C.T. Russell
Editor

The STEREO Mission

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Cover illustration: STEREO performing stereoscopic observations.

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Foreword

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The Sun-Earth Connection is now an accepted fact. It has a significant impact on our daily lives, and its underpinnings are being pursued vigorously with missions such as the Solar TErrestrial RElations Observatory, commonly known as STEREO. This was not always so. It was not until the middle of the nineteenth century that Edward Sabine connected the 11-year geomagnetic cycle with Heinrich Schwabe's deduction of a like periodicity in the sunspot record. The clincher for many was Richard Carrington's sighting of a great white-light flare on the Sun, on September 1, 1859, followed by a great geomagnetic storm 18 hours later. But was the Sun-Earth Connection significant to terrestrial denizens? Perhaps in 1859 it was not, but a century later it became so. Beginning in the 1930's, as electrical power grids grew in size, power companies began to realize that they occasionally had power blackouts during periods of intense geomagnetic activity. This correlation did not appear to be sufficiently significant to bring to the attention of the public but during the International Geophysical Year (IGY), when geomagnetic activity was being scrutinized intensely, the occurrence of a large North American power blackout during a great magnetic storm was impossible to ignore. By this time it was also known that ionospheric storms could disrupt communications, and late in the IGY the first orbiting spacecraft were launched and the radiation belts were discovered. The Sun, the magnetosphere, solar wind, and coronal mass ejections became the topic of news articles of interest to the public as well as to the scientific community.

Space, or at least near-Earth space, was no longer a frontier, it became a terrestrial workplace. Astronauts occupied it. Communication satellites, weather satellites, and navigation satellites depended on it, but these space systems proved to be sensitive to solar variability. Further our power grids continued to prove to be fragile. We learned quickly what the Sun was doing but we learned only slowly why and how the Sun behaved that way. Early missions such as Skylab, Solwind and later SOHO showed us the tremendous ejections from the Sun. HELIOS, ISEE and Ulysses revealed the interior structure of these ejections once they

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left the vicinity of the Sun. Unfortunately, as valuable as these missions were they provided only either projections on the plane of the sky or single cuts through the structure. A stereoscopic view of the Sun was needed, as was a multipoint in situ measurement of the material ejected from the Sun. Thus was born the concept of the STEREO mission, twin spacecraft, separated at launch, that slowly drift further and further ahead and behind the Earth near 1 AU, both triangulating with an optical suite of instruments on solar disturbances, and sounding these same disturbances when they reach the STEREO spacecraft and their suites of in situ devices.

This collection of articles describes the STEREO mission, its spacecraft, instrument and operations. The paper by M.L. Kaiser and colleagues describes the history of the project and its objectives and the article by A. Driesman and colleagues the observatory itself. A unique feature of this space-weather mission is its beacon mode that transmits a low rate data stream comprised of both in situ samples and solar image snapshots to Earth continually to help geomagnetic forecasters. The operation of this system is described by D.A. Biesecker, D.F. Webb and O.C. St. Cyr. The largest investment of the scientific payload is in the Sun-earth Connection Coronal and Heliospheric Investigation (SECCHI) whose acronym invokes the memory of a pioneering solar scientist. This suite of optical instruments includes coronagraphs and heliospheric imagers that can follow disturbances from the Sun until they pass 1 AU. This article is followed by a series of papers covering the elements of the payload that measure the plasma, energetic particles and magnetic and electric fields at the spacecraft. In many senses the radio system too is a remote sensor with direction finding capability that follows the solar disturbances. The first nine of these papers are devoted to the IMPACT investigation, starting with a detailed overview by J.G. Luhmann et al. and followed by discussions of the boom by Ullrich et al., of the magnetometer by M.H. Acuña et al., of the solar wind electron analyzer by J.-A. Sauvaud et al., of the suprathermal electron detector by R.P. Lin et al., of the suprathermal ion detector by G.M. Mason et al., of the low-energy telescope by R.A. Mewaldt et al., of the solar electron and proton telescope by R. Müller-Mellin et al., and the high energy telescope by T.T. von Rosenvinge et al.

The solar wind ion instrument is separate from the IMPACT suite as is the plasma waves investigation. The former instrument named the Plasma and Suprathermal Ion Composition Investigation (PLASTIC) is described by A.B. Galvin et al. The radio and plasma waves investigation has been dubbed the STEREO/Waves or S/WAVES investigation. It is described in an overview article by J.L. Bougeret et al., followed by articles on the electric antennas by S.D. Bale et al. and the direction finding mode by B. Cecconi et al.

