THE ADVANCED COMPOSITION EXPLORER

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Abstract. The Advanced Composition Explorer was launched August 25, 1997 carrying six high-resolution spectrometers that measure the elemental, isotopic, and ionic charge-state composition of nuclei from H to Ni ($1 \leq Z \leq 28$) from solar wind energies (~1 keV nucl^{-1}) to galactic cosmic-ray energies (~500 MeV nucl^{-1}). Data from these instruments is being used to measure and compare the elemental and isotopic composition of the solar corona, the nearby interstellar medium, and the Galaxy, and to study particle acceleration processes that occur in a wide range of environments. ACE also carries three instruments that provide the heliospheric context for ion composition studies by monitoring the state of the interplanetary medium. From its orbit about the Sun–Earth libration point ~1.5 million km sunward of Earth, ACE also provides real-time solar wind measurements to NOAA for use in forecasting space weather. This paper provides an introduction to the ACE mission, including overviews of the scientific goals and objectives, the instrument payload, and the spacecraft and ground systems.

1. Introduction

Particle acceleration is ubiquitous in solar system and astrophysical plasmas. As a result, interplanetary space is filled with diverse populations of energetic nuclei that have been accelerated in the solar wind, by solar flares and coronal shocks at the Sun, in interplanetary space, and in the Galaxy. These accelerated particle populations, illustrated schematically in Figure 1, provide samples of matter originating in other regions of the solar system and Galaxy which cannot be reached for *in situ* measurements. Advances in space instrumentation have made it possible to determine not only the elemental, but also the isotopic and ionic charge-state composition of these samples of matter with much greater precision than was previously achievable. As a result, it is now possible to undertake comparative studies of the origin and evolution of these distinctly different samples of matter, as well as studies of acceleration processes occurring in distinctly different plasma environments.

Because these various components of solar, interplanetary, local interstellar, and galactic cosmic-ray particles are observed over a wide range of energies and intensities, as illustrated in Figure 2, comparative studies of these components are beyond the dynamic range of a single instrument. Rather, these studies require

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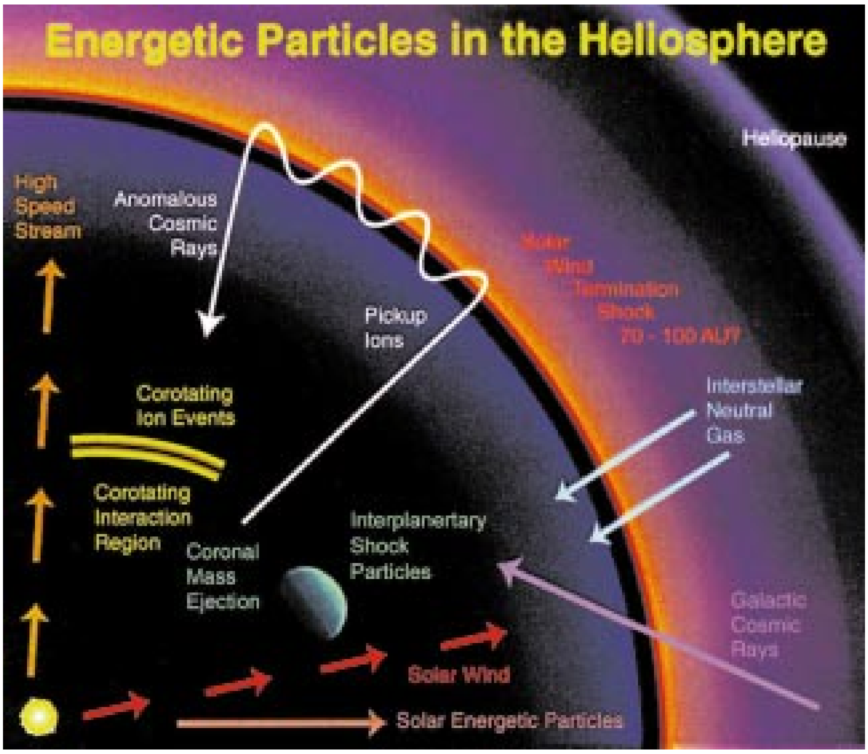

Figure 1. Schematic illustration of some of the various energetic particle populations that can be observed in the heliosphere.

a coordinated approach with a suite of instruments designed to obtain definitive measurements over as broad an energy range as possible.

In response to these opportunities, and recognizing these requirements, the Advanced Composition Explorer (ACE) was proposed in 1986 as part of the Explorer Concept Study Program. ACE is designed to make coordinated measurements of the elemental and isotopic composition of accelerated nuclei from H to Zn ($1 \leq Z \leq 30$) spanning six decades in energy per nucleon, from solar wind to galactic cosmic-ray energies, with sensitivity and with charge and mass resolution much better than heretofore possible. Following a Phase-A definition study, ACE was selected for development in 1989, and began construction in 1994. On August 25, 1997, ACE was successfully launched from Cape Canaveral Air Station by a Delta II rocket. The August 1997 launch was originally scheduled back in 1993.

The ACE observatory, a spinning spacecraft (5 rpm), will orbit around the Sun-Earth L1 libration point at 240 R_E sunward of the Earth. The spin axis of the cylindrically-shaped spacecraft points generally towards the Sun, with 156 kg of science instrumentation mounted both on the flat, Sun-facing side, and on the side of the cylinder. A high-gain antenna for data communications is mounted on the

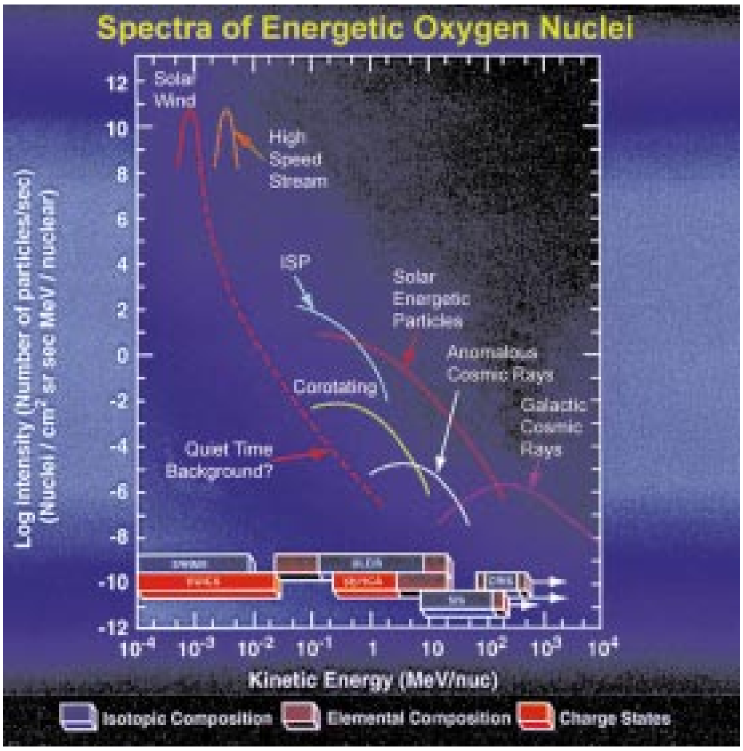

Figure 2. Typical energy spectra of energetic oxygen nuclei resulting from the various particle populations illustrated in Figure 1. The solid curves represent ‘steady state’ components that vary slowly over the solar cycle, while the dashed curves are for ‘transient’ phenomena. The energy ranges of the various ACE instruments are indicated for resolution of isotopes, elements only, and ionic charge states. Other species generally have spectra that are similarly shaped when plotted as a function of energy/nucleon.

