 8	0.0	0.0
NRL-701-QIMS	Top deck	180.0	0.0
LASSII hoop boom	Top deck	71.3	12.0
LASSII P3 boom (2)	Top deck	−134.0, 46.0	65.0
LASSII E-field boom (2)	Top deck	140.0, −40.0	65.0
Magnetometer boom	Compartment 2	270.0	0.0
SWDA booms (2)	Top deck	135.0, −45.0	0.0
WADA boom (2)	Top deck	−135.0, 45.0	0.0

[a]Instruments are described in instrumentation technical notes in this issue and in AFGL-TR-85-0017.[7]
[b]Degrees from $+x$ axis in XY plane (counterclockwise rotation).
[c]Theta = degrees from $+z$ axis; (Theta − 90 deg) = degrees from XY plane.

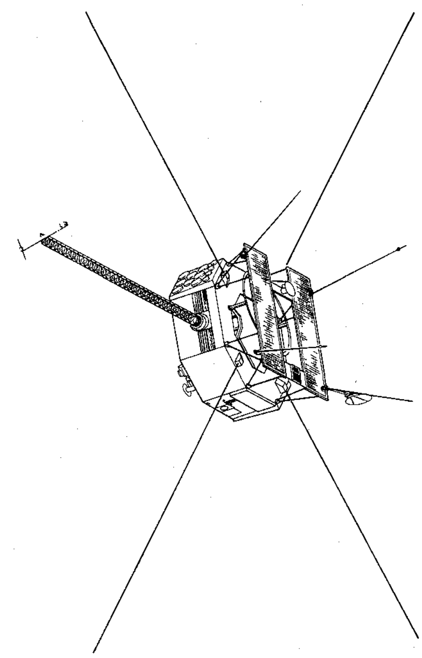

Fig. 1 CRRES deployed configuration.

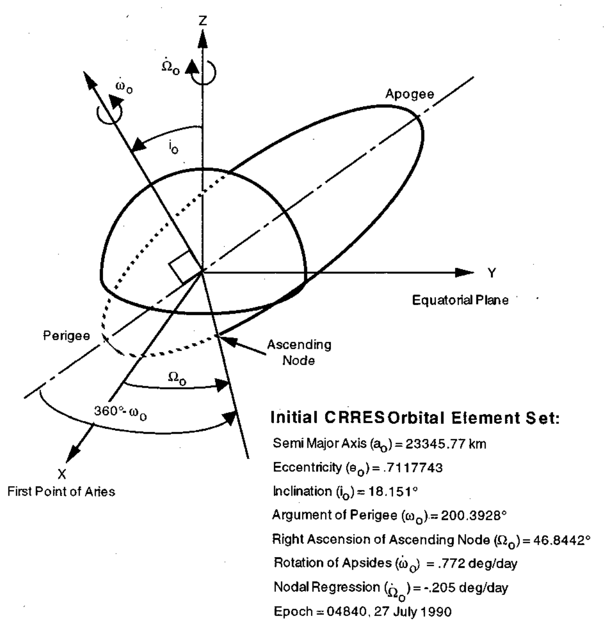

Fig. 2 Initial CRRES orbit (not drawn to scale).

Table 2 CRRES chemical canister contents

Canister	Ti, kg	B, kg	Ba, kg	Sr, kg	Li, kg	Eu, kg	Ca, kg
G-1	1.269	0.572	1.468	0.019			
G-2	1.269	0.572	1.468	0.019			
G-3	1.270	0.574	1.471	0.019			
G-4	1.271	0.574	1.471	0.019			
G-5A	5.770	2.605			0.457	0.299	
G-5B	5.770	2.605			0.457	0.299	
G-6A	5.770	2.604			0.457	0.299	
G-6B	5.767	2.603			0.457	0.299	
G-7A	5.768	2.603			0.457	0.299	
G-7B	5.768	2.603			0.457	0.299	
G-8A	4.556	2.056	5.410				
G-8B	4.282	2.068	5.304	0.067			
G-9A	4.692	2.118	5.202		0.011		
G-9B	4.693	2.118	5.203		0.011		
G-10A	4.584	2.069	5.306	0.067			
G-10B	4.583	2.069	5.305	0.067			
G-11A	1.270	0.573	1.471	0.019			
G-11B	1.270	0.573	1.471	0.019			
G-12A	1.271	0.573	1.471	0.019			
G-12B	1.271	0.574	1.471	0.019			
G-13A	4.254	1.920		3.784			
G-13B	4.554	2.055	5.408				
G-14A	5.214	2.353					1.891
G-14B	4.554	2.056	5.409				

with perigee at 314.1 deg East longitude and drifted 2 deg westward every 3 days in order for the chemical releases to occur over the Caribbean.

