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# Chemical-Release Mission of CRRES

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**The CRRES satellite was a dual-mission spacecraft to perform active experiments in the Earth's magnetosphere and ionosphere and to study the natural space environment and its effects on spacecraft electronics. Here the NASA chemical-release mission is described. The experiments were motivated by the need to address scientific questions in the areas of coupling between the ionosphere and magnetosphere, response of the magnetosphere system to injections of artificial ion clouds, and instabilities and structuring of the ionosphere in response to perturbations. The basic physics and chemistry of chemical-injection experiments are described, and the individual CRRES experiments are detailed. The initial science results from the chemical-release experiments performed to date are 1) demonstration of critical velocity ionization over a narrow range of parameter space; 2) production of diamagnetic cavities by barium and lithium releases over a wide range of parameters; 3) demonstration of the chemical-release technique to study magnetosphere-ionosphere coupling; 4) modification of energetic electron distribution functions with barium injections; 5) stimulation of magnetospheric waves with barium injections; and 6) possible inducement of enhanced auroral activity.**

## Introduction

THE regions of space surrounding the Earth where matter exists in an ionized state and the magnetic field exerts a large degree of control is known as Earthspace. The ionized state has been called the "fourth state of matter," and is unique because charged particles can interact through long-range electromagnetic forces and can carry electric currents. The lower-altitude region is the ionosphere, and at higher altitudes is found the magnetosphere. The source of energy to this system is the Sun. Solar ultraviolet is a source of ionizing radiation and the solar wind carries both energy and particles. In one view, the magnetosphere is a large-scale electric generator driven by the action of the high-speed electrically conducting solar wind moving past the Earth in the presence of a magnetic field. The various regions of the magnetosphere-ionosphere system are coupled by flows of electric currents, energetic particle beams, and electromagnetic waves.[1] There are many manifestations of these processes that affect both technical and nontechnical aspects of life on Earth. The magnetosphere is the reservoir of the high-energy radiation belts, and other papers in this issue address these features and the contribution of combined release and radiation effects satellite (CRRES) to their study.

An obvious manifestation of Earthspace processes is the aurora. The aurora represents a significant input of energy into the ionosphere in polar regions. The ionosphere is actually the sink for excess energy in the magnetosphere and becomes highly structured and variable during periods of intense geomagnetic activity.[2] The structuring in the ionosphere affects high-frequency radio communications, causes scintillations of satellite-Earth signals, and the large currents driven in the ionosphere by the magnetospheric dynamo actually couple into large-scale systems such as power grids and pipelines with destructive effects.

This paper will discuss the NASA chemical-release portion of the CRRES mission. The science objectives pertaining to space physics research will be described. A discussion of the individual campaigns and their operational aspects will follow, and finally will be a brief resume of the principal scientific achievements.

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## Science Background

Research in the physics of space is as old as the time it was first noticed that a correlation between aurorae and sunspots existed, but the modern era can be traced to the first artificial satellites that offered the ability for probing the space environment directly. The research proceeds along tracks that in large measure are influenced by the experimental tools that are available and by the perceived societal needs to understand the forces that have potential effects on terrestrial activities. In recent years, various techniques of active experiments have played an ever-increasing role. Active experiments involve injections of energy and matter in the forms of charged particle beams, electromagnetic waves, and chemical substances. The experiments are designed to produce a controlled and known input to the space environment and the effects are measured with arrays of diagnostic instruments. Coupled with the active experiments have been significant advances in computing capability and computer-simulation techniques that allow complex plasma and electromagnetic field processes to be modeled. The union of these two techniques represents a major advance, for an active experiment can be designed with a perturbation input and multipoint measurements of the output to test the predictions of a theory or model.

The CRRES satellite was a dual-mission spacecraft with a NASA mission to perform active chemical-release experiments. Chemical-release experiments may be broadly grouped into categories of *tracer, modification,* and *simulation* experiments. Tracer experiments inject relatively small amounts of material that can be detected by remote sensing means, and thereby illuminate natural dynamic processes in the environment. These experiments are analogous to introducing smoke into a wind tunnel to illuminate the motion of air around a test article. Larger amounts of material can be used to modify or perturb the environment in a controlled manner, and the "system response" to this perturbation is studied. This is analogous to measuring the impulse or step-function response to an electrical network. The simulation function is designed to mimic a natural process. For example, the active magnetospheric particle tracer experiment (AMPTE) spacecraft released a cloud of barium vapor in the solar wind thus simulating a comet.[3]