back side pointing towards the Earth. The spacecraft will operate in the vicinity of the L1 point with >90% duty cycle for 2 to 5 years studying solar wind and solar energetic particles, particles energized by interplanetary shocks, partially ionized particles from the local interstellar medium (pickup ions and anomalous cosmic rays), and galactic cosmic rays. Sensors on ACE are designed to measure the properties of ions from solar wind energies of 100 eV up to several hundred MeV galactic cosmic rays (GCR), determining the mass and charge of incident particles during both solar quiet and solar active periods.

ACE has nine science instruments that are identified below. The various articles in this volume discuss the contributions each will make to meeting ACE’s scientific objectives. ACE will make possible simultaneous measurements over a very broad energy range, with large-area, high-resolution instruments, each optimized for a specific energy range. In addition, ACE will provide real time *in situ* monitoring of the solar wind that will allow NOAA to make timely forecasts of impending space weather.

The ACE mission development was managed by the Goddard Space Flight Center (GSFC) Explorer Projects Office of the Flight Projects Directorate. The spacecraft was developed by the John's Hopkins University Applied Physics Laboratory (JHU/APL). Instrument development was the responsibility of the California Institute of Technology (Caltech) under contract to NASA. The development of the ACE payload, spacecraft, and ground system was managed under a strict cost cap and schedule constraint, both of which were satisfied. Following integration of the instruments onto the spacecraft at APL, the observatory was taken to the GSFC for final testing and checkout and then shipped to the Kennedy Space Center for launch.

In addition to describing the scientific goals for ACE, this paper outlines the capabilities of the scientific payload, describes the mission operations plan, and discusses the unique aspects of the spacecraft and its supporting ground test and operating equipment. It is meant as a brief overview of the more detailed papers in this special edition of *Space Science Reviews*.

2. Scientific Goals

The prime objective of ACE is to determine and compare the elemental and isotopic composition of several distinct samples of matter, including the solar corona, the interplanetary medium, the local interstellar medium, and galactic matter. Some of the processes undergone by this material as it flows to 1 AU are illustrated in Figure 3, along with the populations of energetic nuclei that result.

Matter from the Sun will be studied directly by measuring the composition of the solar wind, of coronal mass ejections (CMEs; large plasma clouds ejected by the Sun), and of solar energetic particles (SEPs) accelerated in impulsive solar flares and by coronal and interplanetary shocks initiated by CMEs. Matter from the local interstellar medium enters the solar system as interstellar neutral particles that are subsequently ionized, picked up by the solar wind to become solar-wind 'pickup ions' and then accelerated to cosmic-ray energies at the solar wind termination shock. Both the pickup ions and the accelerated nuclei (known as 'anomalous cosmic rays' or ACRs) provide a sample of matter from the local interstellar medium (LISM). Galactic cosmic rays (GCRs) provide a sample of matter from more distant regions of the Galaxy that is believed to be accelerated by supernova shock waves. Each of these samples of matter has undergone a distinctly different history: the pickup ions and anomalous cosmic rays sample the present-day interstellar medium; galactic cosmic rays provide a sample of matter from the Galaxy that is thought to have been accelerated $\approx 10^7$ years ago; and matter in the Sun represents a still older sample of interstellar matter that has been stored in the Sun for the last 4.6 billion years.

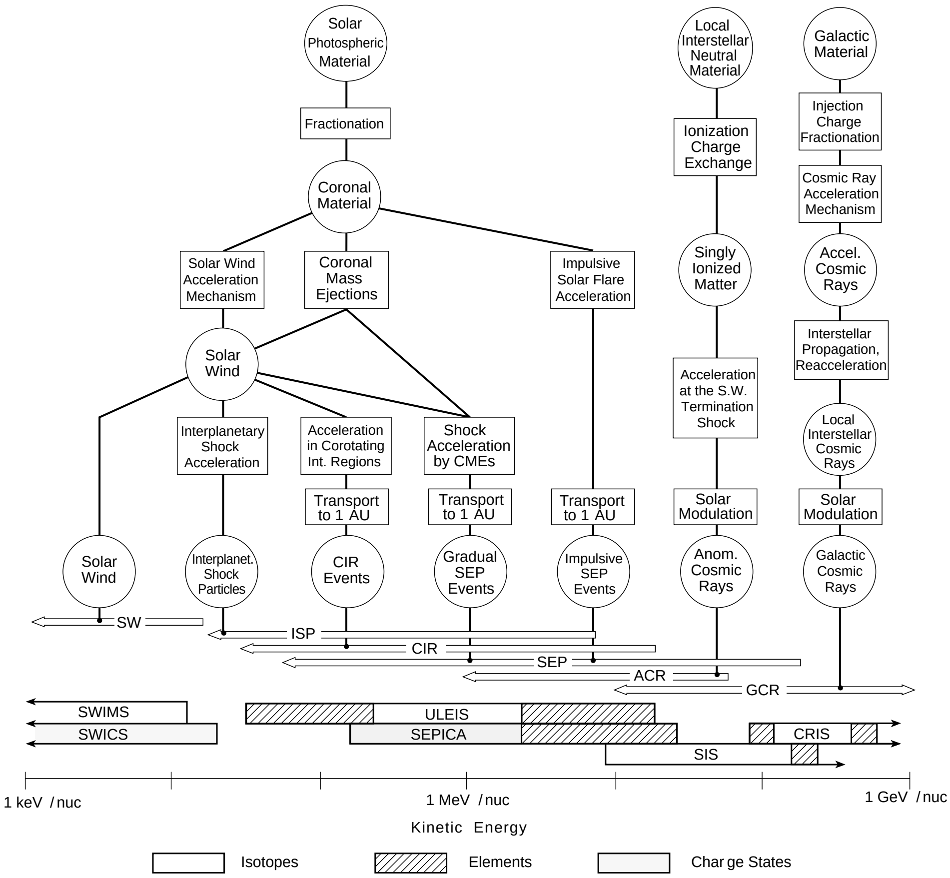

Figure 3. Diagram showing how energetic particles provide a flow of material to 1 AU from the solar photosphere, the neutral interstellar medium, and galactic cosmic-ray sources. Circles represent particle populations, rectangles represent fractionation, acceleration, and/or transport processes. Also indicated are the energy ranges over which the ACE instruments can measure the elemental, isotopic, and ionic charge-state composition of these particle populations.