DOD Low-Altitude Scientific Studies of Ionospheric Irregularities

LASSII is studying naturally occurring and artificially produced ionospheric perturbations and the effects of ionospheric perturbations on communications paths. The LASSII measurements are being made near perigee of selected orbits.[6] In addition, LASSII made observations of the low-altitude chemical releases. The onboard set of LASSII instruments consists of two pulsed plasma probes, a very low frequency wave analyzer including two electric field antennas and magnetic hoop antenna, and a quadrupole ion mass spectrometer.

Orbital Perturbations and the CRRES Mission Design

Perturbations to the CRRES orbit have played an important role in the design and planning of the CRRES mission. Specifically, perturbations due to the Earth's oblateness (J2 perturbations) cause cumulative secular variations (i.e., increasing with time) in the argument of perigee and the right ascension of the ascending node. These variations, coupled with the apparent 1 deg/day motion of the Sun, result in a net rotation of orbit perigee and apogee toward earlier local time, as the mission proceeds (Fig. 3). Apsidal rotation also produces a periodic variation (36 deg peak to peak) in the latitude of perigee with a period of ~525 days. These two motions, given the initial local time of apogee, determined when and where, in local time and latitude, significant mission events such as the CRRES chemical releases occurred.

Third body influences of the Sun and Moon, along with atmospheric drag, cause periodic and secular variations in the semimajor axis, eccentricity, and inclination. Third body effects and atmospheric drag are highly coupled and can have a dramatic effect on the stability of high eccentricity orbits, especially those slightly more eccentric or inclined than CRRES. Thousands of orbits in the neighborhood of the CRRES orbit were investigated in a study of high-eccentricity orbit stability and evolution.[3] No eccentric re-entries were found to be possible for the range of CRRES orbits of interest.

Spacecraft Description

The CRRES is composed of two basic components: the satellite and the payload adapter (Fig. 4). The adapter interfaced with the launch vehicle both mechanically and electrically. The total weight of the CRRES system at launch, including the adaptor, was 1753 kg. The satellite weight at launch was 1716 kg, whereas the total payload weight was 678 kg including the chemical canister payload. The total weight of the 24 chemical canisters including chemicals and release control units was 425 kg.

The satellite consists of the structure; deployable mechanisms (booms and chemical canisters); the telemetry, tracking and command (TT&C) subsystem; the electrical power and distribution (EPDS) subsystem; the attitude determination and control (ADCS) subsystem; the thermal control subsystem; the chemical module/canister assembly subsystem; and the scientific payloads. Because of the sensitivity of the scientific payloads, very stringent electromagnetic compatibility and magnetic cleanliness controls were maintained on the spacecraft. The structure, mechanisms, and other spacecraft subsystems are described in the following subsection. The science payloads are described in the instrumentation technical notes contained within this issue.

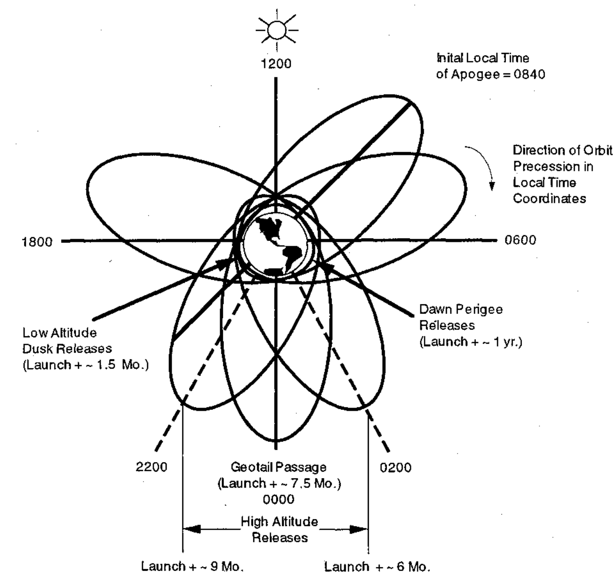

Fig. 3 Precession of CRRES orbit in local time coordinates.