## Chemistry and Physics of Chemical Injections

There are a large number of substances that have been used in chemical-injection experiments, and here we will discuss two generic types that are used in the CRRES program. The alkali metals and alkali earths are used for injections of positive ions. These materials have low ionization threshold energies and photoionize in the presence of solar ultraviolet radiation. In order for the process to function, the material must be injected in vapor form. In the CRRES program, the necessary heat of vaporization was provided by the reaction

$$Ti + 2B \Rightarrow TiB_2$$

and the substance to be vaporized was mixed with the thermite charge in a canister. The most common substance used in CRRES was barium, and barium photoionizes rapidly in sunlight according to

$$Ba^o + h\nu \Rightarrow Ba^+ + e^-$$

Thus, an artificial ion cloud is produced by a reaction of this type. Barium has strong resonance lines when exposed to sunlight, and the ions and neutrals are visible optically. $Ba^o$ has a resonance line at 5535 Å and $Ba^+$ has a strong line at 4554 Å. In the latter case, the oscillator strength coupled with the solar spectrum is such that each barium ion emits 0.4 photons/s.[4] Thus, the artificial ions mimic natural ions but, unlike the natural ion species in the magnetosphere, these artificial ions are visible and their dynamics can be observed with optical instruments. Furthermore, since the optical emissions are a resonance spectrum, interference filters or spectrographs can be used to isolate uniquely the emissions from one specie. The other metals used in the CRRES experiments were calcium, strontium, lithium, and europium. All photoionize with various time constants and all, except for $Li^+$, have resonance lines in the visible spectrum.

A second class of substances produces depletions of the natural plasma populations by chemical and ionic reactions. These are used primarily for experiments involving modifications of the ionosphere. The ionosphere is produced primarily by the action of solar ultraviolet on the upper atmosphere. The primary production process is

$$O + h\nu \Rightarrow O^+ + e^-$$

and this is balanced by several loss processes involving recombination and chemical reactions. The primary loss process is[5]

$$O^+ + N_2 \Rightarrow NO^+ + N, \qquad k = 1.2 \exp - 12 \ s^{-1}$$

$$NO^+ + e^- \Rightarrow N + O, \qquad k = 4.1 \exp - 7 \ s^{-1}$$

and this process is limited by the slow reaction rate of the first step. Parenthetically, this is the reason that the *F* region of the ionosphere continues to exist at night after the production from solar ultraviolet is removed. Introduction of certain chemicals can increase the recombination rate of oxygen ions to oxygen neutrals, and thereby create a localized density depletion. The first large-scale demonstration of this effect was observed as a result of exhaust products from the launch of Skylab.[5] A large number of chemicals are capable of producing these effects, and one such used in the CRRES program is sulfur hexafluoride. This chemical causes $O^+$ depletion with the reactions[6]

$$SF_6 + e^- \Rightarrow SF_5{-} + F, \qquad k \sim 2.0 \exp - 7 \ s^{-1}$$

$$SF_5{-} + O^+ \Rightarrow SF_5 + O^*, \qquad k \sim 0.5 \exp - 7 \ s^{-1}$$

$$O^* \Rightarrow O + h\nu$$

Notice that the reaction rates here are many orders of magnitude larger than the rates for the natural recombination reactions stated previously, and therefore the net result is to produce an ionospheric "hole." The process as well leaves the oxygen atom in an excited state, and the subsequent photon emission results in an optical signature that allows diagnostics of the size and magnitude of the density depletion.

## Structuring of the CRRES Program

The CRRES satellite was originally designed for a Shuttle launch, but the Challenger accident in 1986 forced a major restructuring of the program. With no immediate Shuttle launch opportunity, the decision was made to launch CRRES on an Atlas-Centaur. Originally, the CRRES mission was to have been conducted in two phases. The low-Earth-orbit (LEO) phase immediately following launch would have conducted a series of experiments in the ionosphere from a 358-km circular orbit. Following this phase, a transstage motor was to have placed CRRES in the final elliptical geosynchronous transfer orbit (GTO) for the Department of Defense (DOD) missions and high-altitude chemical releases. The Atlas-Centaur did not have the payload weight capability to allow this mission, and the end result was that CRRES was launched directly to the GTO orbit. Of greater significance to the chemical-release mission, it was necessary to delete one-half of the original chemical canisters, a reduction from 48–24.