The comparison of these samples of matter will be used to study the origin and subsequent evolution of both solar system and galactic material by isolating the effects of fundamental processes that include nucleosynthesis, charged and neutral-particle separation, bulk plasma acceleration, and the acceleration of suprathermal and high-energy particles. Specifically, these observations would allow the investigation of a wide range of fundamental problems in the following four major areas:

(1) The elemental and isotopic composition of matter. A major objective is the accurate and comprehensive determination of the elemental and isotopic composition of the various samples of 'source material' from which nuclei are accelerated. These observations will be used to:

– Generate a set of solar isotopic abundances based on direct sampling of solar material.

– Determine the coronal elemental and isotopic composition with greatly improved accuracy.

– Establish the pattern of isotopic differences between galactic cosmic-ray and solar system matter.

– Measure the elemental and isotopic abundances of interstellar and interplanetary ‘pickup ions’.

– Determine the isotopic composition of the ‘anomalous cosmic-ray component’, which represents a sample of the local interstellar medium.

(2) Origin of the elements and subsequent evolutionary processing. Isotopic ‘anomalies’ in meterorites indicate that the solar system was not homogeneous when formed. Similarly, the Galaxy is neither uniform in space nor constant in time due to continuous stellar nucleosynthesis. ACE measurements will be used to:

– Search for differences between the isotopic composition of solar and meteoritic material.

– Determine the contributions of solar wind and solar energetic particles to lunar and meteoritic material, and to planetary atmospheres and magnetospheres.

– Determine the dominant nucleosynthetic processes that contribute to cosmic-ray source material.

– Determine whether cosmic rays are a sample of freshly synthesized material (e.g., from supernovae) or of the contemporary interstellar medium.

– Search for isotopic patterns in solar and Galactic material as a test of galactic evolution models.

(3) Formation of the solar corona and acceleration of the solar wind. Solar energetic particle, solar wind, and spectroscopic observations show that the elemental composition of the corona is differentiated from that of the photosphere, although the processes by which this occurs, and by which the solar wind is subsequently accelerated, are poorly understood. The detailed composition and charge-state data provided by ACE will be used to:

– Isolate the dominant coronal formation processes by comparing a broad range of coronal and photospheric abundances.

– Study plasma conditions at the source of solar wind and solar energetic particles by measuring and comparing the charge states of these two populations.

– Study solar wind acceleration processes and any charge or mass-dependent fractionation in various types of solar wind flows.

(4) Particle acceleration and transport in nature. Particle acceleration is ubiquitious in nature and understanding its nature is one of the fundamental problems

of space plasma astrophysics. The unique data set obtained by ACE measurements will be used to:

– Make direct measurements of charge and/or mass-dependent fractionation during solar energetic particle and interplanetary acceleration events.

– Constrain solar flare, coronal shock, and interplanetary shock acceleration models with charge, mass, and spectral data spanning up to five decades in energy.

– Test theoretical models for ^{3}He-rich flares and solar γ-ray events.

In January of 1997, a three-day workshop was held at Caltech to review the ACE scientific goals, and to identify and assess progress that has been made by other on-going missions such as Voyager, *Ulysses*, SAMPEX, and Wind. A number of the invited papers from this workshop are included here, along with papers that describe the capabilities of the individual ACE experiments and the ACE mission. These invited review papers provide an excellent introduction to the scientific context in which ACE will begin its investigations.

During the period since ACE was first selected for flight, Voyager-1 and Pioneer-10 both moved to beyond 65 AU in the outer heliosphere, and *Ulysses* completed its first two passes over the solar poles. This armada of spacecraft has provided us with our first three-dimensional view of energetic particles and plasma in the large-scale heliosphere and they have revealed a variety of new heliospheric phenomena. For example, the SWOOPS and SWICS instruments on *Ulysses* (the forerunners of those on ACE) have demonstrated that there are distinct differences between fast- and slow-speed solar wind that provide important clues to their origin in the corona, how they may have been fractionated, and how these components were accelerated (e.g., Fisk et al., 1998). ACE will build on these studies by adding simultaneous measurements of isotopic mass to the elemental and ionic charge state measurements made on *Ulysses*.

Pioneer-10 first discovered that extensive particle acceleration occurs when high-speed solar wind streams overtake slow-speed streams to form co-rotating interaction regions (CIRs). *Ulysses* has found that there are a number of mysteries that arise in our understanding of these events when the third dimension of the heliosphere is explored. ACE will be able to track interplanetary acceleration events continuously over more than four decades in energy per nucleon.

Although the Sun has been remarkably quiet at energies $>$ 10 MeV over the past few years of solar minimum (1993–1996), new instrumentation on the Wind spacecraft (Lin, 1998) has demonstrated that the Sun is never really quiet at lower energies. While there are very few large solar particle events near solar minimum, there continue to be small ‘impulsive’ solar events that are rich in ^{3}He, electrons, and heavy elements. An important goal of ACE will be to try to understand the energy-release and particle-acceleration mechanisms in these impulsive events (Miller, 1998), as well as those in larger ‘gradual’ events that are apparently caused by shocks associated with coronal mass ejections. ACE will be ideally suited for these studies because it can measure elemental, isotopic, and ionic charge states from solar wind energies to several MeV nucl^{-1}, and because the greatly improved collecting power of its instruments can provide the statistical accuracy required to study a wide range of species in these events.

The elemental composition of particles in gradual SEP events is observed to be similar to that of the corona. A primary goal of the SEP studies (as well as solar wind studies on ACE) will be to determine the elemental and isotopic composition of the solar corona, and, ultimately, the solar photosphere, by direct sampling of solar material. These studies will complement spectroscopic studies and composition measurements of other solar system bodies such as meteorites and comets, which form the backbone of our understanding of the origin and evolution of solar system material.

Over the past decade there has been significant progress in understanding the sequence of events by which interstellar neutral atoms become solar wind pickup ions, some fraction of which are then accelerated to become anomalous cosmic rays. *Ulysses* has measured directly neutral interstellar He and the composition of solar wind pickup ions that result when the neutral interstellar gas is ionized (Gloeckler and Geiss, 1998). In addition, SAMPEX has shown that while most ACRs are singly-charged as expected, there are also multiply-charged ACRs that dominate at higher energies (> 20 MeV nucl^{-1}) and there is now considerable indirect evidence that the bulk of the acceleration of ACRs occurs at the solar wind termination shock (see Jokipii, 1998). ACE will make improved measurements of the elemental and isotopic composition of both pickup ions and ACRs in an effort to relate these to the composition of the local interstellar medium (see Frisch, 1998). It now appears that there are also other sources of solar wind pickup ions, including interplanetary and perhaps interstellar dust (Gloeckler and Geiss, 1998).