The collection of articles closes with topics that cross all discipline areas. The first of these articles by M.J. Aschwanden et al. describes the theory and modeling effort supporting the STEREO mission. The next by J. Eichstedt, W.T. Thompson and O.C. St. Cyr describes the operations and data archive and the last led by L.M. Peticolas describes the education and public outreach program.

The success of this volume is due to the efforts of many people. The editor is extremely grateful for the assistance he received in assembling this volume. First of all he is grateful to the authors themselves who responded well to the comments of the referees. He is also grateful to the many referees who assisted by spending their time improving the contents of this volume. These referees include J.-L. Bougeret, S.R. Cranmer, A. Cummings, A. Davis, W. Farrell, J. Gosling, E. Grayzeck, S. Gulkis, S.R. Habbal, D. Haggerty, R.C. Harten, T. Horbury, R. Howard, M.-B. Kallenrode, W.S. Kurth, P. Lamy, L.J. Lanzerotti, J.G. Luhmann, W. Magnes, G. Mason, J. McCarthy, L.A. McFadden, B. McKibben, R. Mewaldt, R. Mueller-Mellin, M. Neugebauer, D. Reames, B. Reinisch, H.O. Rucker, R. Schwenn, A.C. Stewart, J. Wise, T. Zurbuchen. The editor also wishes to thank Markus J. Aschwanden

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March 24, 2008

The STEREO Mission: An Introduction

M.L. Kaiser · T.A. Kucera · J.M. Davila · O.C. St. Cyr · M. Guhathakurta · E. Christian

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Abstract The twin STEREO spacecraft were launched on October 26, 2006, at 00:52 UT from Kennedy Space Center aboard a Delta 7925 launch vehicle. After a series of highly eccentric Earth orbits with apogees beyond the moon, each spacecraft used close flybys of the moon to escape into orbits about the Sun near 1 AU. Once in heliospheric orbit, one spacecraft trails Earth while the other leads. As viewed from the Sun, the two spacecraft separate at approximately 44 to 45 degrees per year. The purposes of the STEREO Mission are to understand the causes and mechanisms of coronal mass ejection (CME) initiation and to follow the propagation of CMEs through the inner heliosphere to Earth. Researchers will use STEREO measurements to study the mechanisms and sites of energetic particle acceleration and to develop three-dimensional (3-D) time-dependent models of the magnetic topology, temperature, density and velocity of the solar wind between the Sun and Earth. To accomplish these goals, each STEREO spacecraft is equipped with an almost identical set of optical, radio and in situ particles and fields instruments provided by U.S. and European investigators. The SECCHI suite of instruments includes two white light coronagraphs, an extreme ultraviolet imager and two heliospheric white light imagers which track CMEs out to 1 AU. The IMPACT suite of instruments measures in situ solar wind electrons, energetic electrons, protons and heavier ions. IMPACT also includes a magnetometer to measure the in situ magnetic field strength and direction. The PLASTIC instrument measures the composition of heavy ions in the ambient plasma as well as protons and alpha particles. The S/WAVES instrument uses radio waves to track the location of CME-driven shocks and the 3-D topology of open field lines along which flow particles produced by solar flares. Each of the four instrument packages produce a small real-time stream of selected data for purposes of predicting space weather events at Earth. NOAA forecasters at the Space Environment Center and others will use these data in their space weather forecasting and their resultant products will be widely used throughout the world. In addition to the four instrument teams,

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there is substantial participation by modeling and theory oriented teams. All STEREO data are freely available through individual Web sites at the four Principal Investigator institutions as well as at the STEREO Science Center located at NASA Goddard Space Flight Center.

Keywords CME · Solar · Three-dimensional

1 Preface: "Heliophysics: The New Science of the Sun–Solar System Connection"

These are the words from the recent strategic plan of the Heliophysics Division within NASA's Science Mission Directorate. An integral part of exploration, Heliophysics is the system science that unites all of the linked phenomena in regions of the cosmos influenced by magnetically variable stars like our Sun.

That same roadmap also describes the evolving Heliophysics Great Observatory composed of the present fleet of spacecraft which act as a distributed network, providing multipoint measurements of the components. The STEREO mission, depicted in Fig. 1, represents the most significant upgrade and expansion to the Great Observatory in the past decade. In fact, this mission represents more of a "revolutionary" addition than "evolutionary", as it will provide not only a rich package of upgraded sensors, it will travel to new vantage points.