The task of the chemical-release investigator working group was to restructure the chemical-release program so that the CRRES satellite could accommodate as much of the original science program as possible. Those experiments which could not be accommodated with releases from CRRES were considered for other vehicles. The criteria for choosing were straightforward: Those experiments which required a chemical release at high velocity or at high altitude had to be done from the CRRES satellite. There was no other choice. Those which were designed for relatively low altitudes in the ionosphere (200–500 km) and did not require high velocity were reassigned to sounding rockets.

The chemical-release science program that resulted from this restructuring exercise featured three major campaigns of releases from the CRRES and two campaigns of sounding rocket launches. The timing and location of the CRRES campaigns was determined to a large degree by the characteristics of the orbit, particularly the rates of precession of the local times of apogee and perigee, and of the argument of perigee, the latter determining the latitude of perigee.

The first CRRES campaign, conducted in September 1990 was designed to investigate the critical velocity mechanism. This theory, first proposed by Alfven,[7] states that under certain conditions a neutral gas moving at high speed through a magnetized plasma will, through the action of collective plasma processes, become ionized to an extent greater than that predicted by the two-particle collision and charge-exchange cross sections. The critical velocity required is the velocity such that the kinetic energy of the neutral atom ex-

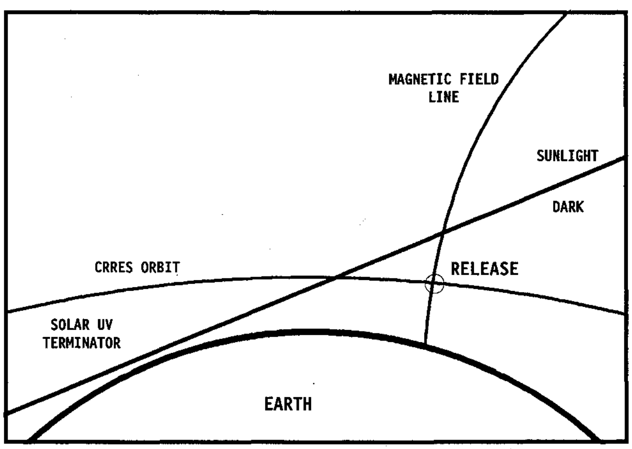


**Fig. 1 Geometry of a critical-velocity experiment.**

ceeds the energy required for ionization. This criterion is met for the elements barium, calcium, and strontium for releases near perigee with the satellite velocity of 9.5 km/s relative to the ionosphere co-rotating with the Earth. Figure 1 shows schematically how this experiment was conducted. The release was required to be in darkness, for the presence of photoionization would have invalidated the results. Yet in order to see any ions created, they had to move upward along magnetic field lines into sunlight where they could be identified by their characteristic resonance emissions. The mirror force of the converging magnetic field provided the upward force, and this is the same force that causes energetic particles to bounce back and forth along magnetic field lines to form the Van Allen radiation belts. The experiments required the dusk terminator, and the magnetic field geometry coupled with the orbit characteristics placing the perigee near the dusk terminator at southerly latitudes required that these experiments be conducted over the South Pacific. Two aircraft based in American Samoa were used to make the observations. These aircraft, used for this and for other campaigns, featured optical-quality glass windows and gyroscopically stabilized tracking mirrors for maintaining a stable image in the presence of aircraft motions.

The high-altitude release campaign featured a series of releases to investigate the reaction of the magnetosphere to injections of artificial ion clouds. These releases were required to be near local midnight over the western hemisphere. A series of small (1.5 kg) barium releases was designed to study coupling between plasma injections and the magnetosphere-ionosphere system over altitudes ranging from 6000–30,000 km, or a range of magnetic field strength ranging from 5000–100 nT. Releases of large amounts of lithium (0.9 kg) and barium (10.8 kg) at high altitudes in the region of the auroral particle reservoir had the objective of attempting to modify the local natural particle populations and to cause stimulated particle precipitation into the upper atmosphere thus creating "artificial aurorae." The conjugate point, or the point where the magnetic field line from CRRES traced to the upper atmosphere level of 100 km, was required at the time of the release to be over northeastern Canada in the vicinity of Hudson Bay, so that the region would be accessible to aircraft optical observatories based in northern Michigan. Furthermore, the conjugate regions had to be accessible to the incoherent scatter radar at Millstone Hill, Massachusetts. This radar was able to measure ionospheric densities, temperatures, and electric fields over a wide area and thus give a large-scale view of the geophysical conditions.