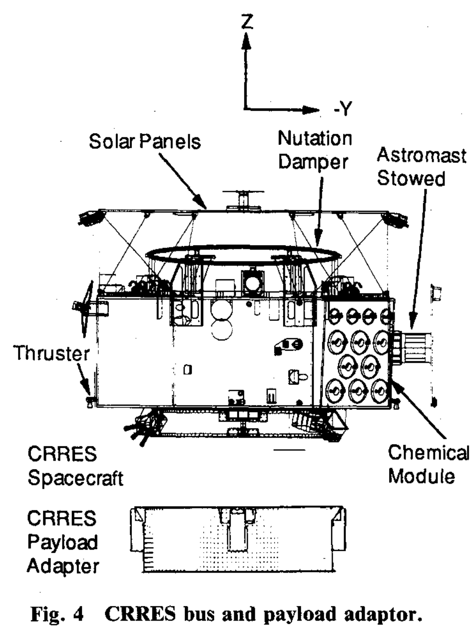

Fig. 4 CRRES bus and payload adaptor.

Structure and Mechanisms Subsystems Description

The CRRES basic structure is octagonal in shape. Onto this various booms, antennae, and the solar arrays are attached. The maximum overall dimensions are 2.6 m along the x and y axes and 1.9 m along the z axis, excluding booms.

The vehicle contains eight compartments (Fig. 5). Vehicle subsystems and science payloads are contained in the "corner" compartments (2, 4, 6, and 8), whereas two of the "side" compartments (3 and 7) carry the chemical canisters. The other two side compartments (1 and 5) are empty.

With a few exceptions, compartments 2 and 6 house spacecraft subsystem components, whereas compartments 4 and 8 house science instruments. In addition, some experiments and spacecraft components are mounted on the top and bottom decks. Table 1 contains the location of each of the CRRES science instruments, their associated look angles, and boom-deployment angles. Look angles are measured with respect to the spacecraft coordinate axes, which form a right-handed system, as defined in Fig. 4.

Because of the severe radiation levels, a detailed model of the radiation dosage expected over a 3-year mission was calculated at the electronics box level. Shielding was provided as necessary to assure survival. In particular, the tape recorders were shielded with lead tape and extra thin-wall aluminum structure was put along the walls of compartments 1 and 5 to protect hardware in the corner compartments. Wiring on the top and bottom decks was double wrapped with copper tape to protect the insulation from radiation degradation.

Many of the experiments have deployable booms. Onto these are attached various probes, sensors, and antennae. The LASSII magnetic field hoop antenna is on an articulated stiff boom extending 2 m from the CRRES skin line. There are also two pairs of hinged (LASSII P^3 and E-Field) 1.7-m-long antennas which extend upward and outward from the solar array panels.

Four wire booms extend radially outward from the upper deck above the corner compartments. One pair of these wire booms has small spheres near the ends; the other pair has cylindrical tip masses. All four of these booms are 50-m-long flexible wires.

The remaining boom is the science magnetometer boom. This is a 6.1-m Astromast boom that extends radially outward from compartment 2. Analysis of magnetometer data has determined that the magnetometer boom assembly (MBA) did not quite fully deploy. The result is that the x and y sensors of the AFGL-701-13 magnetometer are rotated approximately 15 deg from the originally desired orientation. This misalignment is tolerable however, since both the ground and onboard software, used to process the magnetometer data, has been modified to compensate for the misalignment. The most likely cause for the MBA deployment anomaly is interference between the braided overshield on the MBA wire harness and the Velcro on the MBA thermal blankets, i.e., the overshield was snagged by the Velcro during deployment.

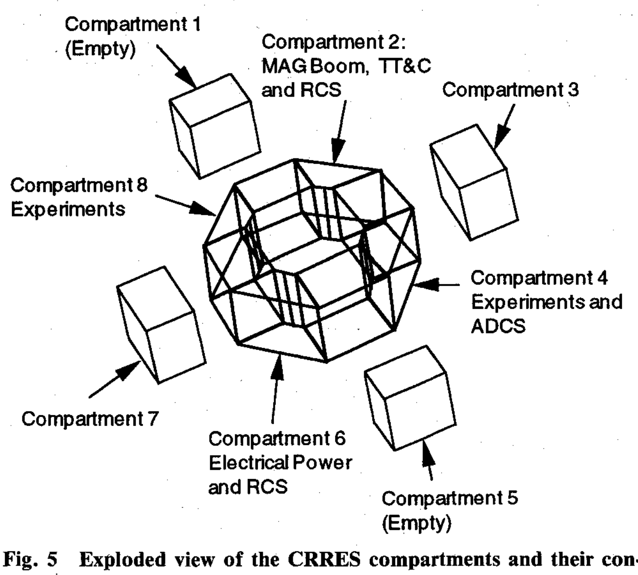

Fig. 5 Exploded view of the CRRES compartments and their contents.