Galactic cosmic-rays are believed to result from shock acceleration processes on yet a larger scale, in this case powered by supernova shocks. While there appears to be a consensus that supernova shocks provide the necessary energy, there remains considerable debate on the origin of the accelerated material. In a recent model (Meyer et al., 1998; Ellison et al., 1998) all but the volatile elements in cosmic rays result from the sputtering products of dust grains that have themselves been accelerated to energies approaching 1 MeV nucl^{-1} by supernova shocks. This model helps explain the observed cosmic-ray elemental composition but requires an additional source to explain the overabundance of ^{22}Ne in cosmic rays. ACE will test this and other models with detailed measurements of the elemental and isotopic composition of cosmic-ray source material (Webber, 1998), building on recent progress by *Ulysses* (Simpson, 1998). A second objective of these studies is accurate measurements of various radioactive clocks that can measure cosmic-ray time scales for nucleosynthesis, acceleration, and transport (Ptuskin and Soutoul, 1998).

3. Mission Requirements and Description

In keeping with the ‘Better, Faster, Cheaper’ philosophy of modern day NASA, the ACE mission was developed in a non-traditional, low-cost manner in which the Principal Investigator and his team at Caltech had responsibility for the development of the instrument suite with minimal NASA oversight. With the Project Management, Spacecraft, and Instrument teams all keeping in close contact, it was Caltech’s responsibility to ensure that the science payload was delivered within cost and on time. If any instrument was to have gotten into serious development trouble, a series of agreed-to descope options was available, including the possibility of leaving an instrument off the spacecraft, since the scientific goals of ACE are broad enough that no single instrument was deemed critical to its mission success. This philosophy permitted the instruments to be developed under a somewhat lower level of quality assurance requirements, and helped reduce instrument costs. In the end, no instruments required significant descoping, and this approach led to the successful development of all nine instruments.

The focus of ACE studies will depend on the phases of the solar cycle which ACE will be able to observe. The mission was launched in August, 1997, near the minimum of solar activity. The high fluxes of galactic cosmic rays and the presence of the ACR component make this the ideal time to study particles from more distant sources as well as solar wind from the quiet Sun. In the years following launch, solar activity will increase and solar energetic particles can be studied. While the instrument and spacecraft design requirements were for a 2-year mission, ACE has enough hydrazine and proportional counter gas to last more than 5 years. During this time, ACE will be able to study phenomena important at all phases of the solar cycle.

In order to provide continuous measurements of the solar wind, low-energy solar and interplanetary particles, and cosmic rays, ACE must be stationed well outside of the Earth’s magnetosphere. The modified halo orbit about the Earth–Sun interior libration point, L1 (see Figure 4) meets this requirement. This orbit is similar to that originally attained by the ISEE-3 mission in 1978.

4. Instrumentation

To address the objectives described in Section 2 requires coordinated, high-precision measurements of the elemental, isotopic, and ionic charge-state composition of energetic nuclei over a broad energy range, with time resolution adequate to investigate the dynamical processes affecting the composition. Table I summarizes properties of the nine instruments that will provide these measurements on ACE. They are as follows:

CRIS is a Cosmic-Ray Isotope Spectrometer designed to measure the elemental and isotopic composition of galactic cosmic rays over the energy range from

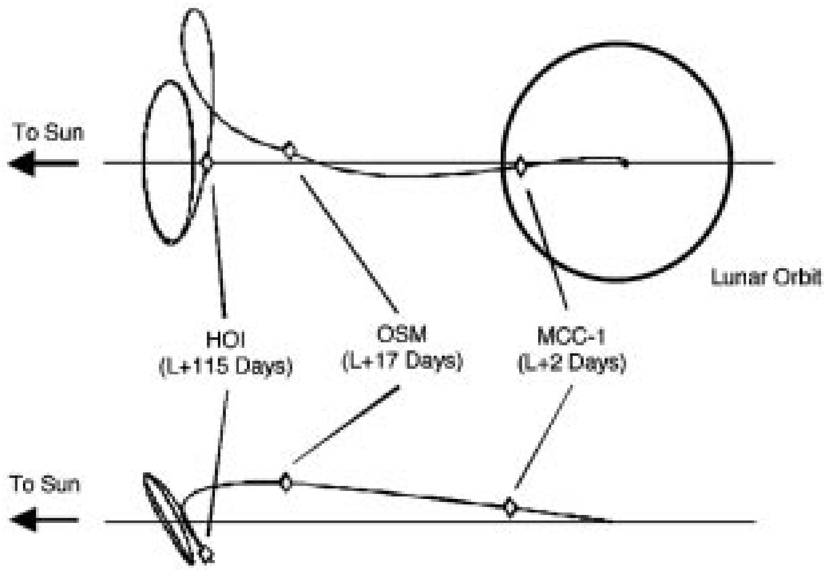

Figure 4. Schematic of the ACE transfer trajectory out to the Earth–Sun interior libration point (L1), and subsequent halo orbit about L1. The actual modified halo orbit is a complicated lissajous-like path about L1 with a major axis of about 150,000 km and a minor axis of about 75,000 km. The diamonds signify a mid-course correction (MCC-1) orbit-shaping maneuver (OSM), and halo-orbit intersection (HOI) at the indicated intervals following launch (L).

approximately 100 to 600 MeV nucl^{-1} (see Stone et al., 1998a). CRIS uses a scintillating optical-fiber trajectory system viewed by two CCD cameras to track the trajectories of energetic nuclei that stop in four co-aligned stacks of large-area silicon detectors.

SIS is a Solar Isotope Spectrometer that will measure the elemental and isotopic composition of energetic nuclei from $\approx$ 10 to $\approx$ 100 MeV nucl^{-1} using two identical stacks of silicon detectors (see Stone et al., 1998b). Particle trajectories are tracked with position-sensitive silicon-strip detectors instrumented with custom low-power VLSI circuitry. The energy range covered by SIS includes transient fluxes of energetic nuclei accelerated in large solar particle events, as well as anomalous cosmic rays and low-energy galactic cosmic rays.

ULEIS is an Ultra Low Energy Isotope Spectrometer that measures the mass and kinetic energy of nuclei from He to Ni by combining precise measurements of their time-of-flight over a 50 cm flight path and a measurement of their total kinetic energy (see Mason et al., 1998). The energy range covered by ULEIS includes solar energetic particles, particles accelerated by interplanetary shocks, and low-energy anomalous cosmic rays.