The final campaign from the CRRES satellite will be (at the time of this writing) conducted in the Caribbean with observatories both near the releases and at the opposite end of the magnetic field line in South America. These experiments have several objectives, but may be divided into two primary areas. The first is the study of the momentum and energy coupling between fast-moving ion clouds and the ambient ionosphere. Initially the ion clouds have the satellite velocity of near 9.5 km/s, but it is known from past experiments that the ion clouds slow down by loss of energy and momentum to the ionosphere. CRRES will undertake detailed studies of these processes, with a view to understanding the details of the coupling process and as well the effects upon the ionosphere from this input of energy. The injection of ions at orbital velocity means that some portion of them will have sufficient energy to overcome the gravitational force and travel upward along the magnetic field line by means of the magnetic mirror force. These ions are expected to travel to the conjugate point of the magnetic field line in South America and they will be visible owing to their resonance emissions. This will be a powerful diagnostic tool for studying the configuration of electric and magnetic fields in the magnetosphere. The ions will essentially "paint" the field line, and their motions will be reconstructed by triangulation of multipoint optical measurements. This experiment requires summer in the northern hemisphere so that the southern hemisphere will be sufficiently dark for observations 15–40 min after the release, which represents the travel time for the barium ions from the release point to the conjugate point.

## Orbit Determinations

The experiments detailed previously shared one crucial requirements. All required very precise prediction of the CRRES orbit in order to select the proper instant for the chemical release. The critical velocity releases required canister ignition shortly after passing the terminator from sunlight into darkness. The high-altitude releases required precise pointing of high-resolution (0.1 deg field-of-view) ground-based optics. The Caribbean releases required releases shortly after the canisters crossed the terminator into sunlight.

The United States Air Force Consolidated Space Test Center (CSTC) and The Aerospace Corporation provided orbit determination and predicted Keplerian elements for future times near the expected release time. The CSTC and Aerospace orbit predictors which included high-order harmonics of the gravitational potential, lunar and solar perturbations, and drag models supplied the best possible predictions to the science investigators in the field. The investigators had available less-accurate orbit predictors running on portable computers, but these programs would include calculations unique to the science investigation such as the distance along the magnetic field line to the terminator, the terminator position relative to the magnetic field geometry, and the location of the point in the ionosphere that connected along the magnetic field to the CRRES at high altitude. Essentially, the computing task for release timing determination was split into two parts, with the large mainframe complex programs providing predicted Keplerian elements at the time near the release. These elements in turn were input to the field programs that were not then required to perform accurate orbit predictions.

In this process, it was important to track the sets of predicted Keplerian elements to check the stability of the process. The predicted time and location of perigee was a particularly sensitive indicator. It was found that as the date of predicted epoch approached, the only Keplerian element that changed significantly was the mean anomaly. The predicted orbit did not change, only the time the satellite reached a particular point. This point is illustrated in Fig. 2, showing orbit prediction data from the September 1990 critical-velocity releases. Predicted elements were generated each day for the perigee passage on September 10 (day 253) near 0606 UTC, the predicted point of a critical-velocity release. Here is plotted the predicted perigee time in seconds of 0606 UTC as a function of the day of the orbit determination and perigee prediction. This illustrates the convergence of the prediction process, for the predicted perigee time changed by less than 1 s for the last 24 h prior to the actual event. The rather large excursion between