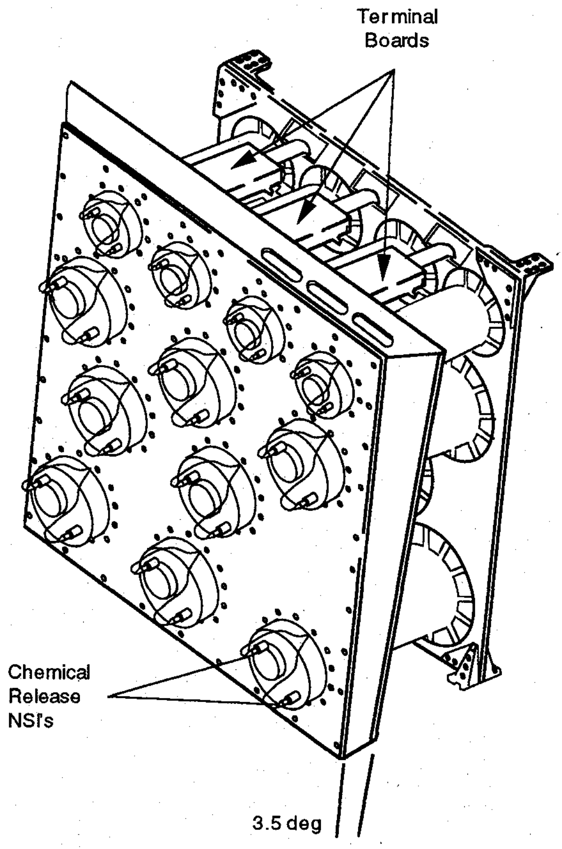

Fig. 6 CRRES chemical module; NSIs and terminal boards are shown.

There is one ring nutation damper, a circular tube partially filled with oil, located on the top deck. The nutation damper is used to dissipate dynamic motions that are other than pure spin.

The chemical compartments each provide a "wine rack" for eight large and four small canisters. These canisters carried the various chemicals used and were mounted for spring ejection from the spacecraft. The spring force ensured that the canisters were sufficiently far away from the spacecraft to avoid contamination of the spacecraft when they ignited.

Chemical Module/Canister Assembly Subsystem Description

One of the primary objectives of the CRRES mission was to perform chemical release experiments in the Earth's ionosphere and magnetosphere. For this purpose, it was loaded with over 181 kg of various chemicals. These were contained in 24 cylindrical canisters which were equally partitioned in two chemical modules (Fig. 6). Within each module were three release control unit (RCU) terminal boards. One terminal board controlled RCU battery heating and charging, as well as safing and arming of all canisters in the module. The second terminal board controlled RCU battery discharge and monitored battery discharge voltages. The third terminal board provided for the ejection of canisters on an individual or paired basis by firing redundant NASA Standard Initiators (NSIs) on pin-pullers upon receipt of real time or stored commands.

There were two sizes of canisters onboard the CRRES satellite. The eight small canisters weighed approximately 8.7 kg

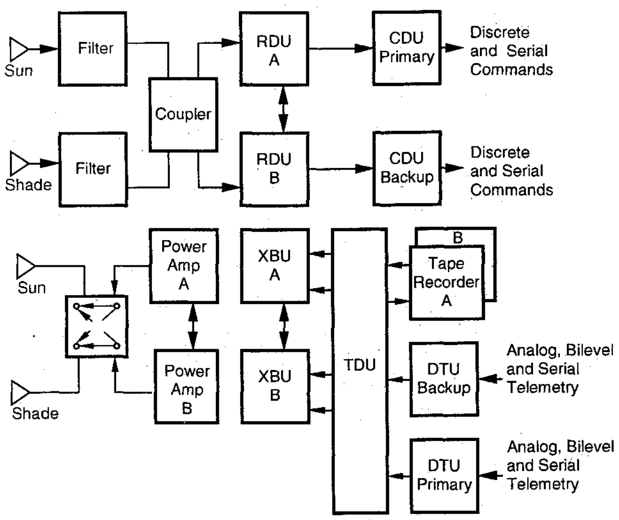

Fig. 7 Telemetry, tracking, and command subsystem simplified functional diagram.