SEPICA is a Solar Energetic Particle Ionic Charge Analyzer designed to measure the charge state, kinetic energy, and the nuclear charge of energetic ions from $\approx$ 0.2 to $\approx$ 3 MeV nucl^{-1} (see Möbius et al., 1998). Particles entering SEPICA's

TABLE I
ACE instrumentation

Sensor	Full name	Measured species	Measured quantities	Typical energy (MeV nucl^{-1})	Technique
CRIS	Cosmic-ray isotope spectrometer	$2 \leq Z \leq 30$	Z, M, E	≈ 200	$\mathrm{d}E/\mathrm{d}x$ – E
SIS	Solar isotope spectrometer	$2 \leq Z \leq 30$	Z, M, E	≈ 20	$\mathrm{d}E/\mathrm{d}x$ – E
ULEIS	Ultra low energy isotope spectrometer	$2 \leq Z \leq 28$	M, E	≈ 1	TOF – E
SEPICA	Solar energetic particle ionic charge analyzer	$2 \leq Z \leq 28$	Q, Z, E	≈ 1	E/Q $\mathrm{d}E/\mathrm{d}x$ – E
EPAM	Electron, proton and alpha monitor	H, He, e^-	Z, M, E	≈ 0.3	$\mathrm{d}E/\mathrm{d}x$ – E
SWIMS	Solar wind ion mass spectrometer	$2 \leq Z \leq 30$	$M, E/Q$	≈ 0.001	E/Q TOF – E
SWICS	Solar wind ion composition spectrometer	$2 \leq Z \leq 30$	Z, E	≈ 0.001	E/Q TOF – E
SWEPAM	Solar wind electron, proton and alpha monitor	H, He, e^-	E/Q dist.	≈ 0.001	E/Q
MAG	Magnetometer	B	B_x, B_y, B_z		Triaxial fluxgate

E = energy, M = mass, Z = nuclear charge, Q = ionic charge, B = magnetic field.

multi-slit collimator are electrostatically deflected between six sets of electrode plates carrrying high voltages up to 30 kV. Measurements of SEP charge states will provide information on the temperature of the source plasma, as well as possible charge-to-mass dependent acceleration processes. SEPICA will also make direct measurements of ACR charge states.

EPAM is an Electron, Proton, and Alpha Monitor designed to characterize the dynamic behavior of electrons and ions with ≈ 0.03 to ≈ 5 MeV that are accelerated by impulsive solar flares and by interplanetary shocks associated with CMEs and CIRs (see Gold et al., 1998). EPAM was developed from the flight spare of the Hi-SCALE instrument flown on *Ulysses*, and it includes two telescope assemblies with five separate aperatures.

SWIMS is a Solar Wind Ion Mass Spectrometer with excellent mass resolution ($M/\mathrm{d}M > 100$) that will measure solar wind isotopic composition in all solar wind conditions (see Gloeckler et al., 1998). The design is based on that of similar instruments on Wind and SOHO. Mass resolution is achieved by measuring the time-of-flight of nuclei through a specially designed electrostatic potential in which their flight-time is proportional to the square root of the mass-to-charge ratio.

SWICS is a Solar Wind Ion Composition Spectrometer that determines the elemental and ionic charge-state composition of all major solar wind ions from H to Fe using a combination of electrostatic deflection, post-acceleration, time-of-flight, and energy measurements (see Gloeckler et al., 1998). SWICS is the flight spare of an essentially identical instrument flown on *Ulysses*, where it has been particularly useful for measuring the characteristics of solar wind pickup ions.

SWEPAM is a Solar Wind Electron, Proton, and Alpha Monitor that is designed to measure the three-dimensional characteristics of solar wind and suprathermal electrons from ≈ 1 to 900 eV and ions from 0.26 to 35 keV (see McComas et al., 1998). It consists of modified versions of the spare solar wind electron and ion sensors from the *Ulysses* mission.

MAG is a twin triaxial flux-gate Magnetometer that will measure the dynamic behavior of the vector magnetic field, including measurements of interplanetary shocks, waves, and other features that govern the acceleration and transport of energetic particles (see Smith et al., 1998). MAG is a flight spare of the magnetometer instrument flown on Wind.

The instrumentation on ACE was designed to provide several key capabilities. First, it was necessary that the ensemble of the instruments provide coordinated measurements of charge and mass of the elements from H to Ni ($1 \leq Z \leq 28$) over a broad range in energy in order to isolate contributions from the various particle populations, and to relate the observed composition patterns back to the appropriate acceleration process and sample of source material. The energy/nucleon range over which the ACE sensors can measure elemental and isotopic composition is shown in Figure 5.

To resolve adjacent isotopes of heavy nuclei typically requires mass resolution of < 0.3 amu. CRIS, SIS, ULEIS, and SWIMS will each use approaches that have been developed and proven in earlier missions such as ISEE-3, *Ulysses*, SAMPEX, and Wind. In ACE these approaches have been optimized to achieve excellent mass resolution over a broad dynamic range with greatly improved collecting power.

Measurements of the ionization states of energetic nuclei are important for determining mass/charge fractionation during acceleration and transport and for characterizing the temperature of the source plasma. SWICS will measure the charge states of solar wind and pickup ions from ~ 0.1 to ~ 60 keV charge^{-1}, while SEPICA can measure ionic charge states of particles accelerated on the Sun and in interplanetary space between ~ 0.2 and ~ 3 MeV nucl^{-1}.

To ensure statistically significant measurements of rare isotopes, it is necessary to have large geometry factors and to process and transmit measurements of a sufficient number of individual particles under conditions ranging from solar quiet time to the most intense solar particle events. The collecting power of CRIS, SIS, ULEIS, and SEPICA typically improves on that of earlier isotope and charge state instruments by factors of ≈ 10 to 100. This improvement leads to a corresponding