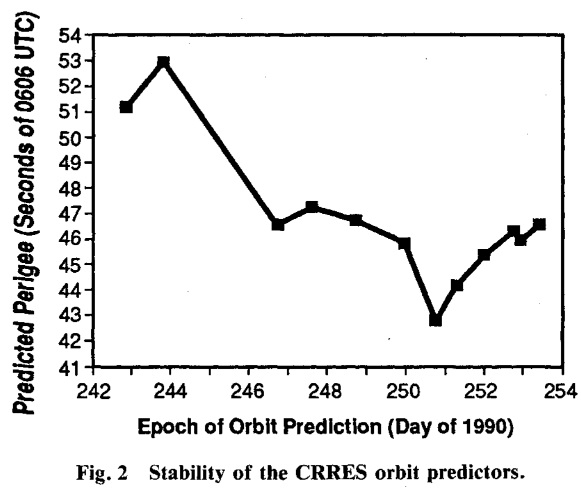


**Fig. 2 Stability of the CRRES orbit predictors.**

**Table 1 Chronology, type, and location of CRRES releases**

| Release | Type | Date | Time | Latitude | Longitude | Altitude |
|---|---|---|---|---|---|---|
| G-13 | 5.4 kg Ba<br>3.8 kg Sr | 09/10/90 | 06:10:25 | 17.5 S | 198.9 E | 517 |
| G-14 | 5.4 kg Ba<br>1.9 kg Ca | 09/14/90 | 08:47:10 | 18.1 S | 161.6 W | 593 |
| G-02 | 1.5 kg BA | 01/13/91 | 02:17:03 | 16.9 N | 103.1 W | 6180 |
| G-07 | 0.9 kg Li<br>0.6 kg Eu | 01/13/91 | 07:05:00 | 8.0 N | 86.7 W | 33403 |
| G-03 | 1.5 kg Ba | 01/15/91 | 04:11:00 | 14.9 N | 71.5 W | 25863 |
| G-04 | 1.5 kg Ba | 01/16/91 | 06:25:00 | 9.6 N | 82.3 W | 33479 |
| G-05 | 0.9 kg Li<br>0.6 kg Eu | 01/18/91 | 05:20:00 | 6.6 N | 62.8 W | 33337 |
| G-10 | 10.8 kg Ba | 01/20/91 | 05:30:00 | 8.9 N | 75.6 W | 33179 |
| G-06 | 0.9 kg Li<br>0.6 kg Eu | 02/12/91 | 04:15:00 | 4.9 N | 76.1 W | 32249 |
| G-08 | 10.8 kg Ba | 02/17/91 | 03:30:00 | 0.4 N | 58.1 W | 33553 |
| G-01 | 1.5 kg Ba | 07/13/91 | 08:35:25 | 17.8 N | 62.9 W | 495 |
| G-09 | 10.8 kg Ba | 07/19/91 | 08:37:07 | 17.4 N | 62.8 W | 441 |
| G-11a | 1.5 kg Ba | 07/22/91 | 08:38:24 | 16.8 N | 60.3 W | 411 |
| G-11b | 1.5 kg Ba | 07/25/91 | 08:37:11 | 17.3 N | 69.5 W | 478 |

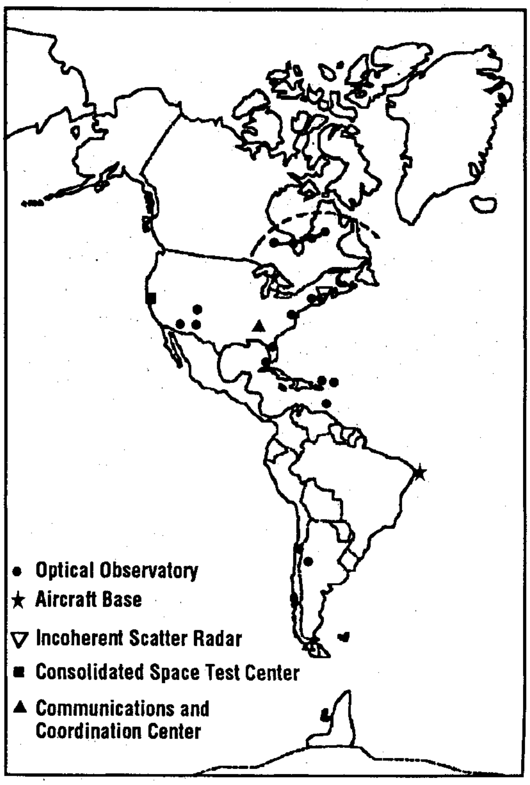


**Fig. 3 Map showing locations of the high-altitude campaign observatories, aircraft bases, and ionospheric radar.**

days 250 and 252 was the result of the precession maneuvers required to keep the satellite spin axis pointed toward the Sun. These maneuvers had a net thrust, and produced an orbital perturbation large enough to seriously affect an experiment if performed too close to the experiment time. A mission rule therefore sets a minimum time between precession maneuvers and release events.