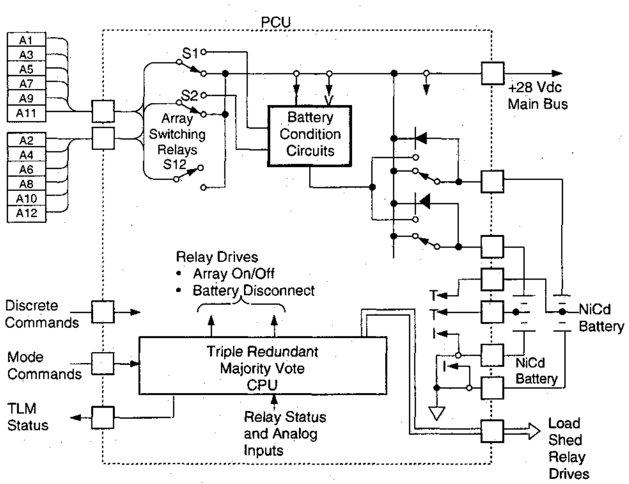

Fig. 8 Electrical power subsystem simplified functional diagram.

each including chemicals. The 16 large canisters ranged in weight from 20 to 24 kg each. The chemicals contained within these aluminum canisters consisted of a titanium-boron thermite with barium, lithium, calcium, europium, and/or strontium as the metal to be vaporized. A listing of the chemical canisters and their contents is given in Table 2. Two NSI ports and a high-pressure burst disk were built into one head of the canister. The burst disk allowed the chemicals to completely vaporize, once the thermite was ignited, before they were expelled from the canister.

Each chemical canister was mounted on a compressed spring, inside its guide tube. It was held in place by a restraining pin. When a canister eject command was sent, the restraining pin for that canister was pulled using a NSI. A timer on the canister was started at the time of ejection through a pullaway connector. When this timer ran down (after an approximately 1498-s delay), the canister contents vaporized and were released. This was sufficient time for the canisters to reach a minimum of 2.5 km away from the satellite at chemical release, thus preventing any significant contamination from the releases onto the satellite. The large canisters were ejected in pairs to maintain spacecraft balance. Several canisters had additional 5- or 2.5-s delays so that nonsimultaneous measurements of the chemical clouds could be made when paired releases were made. The RCUs each contained a nickel-cadmium battery, which was charged up prior to a release. This was done by ground command; approximately 30 h was required to fully charge an RCU battery.

Telemetry, Tracking, and Command Subsystem Description

The TT&C subsystem serves as the interface between CSTC and CRRES. It provides the capability to command and operate the spacecraft and to record and transmit science and engineering telemetry data. The functional arrangement of the subsystem is shown in Fig. 7.

Uplink commands, transmitted from CSTC through the remote tracking stations, are received by the wide-beam command antenna system. The command signals are routed to the receiver/demodulator unit (RDU) where they are detected, demodulated, and routed to a command decoder unit (CDU) for verification and execution. This unit is capable of executing commands in real time or storing them for delayed execution.

Telemetry data is collected and formatted for downlinking by the digital telemetry unit (DTU) which, in turn, routes the data to the transmitter/baseband units (XBUs), to the tape

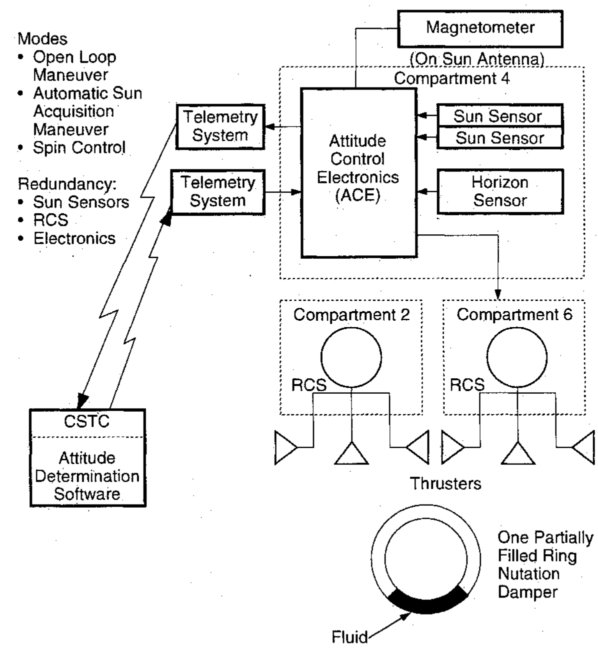

Fig. 9 Attitude determination subsystem simplified functional diagram.