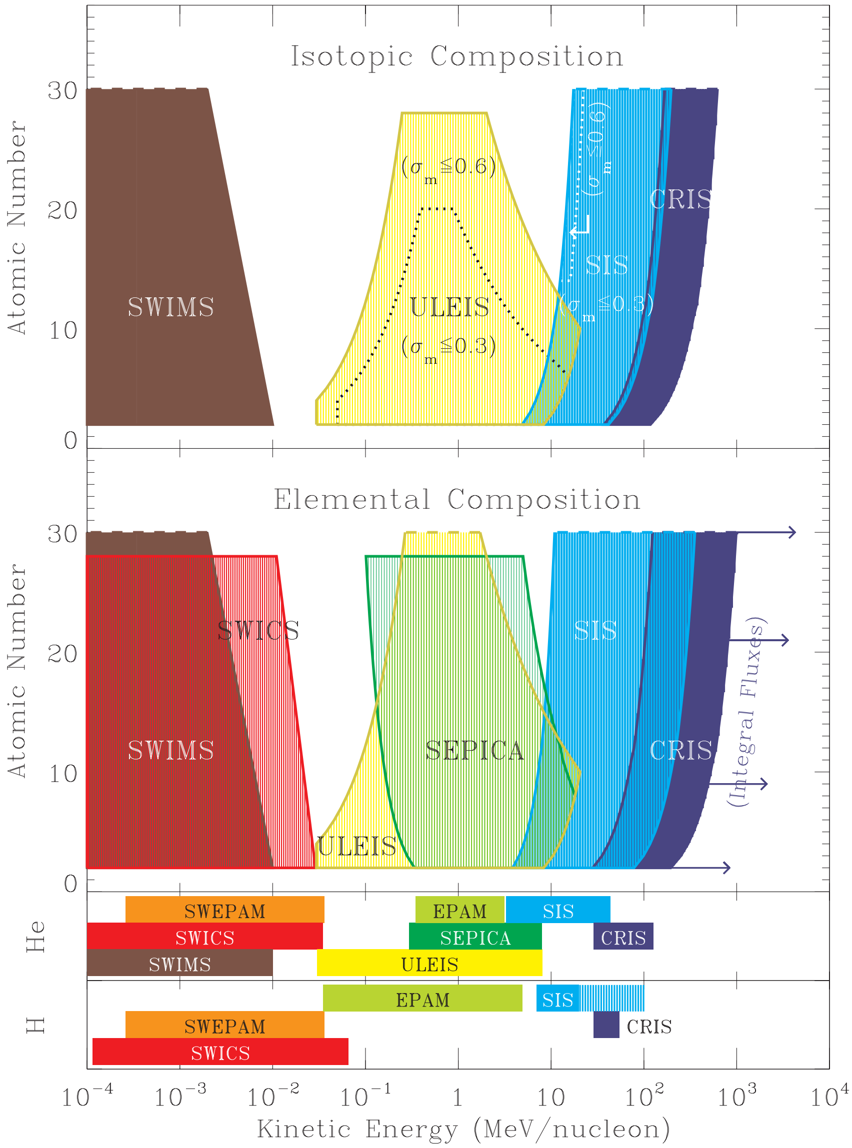

Figure 5. A plot of the energy-per-nucleon range over which the ACE sensors will measure the elemental and isotopic composition of nuclei from He to Zn ($Z = 2$ to 30), with exploratory measurements extending to $Z = 40$ in some cases. In the top panel, boundaries for an rms mass resolution of ≤ 0.3 amu and ≤ 0.6 amu are indicated (note that many studies, e.g., $^{22}Ne/^{20}Ne$, do not require resolution of adjacent isotopes). A 400 km s^{-1} solar wind velocity corresponds to $\sim 0.8 \times 10^{-3}$ MeV $nucl^{-1}$. Note that the SWICS and SEPICA sensors will also measure ionic charge-state composition over the energy and element ranges indicated above.

gain in the time resolution with which temporal variations in composition can be measured.

High quality measurements of solar wind protons, alpha particles, and electrons, and of the interplanetary magnetic field are essential for determining solar wind characteristics that relate solar plasma at 1 AU to its origin in the corona, and energetic particle electron, proton, and alpha particle fluxes are important to characterize transient particle populations in the interplanetary medium. Measurements from SWEPAM, EPAM, and MAG will characterize the interplanetary environment for studies of heavier nuclei.

From its position 1.5×10^6 km in front of Earth, ACE is in excellent position to measure the interplanetary magnetic field and the properties of the solar wind before it impacts the Earth's magnetosphere. The Real Time Solar Wind (RTSW) monitoring system on ACE will sample and transmit interplanetary data in real time that can provide as much as one hour's warning of geomagnetic storms that result from the interaction of the interplanetary and terrestrial magnetic fields (see Zwickl et al., 1998). Such storms are known to affect ground-based power and communications systems, as well as satellite operations, and can lead to sudden increases in the trapped particle populations in the Earth's magnetosphere. The National Oceanic and Atmospheric Administration (NOAA) has responsibility for forecasting space weather for a wide range of government and commercial customers.

Realizing the advantages of the ACE location at L1, NASA and NOAA completed an interagency agreement in 1994 which specifies that (1) ACE will broadcast real-time measurements of solar wind parameters continuously, so that (2) NOAA can track and interpret these data on the ground for use in forecasting space weather. The data to be provided include solar wind velocity, density, and temperature measurements from SWEPAM, magnetic field vectors from MAG, and energetic particle fluxes from EPAM and SIS. The typical time resolution is 1 min. These data will be broadcast continuously at 434 bps during 21 hours of the day and tracked by a worldwide grid of ground stations provided by the Air Force, Japan and England. During the 3 hours a day that ACE is in contact with the Deep Space Network (DSN), the data will be transmitted to NOAA by ground link. The RTSW system is described in more detail in the article by Zwickl et al. (1998).

The final flight element of the science payload was delivered to Goddard 35 months after the start of Phase C/D implementation. Following integration onto the spacecraft and testing of the complete observatory, the science payload was declared flight ready.

5. The ACE Spacecraft

The ACE spacecraft was designed and built by JHU/APL so as to meet mission requirements in as simple and cost-efficient a manner as possible (see Chiu et al., 1998). The team began with a design based upon the Active Magnetospheric Parti-

TABLE II
ACE resources summary

Name	Mass (kg)	Peak power (W)	Nominal power (W)	Data rate (bps)	Field of view
CRIS	31.6	16.6	12.2	464	$120° \times 120°$
SIS	22.4	22.4	17.5	1992	104° conical
ULEIS	21.9	15.1	14.6	1000	$24° \times 20°$
SEPICA	38.3	17.5	16.5	608	$61.5° \times 17.5°$
EPAM	12.8	4.2	3.8	168	60° conical ($\times$5)
SWICS	6.0	6.1	5.0	504	$82° \times 10°$
SWIMS	8.6	7.8	6.8	512	$62° \times 62°$
SWEPAM	6.8	6.1	5.8	1000	$160° \times 30°$ (E) $80° \times 10°$ (I)
MAG	4.1	2.4	1.8	304	
S^3DPU	3.9	3.5	2.5		
Spacecraft	586	248	177	392	
Other/heaters	8.6	34.3	21.5		
Total	751	384	285	6944	

Note: The spacecraft mass includes 195 kg of hydrazine.

cle Tracer Explorer (AMPTE) and other programs. Subsystem heritage was derived from as many as six different flight projects.

The spacecraft is designed to operate in a spin-stabilized mode at 5 rpm. The main body of the spacecraft is a cylinder 2 m in diameter and 1.9 m in length. The ends are inscribed octagonal aluminum honeycomb decks joined by eight flat side panels. With the solar panels and magnetometer booms extended, ACE has a wingspan of approximately 8.3 m (see Figure 6).

To meet observing requirements and to simplify access to the instruments and spacecraft subsystems, all components except the propulsion system are mounted on the external surfaces of the body. Six of the instruments are mounted on the top (sunward facing) deck, and two are mounted on the sides. The instruments are positioned so as to keep their many fields-of-view clear of one another, while retaining a reasonable balance of weight around the spacecraft. Figure 6 shows an exploded view of the spacecraft in which the location of each instrument is indicated. The fields-of-view and the resources required by the instruments are given in Table II. The magnetometer has its two sensors mounted on booms that extend from two of the four solar panels to reduce the magnetic effects from the spacecraft.