The vastness of the inner solar system means we can obtain only sparse and infrequent measurements—at least as compared to other applied sciences like meteorology and

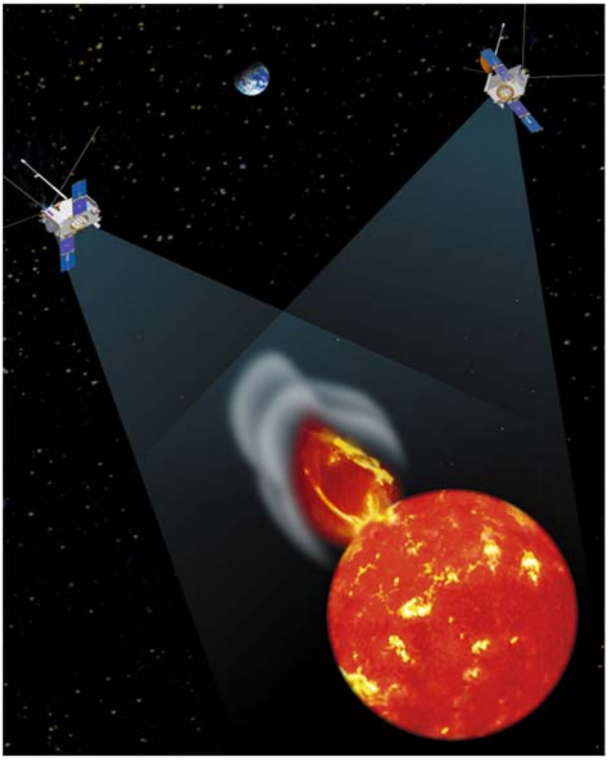

Fig. 1 An artist's conception of the STEREO mission. Two nearly identical spacecraft situated well off the Earth–Sun line, making simultaneous measurements of the Sun

oceanography. A long-term goal of Heliophysics is to emphasize understanding of the underlying physics of this complex, coupled dynamic system by extending measurements and predicting the system behavior as it affects Earth and other remote locations. STEREO will provide unique insight into the physics of coronal mass ejections (CMEs) and provide an ideal opportunity to improve and to test current physics-based models and their predictions in the inner solar system.

As you read the papers in this issue describing the technical details of this rich payload, try to envision the sailing ships of the past, on their voyages of exploration and discovery. The STEREO mission has the potential to be one of those memorable voyages, changing our scientific understanding of how our magnetically variable star affects Earth and all other bodies in our solar system.

2 Introduction

Over a period of two to three decades, solar physicists have come to realize that the extremely energetic solar storms known as coronal mass ejections (CMEs) are the form of solar activity most forcefully felt at Earth. CMEs impacting Earth's environment are the primary cause of major geomagnetic storms and they are associated with nearly all of the largest solar proton events. The growth in society's reliance on technology has led to an increased vulnerability to impacts from the space environment and, hence, to an importance in understanding the multifaceted influence of the Sun and CMEs on Earth. More recently, an initiative to return human and robotic explorers to the Moon and to extend a human presence to Mars has been undertaken, making protection of the space travelers from the harmful effects of radiation storms an important goal in "space weather" research and prediction. Unfortunately, to date we cannot predict reliably when a CME will occur or what its effects will be.

Many current and past space missions and ground-based observations have studied CME disturbances from their initial lift-off at the Sun and through their propagation in the region near the Sun, 10–15% of their way to Earth. Other spacecraft have measured the effects of CMEs in situ near Earth. However, there have not been missions to follow CMEs continuously from Sun to Earth. The evolution of CMEs in the vast space between Sun and Earth has been mostly predicted by empirical and theoretical models, and the estimating CME arrival times at Earth have been disappointing.

The report of the science definition team for the STEREO Mission (Rust et al. 1997) lists a number of fundamental questions about the physical causes of CME eruptions that remain to be answered, such as:

- Are CMEs driven primarily by magnetic or nonmagnetic forces?
- What is the geometry and magnetic topology of CMEs?
- What key coronal phenomena accompany CME onset?
- What initiates CMEs?
- What is the role of magnetic reconnection?
- What is the role of evolving surface features?

Since the corona is optically thin at most wavelengths, all previous single spacecraft observations have suffered from line-of-sight integration effects which cause ambiguities and confusion. None of these questions can be satisfactorily addressed with additional single vantage point observations of the type available prior to STEREO. However, with the range of view angles accessible to the STEREO telescopes, CMEs and coronal structures and even the underlying preeruption features can be reconstructed in three dimensions. Early in the mission, STEREO extreme ultraviolet observations of the underlying active regions will reveal the three-dimensional nature of coronal loops, including their exact cross-sectional shape and their interactions with each other, key to understanding the initiation of CMEs. These same STEREO extreme ultraviolet observations should resolve the three-dimensional nature of the enigmatic waves seen in extreme ultraviolet traveling across the "surface" of the Sun immediately following a CME lift-off. These waves appear not to be "blast waves", but they are intimately involved with CMEs. With the stereoscopic capabilities of STEREO and the rapid cadence of its extreme ultraviolet instrument, the exact relationship to CMEs and the trigger for these waves should be discovered.