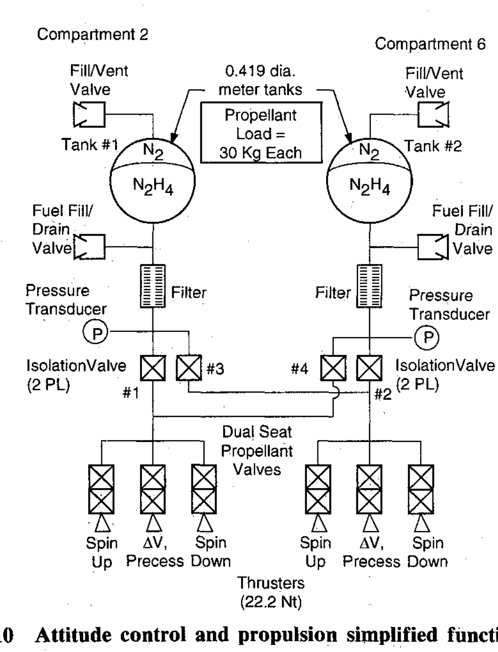

Fig. 10 Attitude control and propulsion simplified functional diagram.

recorders, or both. Playback data is routed from the tape recorders through the telemetry distribution unit (TDU) to the transmitter where it, along with real-time data, is modulated onto the downlink rf carrier. The modulated rf carrier is amplified to 3.0 W, and then routed to the 10-W power amplifier and finally to the wide-beam telemetry antenna.

Telemetry data is collected and formatted for downlinking by one of two redundant DTUs. Three data formats are used; an engineering data format and two science data formats [geosynchronous transfer orbit (GTO) and LASSII]. The GTO format is used primarily; however, the LASSII format is used at low altitudes during selected orbits when the LASSII instruments are gathering data. Two data rates are used nominally; a 16 kbit/s real-time rate and a 256 kbit/s playback rate. A 1 kbit/s rate is also available for use during emergencies although it has not been used during the mission thus far.

In addition to collecting and organizing data, the DTU generates the timing and synchronization signals required by the spacecraft and payloads as well as the vehicle time code word (VTCW). The VTCW has a resolution of 128 ms and a rollover of about 2.18 years. On several occasions the VTCW has jumped ahead in time by a short time relative to Greenwich Mean Time (GMT). Data indicates that this is the result of electrical noise being coupled into the test speedup input wires in the DTU, probably due to internal discharges from the severe particle radiation environment. These VTCW speedups were first noticed during ground data processing at the Phillips Laboratory Geophysical Directorate in Boston, Massachusetts. The necessary modifications were made to the data processing software to compensate for the speedups.

Data are recorded at 16 kbit/s onto either of two 0.75 gbit recorders, storing a maximum of ~13 h worth of data on each recorder. Previously recorded data is played back at 256 kbit/s, simultaneously with the real-time data. Approximately 49 min is required to play-back a full tape, whereas approximately 40 min of playback time is required for each orbit of data; this is based on an orbit period of ~10 h.

After the uplinked commands are received and demodulated by the RDU, the commands are transmitted to their assigned CDU. The CDU is normally in a standby state and activated by the RDU demodulators when an uplink command is present. Upon receipt of the command, both CDUs attempt to validate the command by performing a series of checks. At least one of the CDUs will reject the command since the decoder address for one of the CDUs will be incorrect. Commands are executed in realtime or stored in command storage memory (CSM) for later execution. Each CDU is capable of storing 256 commands along with their associated time tags. When the command time of day (CTD) clock in the CDU matches the time tag of a stored command the command is executed. The CTD clock increments every 1.024 s and rolls over to zero after 12.288 h. The command storage memory has been used extensively throughout the mission for both routine and contingency operations as well as for the precise timing of the canister ejections.

The CRRES antenna system consists of two identical antenna assemblies: Sun and Shade. The Sun antenna assembly is mounted on the solar array side of the spacecraft; the Shade antenna is on the opposite end. Each antenna assembly consists of a wide-beam command and wide-beam telemetry antenna on a common ground plane. The antennas are identical except for operating frequency. The command antenna is tuned to operate at the uplink frequency, whereas the telemetry antenna is tuned to operate at the downlink frequency. Both antennas are right-hand circularly polarized, and both have hemispherical radiation patterns. The antennas are mounted such that their combined coverage provides nearly isotropic coverage for the spacecraft.

CRRES uses standard space-ground link subsystem (SGLS) signal formats and has been assigned SGLS channel 5. Uplink commands are transmitted from AFSCN Remote Tracking Stations at a command bit rate of 1000 bit/s using standard SGLS FSK modulation techniques. The uplink signal is transmitted to the spacecraft at an output power level of 1–10 kW. The 1 kW mode is the nominal operating level; however, up to 10 kW can be used, as required, to maintain a 6-dB link margin. Real-time data is phase shift keying (PSK) modulated onto the 1.024-MHz subcarrier, whereas playback data is PSK modulated onto the 1.7-MHz subcarrier. These are then summed, phase modulated onto the 2222.5-MHz downlink carrier, and amplified to a nominal 3 W level.