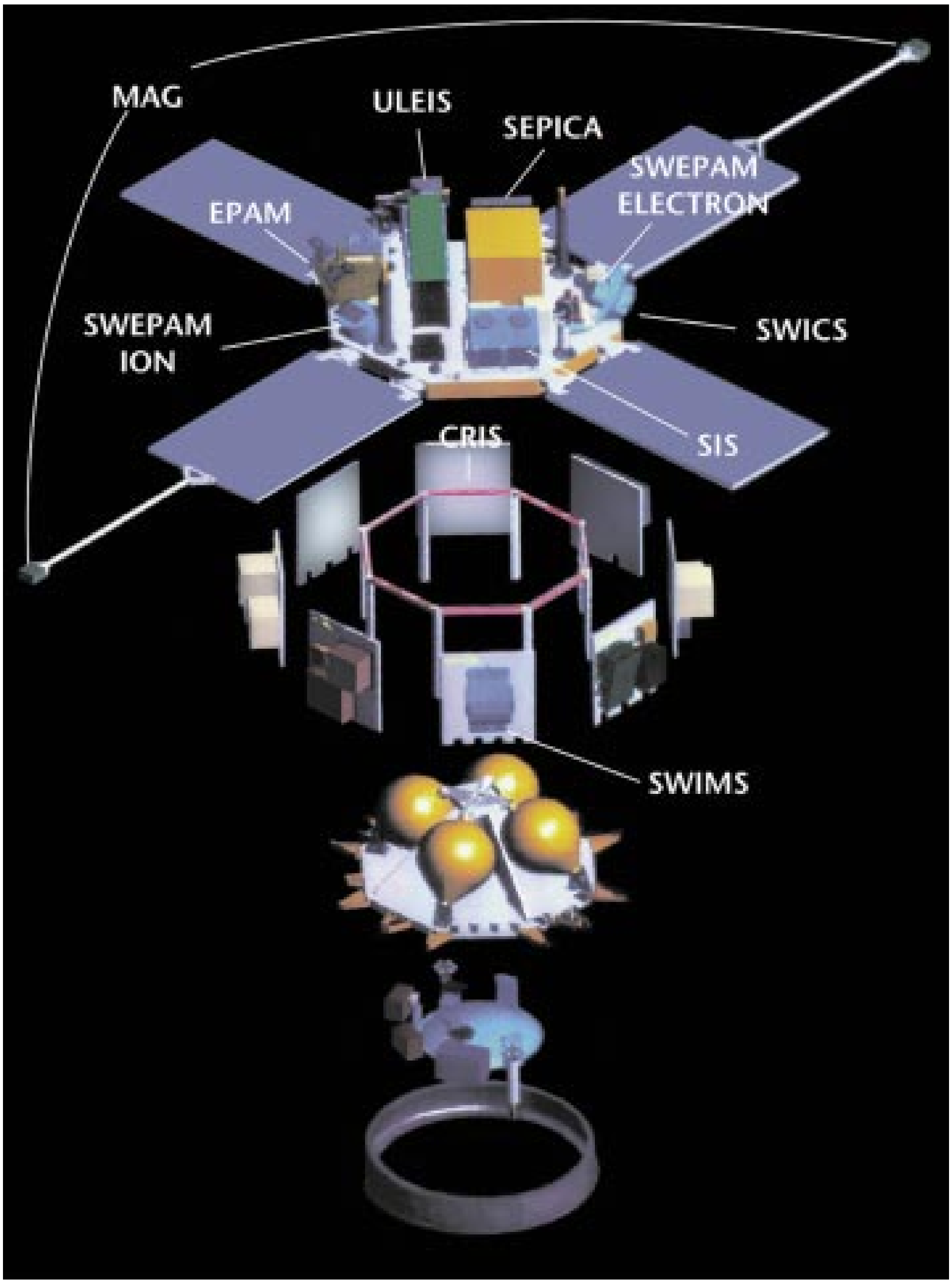

Figure 6. Exploded view of the ACE spacecraft structure. The Z axis is the spin axis of the observatory and will be aligned within 20 deg of the Earth–Sun line. Six of the scientific instruments are on the $+Z$ (sunward) deck, two are on side panels, and the ninth is mounted on the Y-axis booms. Only the four propellent tanks of the propulsion subsystem are mounted in the spacecraft interior. The $-Z$ (earthward) deck has the fixed high-gain antenna for communication.

A propulsion subsystem was needed to correct launch vehicle dispersion errors, make trajectory corrections, inject the spacecraft into its orbit about L1, adjust the orbit, adjust spin axis pointing, and maintain a 5 rpm spin rate. The subsystem is a monopropellant hydrazine blowdown design that uses nitrogen gas as a pressurant. There are four axial thrusters for velocity control along the spin axis and six radial thrusters for spin plane velocity and spin rate control. ACE launched with 195 kg of hydrazine onboard, more than sufficient for a 5-year mission.

Since ACE is spin stabilized with the spin axis always within 20° of the Sun, the power subsystem is quite simple. An array of four silicon solar panels unfold after launch. With quartz covers to provide radiation shielding, the power system should provide in excess of 440 W after 5 years in space, with an observatory peak power load of approximately 425 W.

Maintaining the proper thermal environment for the ACE instruments was complicated by the fact that several of the instruments were inherited from *Ulysses*, which had a different orientation and thermal environment. The thermal design accommodates the planned 4° to 20° angle between the spin-axis and the direction of the Sun with adequate margin.

The main constraint for the attitude control system is to keep the Earth within the radiation pattern of the high-gain antenna. Attitude is determined with a star scanner and redundant Sun sensors. The gyroscopic stability of the spinning ACE spacecraft, two fluid-filled ring nutation dampers, and the ten thrusters of the propulsion subsystem provide for the attitude control.

Because orbital manuevers are required approximately every five days to reorient the spin axis, and several of the instruments use the spinning of the spacecraft to scan the sky, nutation is a concern. The induced nutation of the spacecraft is limited by segmenting the manuevers into many short thruster pulses. This restricts the maximum nutation to less than 1 deg, and the remaining nutation is corrected using on-the-ground analysis and post-processing of the data.

Communications are through the Deep Space Network (DSN) operated by the Jet Propulsion Laboratory (JPL). The DSN receives ACE data and transmits spacecraft commands with the appropriate link margins. The RF system operates at S-band. On board ACE there are two identical and independent communications subsystems, a single high-gain, dual-polarized, parabolic reflector antenna and two sets of broad-beam antennas. In addition to receiving commands and transmitting data, the RF subsystem has the capability of supporting two-way ranging from DSN sites.