The surface features underlying CMEs are best observed near disk center, whereas with prior single vantage point missions, CMEs themselves were best observed near the solar limb where plane-of-sky projection effects are minimal. When the STEREO spacecraft are far apart so that their plane of the sky encompasses Earth, they can detect CMEs that originate above surface locations that are at disk center (when viewed from Earth).

Compounding the problem of incomplete observations of CMEs, the CMEs that most affect Earth are also the least likely to be detected and measured by ground-based or Earth-orbiting coronagraphs because they are viewed only as an expanding "halo" around the Sun, inhibiting measurement of their speed, morphology and even exact direction toward the observer. Arrival times of significant space weather events at Earth have typically only been accurate to about ± 12 hours in the past. However, with the STEREO spacecraft measuring Earth-directed CMEs from well off the Earth–Sun line, a CME's speed and direction can be determined via triangulation and should greatly improve Earth impact prediction times. Furthermore, STEREO's complete observational coverage of CMEs from lift-off to arrival at 1 AU and beyond will allow a determination of the instantaneous distribution of matter in the inner heliosphere. This is currently not possible.

The principal mission objective for STEREO is to understand the origin and consequences of CMEs, the most energetic eruptions on the Sun and the cause of the most severe nonrecurrent geomagnetic storms at Earth. Specific science objectives are to:

- Understand the causes and mechanisms of CME initiation.
- Characterize the propagation of CMEs through the heliosphere.
- Discover the mechanisms and sites of solar energetic particle acceleration in the low corona and the interplanetary medium.
- Develop a three-dimensional, time-dependent model of the magnetic topology, temperature, density and velocity structure of the ambient solar wind.

These four rather generic science goals imply more specific measurements as shown in Table 1. These are the STEREO Level 1 science requirements. Minimum success for STEREO was defined as being able to make the measurements in the table with both spacecraft for a period of 150 days after achieving heliocentric orbit, followed by at least one of the spacecraft continuing to make the full suite of measurements for the remainder of the two year prime mission. The minimum success 150-day interval was reached on June 21, 2007. Full success of the mission requires the measurements to be made by both spacecraft for the entire two-year interval of the prime mission, again after reaching heliocentric orbit. Full success will be reached on January 23, 2009.

For each of the Level 1 science requirement measurements in Table 1, several combinations of instruments from the twin spacecraft contribute so that loss of any one instrument

Table 1 STEREO Level 1 science requirements

Scientific objective		Measurement requirement
Understand the causes and mechanisms of CME initiation	A	Determine CME initiation time to within 10 minutes
	B	Determine location of initiation to within five degrees of solar latitude and longitude
Characterize the propagation of CMEs through the heliosphere	C	Determine the evolution of CME mass distribution and the longitudinal extent to within five degrees as it propagates
	D	Determine the CME and MHD shock speeds to within 10% as it propagates
	E	Determine the direction of the CME and MHD shock propagation to within five degrees
Discover the mechanisms and site of energetic particle acceleration in the low corona and interplanetary medium	F	Develop distribution functions to an accuracy of 10% for electrons and/or ions with energies typical of solar energetic particle populations
	G	Locate regions of particle acceleration in the low corona to within 300,000 km in radius and in interplanetary space to within 20 degrees in longitude
Develop a 3-D time-dependent model of the magnetic topology, temperature, density and velocity of the ambient solar wind	H	Obtain a time series of the solar wind temperature to within 10% accuracy at two points separated in solar longitude
	I	Obtain a time series of solar wind density to within 10% accuracy at two points separated in solar longitude
	J	Obtain a time series of solar wind speed to within 10% accuracy at two points separated in solar longitude
	K	Measure global magnetic field topology near the ecliptic by determining the magnetic field direction to within 10 degrees

does not result in STEREO's inability to satisfy a science requirement. Also, the nominal two-year STEREO mission scientific goals do not depend on acquiring these measurements during any particular phase of the solar cycle because CMEs and other phenomena to be studied are common to all phases of the cycle. Although the CME rate varies from about 0.5 per day at solar minimum to several per day at solar maximum, assuming a CME rate consistent with the minimum of the solar magnetic activity cycle, we expect that STEREO will observe at least 60 CMEs in remote sensing instruments and at least 24 interplanetary events in situ. In fact, the SECCHI coronagraphs have already recorded $>$60 CMEs during the initial 150 days of the mission.