## Observing Stations and CRRES In-Situ Data

Reference has been made to the various observing stations employed in the CRRES chemical-release program. The campaigns have used three aircraft in various combinations, the ALTAIR, Millstone Hill, and Arecibo incoherent scatter radars, up to 12 simultaneous optical ground sites, and vhf portable coherent scatter radars. These latter instruments measure ionospheric irregularities at 3-m and 6-m scale lengths.

Figure 3 is a western hemisphere map showing the locations of the ground-observing sites for the high-altitude campaign. The sites were grouped into western U.S., northeastern U.S., Florida and Caribbean, and South America. This gave both east-west and north-south baselines, important for determining motions of ions both parallel and perpendicular to the magnetic field. A typical conjugate point track is shown over the southern end of Hudson Bay (solid line) and the limit of Millstone Hill radar coverage is shown as a dashed portion of a circle.

No less important to the chemical-release science were the in-situ observations provided by instruments on the CRRES spacecraft. The combining of the DOD and NASA missions on a single spacecraft led to an invaluable synergism. The plasma wave instrument, electric field instrument, LASSII, and the lower-energy plasma detector instruments provided data that not only complemented the chemical-release investigations, but in many cases these data monitored the state of the magnetosphere and measured parameters that were a precondition for conducting a release. These instruments are detailed in individual contributions elsewhere in this issue.

## Summary of Releases and Preliminary Results

Table 1 gives the date, time, location, and type of each chemical release conducted from the CRRES satellite as of the date of this writing. The July 1991 Caribbean releases are included in the table, but at this point it is premature to discuss scientific results. In June 1991, the CRRES orbit was adjusted by raising apogee to place it in a near 3-day repeater, such that the location of perigee was over the Caribbean every 3 days with a slight westward drift of 0.67 deg/day. This slight variation was to compensate for the change of the position of the solar terminator with calendar date.

## Scientific Accomplishments

Advances in scientific understanding resulting from the CRRES experiments require the synthesis of large pools of data collected by many diverse diagnostic instruments. This process will by necessity continue for a considerable period of time, and the preliminary results are very encouraging.

The critical-velocity experiments showed that ionization of all three elements barium, calcium, and strontium did occur with a mixture of ionization mechanisms.[8] The critical-velocity process operated but only for the first few seconds following the neutral cloud injection. This was deduced by comparing the total ionization rate at the beginning of the release which exceeded the later rates of ionization from charge exchange and collisions. As the releases were done below the terminator, photoionization made no contribution. These data are consistent with a recent theoretical simulation of the process[9] which showed that the conditions for operation of the process were quite restrictive in terms of the ratio of the neutral cloud density to the ambient ion density. The remainder of the ionization observed could be accounted for by charge exchange and collisional ionization.

The series of small barium releases at varying altitudes (see above) showed vastly different behavior. In the lowest-altitude release (G-2) at 6180-km altitude, the ion cloud velocity was quickly braked by the close coupling to the ionosphere. The G-3 release at 25,863-km altitude showed a time constant for braking consistent with the velocity of hydromagnetic waves, about 500 km/s, traveling from the release point to the ionosphere. These releases therefore have yielded valuable data on the coupling between the ionosphere and the magnetosphere.

The large high-altitude barium releases produced significant modifications to the ambient particle and field environment for a brief period. The magnetic field measured at the satellite was reduced to zero,[10] and significant changes in the distributions of high-energy electrons were observed.[11] Observations of aurorae from the aircraft observatories suggest that intensifications of activity occurred following the releases, but exact causal mechanisms are still under study to determine if an exact cause-and-effect relationship can be ascribed.[12]

## Acknowledgments

A listing of persons who have contributed in a substantial way to making CRRES a success would require doubling the length of this paper. From the inception of CRRES, the program and project offices at NASA Headquarters, Marshall Space Flight Center, USAF Space Test Program, Air Force Geophysics Laboratory, and The Aerospace Corporation have put forth tireless effort. Relations with Ball Space Systems Division, the CRRES prime contractor, have been very rewarding and their personnel have always shown great interest in the scientific missions of CRRES. In the operational phase, the personnel at the USAF Consolidated Space Test Center (CSTC) have always "turned to" and given that extra bit of effort when needed. The contributions of the aircraft from the 4950th Test Wing at Wright-Patterson AFB, The Aeromet Corporation, and the Argentine National Space Commission were essential to the program. And lastly, a special thanks to the CRRES principal investigators and co-investigators for their (mostly) unfailing good humor in the course of bringing this CRRES science mission to reality.

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