The ACE mission is designed to communicate with the DSN for one pass per day of approximately 3 hours duration. It is also designed to be able to miss one pass without the loss of any data. Data storage is accomplished via two solid state recorders, developed for both the ACE and NEAR missions, which have a capacity >1 Gb and are one of the ‘state of the art’ components on ACE.

The spacecraft was built and ready for instrument integration 30 months after permission to proceed was received from NASA. JHU/APL met all of its required milestones and delivered the spacecraft at a cost much less than that allocated at the start of the contract.

6. The ACE Common Ground-Support Systems

The ACE mission, driven in part by requirements to keep total mission costs within a given cap, took some common sense (but uncommon in practice) steps in the development of mission ground support and testing equipment. The three major subsystems, the ACE Science Center (ASC), the Mission Operations Center (MOC), and the spacecraft Integration and Testing (I&T) ground-support system, have many common functions and were able to share software, databases and testing procedures. Smaller programs, especially balloon and sounding rocket experiments, have often taken advantage of this synergy to design, test, and operate one system, but for larger missions, including Explorers, this has not done. For ACE, the ground-support and testing teams used a common system architecture that supports all three ground elements.

Historically, larger satellites have been developed and operated by separate teams. In 1993, when the ACE Project sought innovative approaches to reduce its budget, it was realized that an important step would be to provide a basic backbone for a common ground system. It was also recognized that this approach required conquering political and financial barriers (until recently, budgets within NASA for operations were kept separate from project development funds).

In this common system architecture approach the three ground-support system elements each utilize the same computational platforms (i.e., HP 715's and HP 748's) and, to the extent possible, use a common set of software modules. To make this possible, the performance requirements for instrument checkout and data verification had to be understood far earlier than is usually the case and procedures had to be developed on a pace that matched the spacecraft development.

The ground-support equipment for the integration and test of the spacecraft and its instruments is known as the Integration and Test Operations Control Center (ITOCC). Spacecraft operations and level zero processing of payload data are performed in the mission operations center (MOC) at GSFC. The data is then transmitted to the ACE Science Center (ASC) at Caltech (see Garrard et al., 1998). The ASC is responsible for initial processing of the data and for making the data accessible to the co-investigators and guest investigators located at their home institutions. Instrument teams are located at ACE Science Analysis Remote Sites (ASARS) where they can review and analyse data and evaluate instrument performance and, as necessary, forward instrument commands to the ACE MOC for transmission to the satellite. In practice, three teams (including contractors) at JPL, GSFC and Caltech had to work together to make this common ground-support system plan work.

A trade study early in the mission development cycle led to the conclusion that Transportable Payload Operations Control Center (TPOCC), a Unix-based system which has been a foundation system for the past several years for most spacecraft control centers at the GSFC, could provide much of the needed functionality in the ITOCC, the MOC, and the ASC. A generic ACE TPOCC, including all functionality common to the three subsystems, was adapted from the X-ray Timing Explorer (XTE) version of TPOCC. Separate copies of the generic system were then augmented individually with unique capabilities needed in the three subsystems. Most of the MOC unique capabilities will eventually be transferred to the ASC, making it possible to extend the duration of the ACE mission by operating it at low cost from the ASC.

Functions of the MOC system being included in the ASC include mission planning and scheduling, and attitude determination. Special requirements for the ITOCC included in the generic system are for Ground Support Equipment (GSE) commanding and data collection, the counting of relay state changes, and spacecraft system and subsystem run time processing. The ASC will use essentially the same system as the MOC with the addition of the science data analysis software.

A single database was used for spacecraft development and testing and is now being used for spacecraft and instrument operations. Using the TPOCC System Test and Operations Language (TSTOL) for all procedures and displays allows the instrument teams to use common elements throughout all phases of instrument development, test, checkout and monitoring during spacecraft integration and testing, and flight operations. Developmental phase checkout procedures are the same as activation procedures during initial phases of the mission, and the instrument development teams have had the opportunity to ‘practice’ and debug the approaches to monitoring the health and status of their instruments.

Members of the Flight Operations Team (FOT) were included in the design and development from the early phases of the mission. This enabled a smooth transition between spacecraft design and ground operations and avoided the frequently encountered situation where ground operations can be made unnecessarily complicated by spacecraft design decisions. The concept of the Integrated Team approach working across spacecraft design, integration and test, and operations has worked successfully on smaller spacecraft, but this is the first time NASA has attempted this approach on a program of this magnitude. The approach worked very well and is recommended for future missions.

The combined approach has worked in spite of the different institutional responsibilities for mission operations and I&T. The development of TPOCC was contracted to Computer Sciences Corporation (CSC). This task also included development of the MOC-specific enhancements. JHU/APL let a separate contract to CSC for development of the ITOCC-specific enhancements. Many personnel at CSC worked on both the ITOCC and MOC contracts, providing common ground and approaches for both developments. This effort required close cooperation between all users and the developers.

Significant benefits have accrued from the multiple use of the generic system, saving NASA millions of dollars. Although the generic TPOCC task required more lines of code than needed for the MOC alone, it was substantially less than the lines of code required for the three separate systems. A similar savings in maintenance will be realized; enhancement or correction in one system will enhance or correct all three systems. The approach led to the deletion of the software training simulator for the FOT. Instead, the FOT received high fidelity training with the spacecraft at JHU/APL, thus reducing risk to mission operations. The one database utilized for all three systems eliminated time consuming, costly translations from one database to another while increasing the reliability of the operations database. Also, the content of the TSTOL procedures, developed for spacecraft I&T, is easily adapted for the ACE MOC and the ASC.

7. Conclusion

The ACE mission promises to return exciting new results on a broad range of topics related to two of the NASA science themes: the structure and evolution of the Universe, and the Sun–Earth Connection. The fixed cost imposed by NASA for the development of ACE has led to new management approaches for the development of the instrumentation and the integration and testing of the spacecraft. The final cost of developing ACE was significantly less than had been allocated by NASA, and considerable funding was returned to the Explorer Program for other future missions. The discipline and dedication of the large team from many institutions and companies in the US and Europe also enabled the spacecraft and its instruments to meet the challenging schedule. The common ground-support system architecture supported observatory integration and testing, and will support the flight operations and science analysis.

A major factor in the success of the ACE development was the close cooperation of all members of the various teams: the instrument teams, the contractors, the spacecraft development team at JHU/APL, and GSFC and Caltech. Working as an integrated team, the challenges of each subsystem were recognized, and the talented scientists, engineers, and system developers provided cost-effective system solutions. ACE has successfully reengineered the mission development processes, resulting in contained development costs for the ACE Project, and lower-cost and more reliable flight operations.

We look forward to an exciting mission that will pursue the scientific questions posed here and discussed in more detail in the other articles of this special edition of *Space Science Reviews*.

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