STEREO is managed by NASA's Goddard Space Flight Center (GSFC) in Greenbelt, MD. GSFC provided science instrument management, systems engineering, mission assurance and reliability during the design and build phase, as well as science and data analysis, data archiving and coordination of Education and Public Outreach (EPO) efforts after launch. The Johns Hopkins University Applied Physics Laboratory (JHU/APL) in Laurel, MD, was responsible for the design, construction, integration and testing of the spacecraft and conducts the mission operations of the observatories during the post-launch period.

3 History

The first appearance of a multi-spacecraft mission to observe the Sun within NASA strategic planning documents (Space Physics Missions Handbook and Space Physics Strategy-Implementation Study) was the appearance of the Global Solar Mission in 1991. These documents were the result of a planning session convened in Baltimore, MD, by Stan Shawhan to develop missions for the new Sun–Earth Connection division. The Global Solar Mission envisioned a large number of spacecraft to observe the Sun from around the ecliptic and with polar orbiting spacecraft.

On June 11, 1992, at the 23rd meeting of the Solar Physics Division (SPD) of the American Astronomical Society in Columbus, OH, an open evening town hall session was organized to discuss future solar physics mission concepts. At this session two mission concepts were presented for the first time, which eventually were united to become the STEREO mission.

The Solar Tomography Mission, presented by one of us (JMD), envisioned a set of two to four spacecraft in heliocentric orbit, providing simultaneous images of the corona. From these images, the three-dimensional structure of active regions, streamers, coronal holes and other solar features would be deduced. Subsequently, at the 24th meeting of the SPD in Stanford, CA, in July 1993, Davila presented a paper reporting the results of an informal mission feasibility study conducted at Goddard Space Flight Center, and preliminary results of tomographic reconstruction simulations, which were eventually published (Davila 1994a, 1994b).

In the same SPD session (23rd), Ernie Hildner of the NOAA Space Environment Laboratory (now the SEC-Space Environment Center) outlined a mission called Global Understanding of the Sun (GUS), which later evolved into Special Perspectives Investigations (SPINS; Pizzo 1994). In this concept, a coronagraph similar to SOHO/LASCO-C2 is placed in heliocentric orbit, at roughly 90 degrees from the Sun–Earth line to observe Earth-directed CMEs from the Sun. The 90-degree position was selected to provide the optimum visibility of a CME in the occulted field of view of the coronagraph. Studies of the SPINS concept were conducted at Ball Aerospace.

It was soon recognized that these missions had elements in common, and a workshop was organized at SEL in Boulder, CO, by Vic Pizzo and David Sime in November 1993 to discuss a possible mission that would combine the goals of the Tomography Mission and SPINS. Approximately 30 interested scientists attended the two-day workshop. On August 5–6, 1996, a second workshop was held to further refine the combined mission concept in preparation for the initial Sun–Earth Connection Roadmap. A name was chosen, the Solar Terrestrial Relations Observatory (STEREO), and a conceptual mission very similar to the current version of STEREO was agreed upon (Davila et al. 1996). The objectives were to understand the initiation and propagation of CMEs and their effect on the near-Earth environment. To accomplish these goals, it was agreed that the three-dimensional nature of the corona must be observed, i.e., multiple spacecraft were required. Subsequently, the NASA Headquarters selected STEREO as the second mission (after TIMED) in the newly formed Solar Terrestrial Probe (STP) mission line.

In 1996, a Science and Technology Definition Team (STDT) was formed with David Rust (APL) as the chair, and Joseph Davila (GSFC) as the Study Scientist. After several meetings, intermediate studies, and vigorous discussion among the committee members, the straw man payload was defined and instrument priorities were established. The report of the STDT formed the basis for the NASA Announcement of Opportunity soliciting instrument proposals in 1999. Additional mission architecture studies provided the technical information needed for the release of the STEREO mission AO (Watzin and Davila 1997; Rowley 1997; Galloway 1998).

A mission similar to STEREO, but much larger in scope was studied at JPL in 1982 (Schmidt and Bothmer 1995). Other multi-spacecraft missions to observe the Sun were proposed in Russia (Grigoryev 1993; Grigoryev et al. 1996; Chebotarev et al. 1997), in Europe (Schmidt et al. 1993), Canada (Timothy et al. 1996) and the United States (Liewer et al. 1998). Workshops provided the opportunity for the Heliophysics community to provide input into the ongoing studies (Bothmer and Foing 1996). Two missions were proposed in the Explorer proposal opportunity of 1995 that used a single spacecraft in heliocentric orbit combined with near-Earth observatories like SOHO to obtain multiple views of the solar corona, and multipoint measurements of the heliosphere (Brueckner et al. 1995; Davila et al. 1996). The NRL mission provided the acronym STEREO, though it represented a slightly different underlying title.