Electrical Power and Distribution Subsystem Description

The EPDS provides for the generation, storage, distribution, and control of power required to operate the spacecraft and experiments. It does not require ground-based power management computer programs. While sunlit, power is normally supplied by the solar arrays. Batteries supply power while in the Earth's shadow, or during specific functions requiring CRRES to be pointed away from the Sun.

The EPDS is comprised of two fixed solar arrays, two batteries, a power control unit (PCU), and the electrical distribution system. The subsystem is a conventional direct-energy-transfer solar array/battery system. The solar arrays are sized to provide the total spacecraft power requirements during sunlit periods with sufficient margin to charge the batteries. Battery charging is controlled by the PCU. Power is distributed, as required, to the spacecraft and experiments by the power distribution subsystem. A simplified functional diagram of the electrical power system is shown in Fig. 8.

Each battery consists of 21 active nickel-cadmium cells, and has a nominal charge capacity of 18 A-h. Their nominal operating temperature is in the range from 10 to 15°C; each battery has three temperature sensors, which provide temperature to the telemetry stream.

The batteries were sized to supply the total spacecraft power requirements during shadow periods up to 90 min, and to sustain limited spacecraft operations for at least 2 h; the longest shadow period the spacecraft is expected to encounter is 130 min for short periods of time. However, approximately 6 months after launch, one of the batteries failed, necessitating the implementation of single battery operations.

As a result of operating with only one battery, the total spacecraft power requirements can now only be met for shadows up to approximately 45 min, with some instruments being duty cycled during longer shadows. However, the spacecraft still has the capability to collect greater than 90% of the science data for hour-long shadows, as the original specification required.

Conventional battery reconditioning (where one battery is taken off-line and deeply discharged) is no longer possible due to a safety feature of the PCU which allows only one battery at a time to be removed from operation. A method for performing a partial reconditioning (referred to as a battery letdown) of the operative battery has been developed which does not require the operative battery to be taken off-line. Although the battery voltage cannot be lowered as far as with conventional reconditioning, it can be lowered far enough to provide some improvement in the battery capacity. This can be accomplished by powering off all instrument payloads and any nonessential spacecraft loads and discharging the battery as far as possible while providing sufficient power to essential spacecraft loads such as the CDU.

CRRES has two fixed solar arrays located on the top deck of the spacecraft whose surface normals are parallel to the spacecraft spin axis. The solar arrays are sufficiently oversized so they can supply the spacecraft with the required operational power as well as current to recharge the batteries. Each array has six circuits making a total of 12. Relays in the PCU switch these circuits on or off the main bus, as required, to maintain the proper bus voltage for achieving the desired level of battery charge. The solar arrays are susceptible to degradation from ultraviolet rays and particle radiation. Therefore, the available power to the spacecraft will decrease noticeably throughout the mission. As the arrays have a large surface area, and little thermal mass, they experience wide temperature fluctuations throughout a Sun/Shade cycle.

The brains of the EPDS is the PCU, a triply redundant, majority vote "smart" system. The main purpose of the PCU is to automatically perform battery charge control, and to provide for EPDS telemetry monitoring and ground command control. The voltage/temperature (V/T) method of battery charge control is utilized. Based on battery temperature, bus voltage, and various mode command states, the PCU central processing unit makes decisions whether to open or close the array switching relays. To enable fine adjustments to the system, and allow for battery degradation, there are eight different V/T curves, selectable by ground command.

In addition to its automatic charge control feature, the PCU is capable of making decisions and outputting commands to remove an overtemperature battery from the main bus, or to safely shed up to three levels of spacecraft and instruments loads due to overcurrent or undervoltage. If it is determined that the power subsystem is not performing properly, the PCU may be commanded to an altered operating mode, or the PCU may be completely overridden by ground commands.

Analog signals used by the PCU are provided to the spacecraft telemetry system. Signals representing solar array current, load current, battery terminal voltage, battery current, battery temperature, and battery state-of-charge are telemetered.

The EPDS is an autonomous system and nominally requires very little operator intervention. Operators are normally required only to perform battery reconditioning and power system monitoring.