In this paper, we provide an introduction to the STEREO mission. Each of the areas described below receives in-depth treatment in the other papers in this issue. Some aspects of the history of the mission and some of the important trade-studies that define the final mission design will be described here.

4 The Science Investigations

The STEREO science payload consists of four measurement packages, each of which has several components totaling at least 18 individual sensors. Together, this suite of instruments will characterize the CME plasma from the solar corona to Earth's orbit. The instrument packages are described in detail in the other papers in this issue, but here we provide a brief introduction.

- Sun–Earth Connection Coronal and Heliospheric Investigation (SECCHI). SECCHI encompasses a suite of remote sensing instruments including two white-light coronagraphs, an extreme ultraviolet imager and two white-light heliospheric imagers all designed to study the three-dimensional evolution of CMEs from the Sun's surface through the corona and interplanetary medium to their eventual impact at Earth. Russell Howard of the Naval Research Laboratory of Washington, DC, leads this investigation. A comprehensive description of the SECCHI suite of instruments is given by Howard et al. (2007).
- In situ Measurements of PArticles and CME Transients (IMPACT) was designed, built and tested by an international team led by Janet Luhmann of the University of California, Berkeley. It measures the interplanetary magnetic field, thermal and suprathermal solar wind electrons, and energetic electrons and ions. IMPACT is a suite of seven instruments, three of which—the solar wind electron analyzer (SWEA), the suprathermal electron instrument (STE) and the magnetic field experiment (MAG)—are located on a six-meter deployable boom deployed anti-sunward. The remaining IMPACT instruments—the low-energy telescope (LET), the high-energy telescope (HET), the suprathermal ion telescope (SIT) and the solar electron and proton telescope (SEPT)—are all located on the main body of the spacecraft and are dedicated to measuring solar energetic particles (SEPs). The IMPACT suite is described in a series of papers in this issue. Luhmann et al. (2007) provides an overview. The boom suite of instruments are described by Sauvaud et al.

Table 2 STEREO instruments

Instrument	Acronym	Purpose
SECCHI	COR1	Coronagraph 1.4–4.0 solar radii
	COR2	Coronagraph 2–15 solar radii
	EUVI	Extreme ultraviolet imager
	HI	Heliospheric imager 12 → 215 solar radii
IMPACT	SWEA	Solar wind electrons to 3 keV
	STE	Suprathermal electrons 2–100 keV
	SEPT	Electrons 20–400 keV; protons 60–7,000 keV
	SIT	Composition He-Fe 300–2,000 keV/nucleon
	LET	Protons, He, heavy ions to 40 MeV/nuc
	HET	Protons, He to 100 MeV; electrons to 8 MeV
	MAG	Vector magnetic field to 65,536 nT
PLASTIC	SWS	Protons, alpha dist. functions to 100 keV
		Heavy ions to 100 keV
	WAP	Wide angle heavy ions to 100 keV
S/WAVES	HFR	Electric field 125 kHz–16 MHz
	LFR	Electric field 2.5–160 kHz
	FFR	Fixed frequency 32 or 34 MHz
	TDS	Time domain to 250 k sample/sec

(2007) (SWEA), Lin et al. (2007) (STE), Acuña et al. (2007) (MAG) and Ulrich et al. (2007) (the boom itself). Mewaldt et al. (2007) describe the LET instrument and the computer system that controls all the SEP instruments, known as SEP central. The HET instrument is described by Von Rosenvinge et al. (2007), the SIT by Mason et al. (2007) and the SEPT by Müller-Mellin et al. (2007)

- PLAsma and SupraThermal Ion Composition (PLASTIC), built by an international consortium led by Antoinette Galvin of the University of New Hampshire, provides in situ plasma characteristics of protons, alpha particles and heavy ions. It supplies key diagnostic measurements of the mass and charge state composition of heavy ions and characterizes the CME plasma from ambient coronal plasma. The PLASTIC instrument is described by Galvin et al. (2007).
- STEREO/WAVES (S/WAVES) was built by a team led by Jean-Louis Bougeret of the Observatoire de Paris. S/WAVES is an interplanetary radio burst tracker that observes the generation and evolution of traveling radio disturbances from the Sun to the orbit of Earth. As its primary sensors, S/WAVES uses three mutually orthogonal monopole antenna elements, each six meters in length. The three monopoles were deployed anti-sunward so that they remain out of the fields of view of Sun-facing instruments. The S/WAVES instrument is described by Bougeret et al. (2007) There are two companion papers describing the S/WAVES antennas (Bale et al. 2007) and the radio direction finding technique (Cecconi et al. 2007)

Table 2 gives more details about these instrument suites and Fig. 2 shows the "behind" spacecraft with the instrument locations indicated. The spacecraft themselves are relatively small, with a combined mass of about 1,280 kg, including maneuvering fuel (see Dreisman et al. 2007).

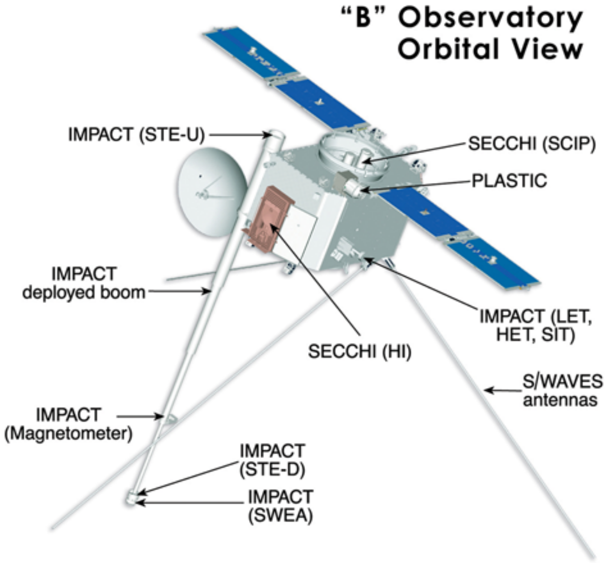

Fig. 2 An artist's conception of the Behind spacecraft with the locations of the instruments shown. The SECCHI instruments point at the Sun and the IMPACT boom and S/WAVES antennas are on the opposite end. There are very slight differences between the Ahead and Behind spacecraft, mainly due to the fact that the spacecraft fly upside down relative to one another so that their high-gain antenna is always on the Earth-facing side of the spacecraft. This means that some of the particle instruments which need to point into the solar wind magnetic field direction have different placements on the two spacecraft

In addition to these four instrument teams, there are several groups devoted to global modeling (see Aschwanden et al. 2007) with the goal of understanding the connection between the solar activity observed near the sun by SECCHI and S/WAVES and the in situ measurements taken by IMPACT, PLASTIC and S/WAVES when the disturbances finally reach the STEREO spacecraft. Modeling includes the coronal plasma and the solar wind and its expansion outwards from the Sun. Modeling of dynamic phenomena associated with the initiation and propagation of coronal mass ejections (CMEs) will be given particular emphasis. The modeling of the CME initiation includes magnetic shearing, kink instability, filament eruption and magnetic reconnection in the flaring lower corona. The modeling of CME propagation entails interplanetary shocks, interplanetary particle beams, solar energetic particles (SEPs), geoeffective connections and space weather.

5 The STEREO Orbits and Mission Phases

During the formulation stage of STEREO, scientists from the instrument teams and mission analysts discussed several different mission designs, including drift rates and formations (e.g., both ahead of Earth, both behind, or ahead/behind) for the two spacecraft. Although valid arguments existed for other formations, the selected mission design featured one spacecraft leading the Sun–Earth line while the other lagged. Likewise, scientific arguments for "slow" drift rates (e.g., a few degrees separation per year) and for "fast" drift rates (e.g., >45 degrees per year) were considered, and an optimum mean rate of ± 22 degrees per year (with an uncertainty of ± 2 degrees per year) was selected as the requirement. An additional goal was to minimize the eccentricity of the heliocentric orbits in order to minimize the variation in solar diameter as viewed from the spacecraft, an important consideration for the SECCHI coronagraph occulters. The STEREO orbits are described in detail by Dreisman et al. (2007).

There is no single angular spacing that is best for all STEREO instruments and science goals. The SECCHI coronagraphs best detect coronal features when they are relatively near the plane of the sky as viewed from each spacecraft. This would imply that an overall angle of at least 60° would be best. On the other hand, stereoscopic measurements of small features like loops visible in the SECCHI extreme ultraviolet imager can only be made with small angular separations between the spacecraft, approximately 3–4° to perhaps 20°. Triangulation on radio emissions from Earth-directed CME-driven shock fronts would be most accurate in the 60–90° separation range. The in situ instruments have a scientific interest in having both spacecraft at different positions inside the same magnetic cloud, which would argue for separation angles less than 50°.