Electrical power provided by the batteries and solar arrays is supplied to the main power bus by the PCU. Main bus power from the PCU is supplied to terminal boards which branch power to lower level buses. Power buses are protected by automatic undervoltage and overcurrent circuits located in the PCU; however, power always remains on the essential bus so that the spacecraft can be commanded to attempt recovery.

Attitude Determination Subsystem Description

The CRRES attitude determination subsystem is used to determine the spacecraft attitude and spin rate. This allows subsystems to keep within nominal environments, and provides a reference frame for science data. The attitude determination subsystem is designed to provide knowledge of the CRRES spin axis in inertial space, to within ± 2.0 deg, 1 sigma.

The CRRES attitude is determined by combining the data from a Sun sensor, a horizon sensor (HS), and a magnetometer. The sensors are supported by individual electronics boxes and controlled collectively by an attitude control electronics (ACE) box. The solar aspect angle determined by the Sun sensor is combined with ephemeris data to compute a cone of possible spin axis orientations in inertial space. The Sun pulses, also generated by the Sun sensor, are used to determine the spacecraft spin rate and spin phase angle for science use. The Earth limb pulses generated by the horizon sensor are used for unique determination of the spin axis direction. Similarly, ephemeris data may be used to compute the expected magnetic field vector and compared to the telemetered zero crossings of a selectable component of the magnetic field vector to compute spin vector direction. The remaining problem of finding the spacecraft spin phase angle is solved by using the Sun crossing pulses from the Sun sensor. Knowledge of the phase angle is not required for operating the spacecraft, but is used for experiment data reduction. CRRES does only rudimentary attitude determination onboard; useful attitude determination is performed by processing spacecraft attitude data on the ground using mission unique software. A functional block diagram of the CRRES attitude determination system is provided in Fig. 9.

Attitude Control and Propulsion Subsystem Description

Attitude control is accomplished by firing the hydrazine thrusters to precess the satellite spin axis and control its spin rate. Small orbital maneuvers are also made by these thrusters. Nutation is damped by a passive nutation damper and coupling with the long wire booms. Once the wire booms are deployed, the flexible body dynamics dominate, and the root damping characteristics of the booms control damping.

The reaction control system (RCS) is responsible for providing the attitude maneuvering torques and small orbit adjust propulsion changes for CRRES throughout the mission lifetime. The RCS consists of two hydrazine propellant tanks feeding six 5 lb (nominal) thrusters in a blow-down mode. Two titanium shell propellant tanks with internal diaphragms are used to store a total of 60 kg of hydrazine (30 kg/tank). The hydrazine is fed under pressure to the thrusters. The thrusters on CRRES are functionally paired to provide spin-up, spin-down, precession, and delta-V capabilities. A functional description of the RCS is provided in Fig. 10.

In addition to its attitude determination functions, the ACE provides valve driver circuits to actuate the six RCS hydrazine thrusters. The valve drivers respond to internal microprocessor-derived actuation signals or to external real-time or stored commands. The thrusters provide a minimum impulse bit dictated by the shortest command time available from the ACE box (50 ms). Under normal operations the majority of the thruster firings consist of single, short pulses for attitude corrections. The thrusters are also capable of operating in a steady-state mode for spin-up, spin-down and orbit adjust maneuvers. CRRES attitude control is done in an open-loop manner utilizing the maneuver planning function of the ground-based mission unique software.

Based on actual hydrazine propellant usage during the first year and a half of mission operations, including the orbit phasing and associated spin-up and attitude maintenance maneuvers, the propulsion system performance is exceeding prelaunch predictions. For example, the thruster efficiency during orbit adjust maneuvers proved to be significantly higher ($\sim 7\%$) than originally modeled. The extended mission life resulting from the high thruster efficiency however far exceeds the expected radiation survival lifetime, which is 3–6 years.

Thermal Control Subsystem Description

The various spacecraft subsystem and experiment components on CRRES must be kept within certain temperature limits for proper operation. CRRES is designed to accomplish this primarily by using passive thermal control, i.e., with thermal finishes and thermal blanketing. There are no thermal louvers or shading mechanisms to complicate operations. Aside from telemetry monitoring, the only operator task required is occasional heater operation. On-orbit data indicates that the temperature predictions made with the CRRES thermal math model are quite close (± 5 deg) to the observed temperatures.

Concluding Remarks

By the time this issue is in print, CRRES will have completed its first year and a half of mission life. With the exception of the loss of one of the spacecraft batteries and occasional spacecraft component misconfigurations during periods of high geomagnetic activity,[8] the spacecraft performance during the past year has been superlative, providing the CRRES experimenters with an onboard science data return capability of greater than 95%, and the successful release of all chemical canisters.

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