Because of these scientific considerations and the final orbit selections where the spacecraft are continually separating, the mission has four distinct phases. Phase 1 occurs approximately the first year when the spacecraft are less than 50° apart when the configuration is optimum for making high cadence 3-D images of coronal structures. Stereoscopic image pairs and sequences will capture the 3-D of the corona before, during and after CMEs. It is also during phase 1 that intercalibrations between like instruments on the two spacecraft are possible.

Phase 2 is centered on quadrature between the two spacecraft with separations between 50° and about 110°, corresponding to days 400 to 800. During this interval, triangulation on CMEs is optimal. It is also quite likely that one spacecraft will be able to observe a CME in the plane of the sky that actually impacts the other spacecraft, thereby linking characteristics of a CME (composition, magnetic field orientation density and velocity at 1 AU) with its launch and propagation parameters (size, velocity and source region characteristics).

Phase 3 (and 4) corresponding to days 800 to 1,100 would occur during an extended mission period, since the STEREO prime mission is only two years after reaching heliocentric orbit. During phase 3, the spacecraft are at angles from 110 to 180 degrees and are both able to view Earth-directed CMEs in the plane of the sky. The two spacecraft will also have a nearly complete view of the sun, allowing the longitudinal extent of CMEs and other activity to be measured.

Beyond the 180° point (phase 4), events on the far side of the sun that launch particles toward Earth will be visible for the first time. Active regions can be tracked and studied for their eruptive potential from their emergence, wherever it occurs on the Sun. The results will have a tremendous impact on our ability to anticipate changes in solar activity and to predict changes in space weather conditions. Such predictive capability is vital if we are to build permanent lunar bases or send astronauts to Mars.

6 STEREO Data and the STEREO Science Center

Transmission of the complete data stream to ground is conducted via NASA's Deep Space Network (DSN). The data are then sent to the Mission Operations Center at APL which distributes it to the instrument teams and STEREO Science Center (see below). Each instrument has an allocated telemetry rate during DSN real-time contacts, which occur for each spacecraft once daily during regular operations. When the spacecraft are out of contact, instrument telemetry is written to a solid state recorder and down linked during subsequent contact period.

Launched in late 1995, SOHO, a joint ESA/NASA science mission, demonstrated that the onset of Earth-directed CMEs could be detected routinely from a space-based platform. An informal channel between NOAA's Space Environment Center and the SOHO science operations team at GSFC was opened in 1996 for the purpose of communicating activity seen in EIT (Delaboudiniere et al. 1995) and in the LASCO coronagraphs (Brueckner et al. 1995). With the passage of time and the efforts of researchers, the utility of these observations was clearly demonstrated, and the space weather forecasting community embraced the idea that eruptions at the Sun could be detected and their initial journey into the interplanetary medium tracked. Because of this success with SOHO, the two STEREO spacecraft augment their daily full-resolution data downloads with the broadcast continuously a low rate (∼600 bps) set of data consisting of typically one-minute summaries (or several minute in the case of SECCHI) to be used for space weather forecasting (see Biesecker et al. 2007). Several participating NOAA and international ground-tracking stations will collect the data and send it electronically to the STEREO Science Center (see below) where they are processed into useful physical quantities and placed on the public and scientific STEREO Web pages.

The STEREO Science Center (SSC) serves as the central facility responsible for telemetry distribution and archiving and other central functions, such as long-term science planning and coordination with the science teams (see Eichstedt et al. 2007) and the central node for education and public outreach activities (see Peticolas et al. 2007). The SSC is also responsible for the receipt and processing of the real-time Space Weather data. The SSC is the principal interface with the scientific community and the public at large. Two Web sites are maintained. For the general public, the site is:

http://stereo.gsfc.nasa.gov.

For the scientific research community, the site is:

http://stereo-ssc.nascom.nasa.gov.

Additionally, NASA Headquarters hosts a site

http://www.nasa.gov/stereo

that contains the press releases and other announcements and graphics of wide interest.

It is the policy on the STEREO Project that all data be available within as short a time as possible. The space weather data will be available from the SSC in near real time and the daily instrument data files should start becoming available within 24 hours of ground receipt and finalized with about one month of ground receipt. Higher level data products will be made available as they are produced.

7 Summary

The STEREO mission will move space-based observations of the Sun to the next logical step, the ability to make 3-D measurements. During the early portion of the STEREO mission, many existing spacecraft near Earth—such as SOHO, Wind and ACE—should also still be operating as well as the Hinode spacecraft, launched the same year as STEREO (2006). Also in geospace, there are new additions to the existing fleet such as the recently launched THEMIS to study effects in Earth's magnetosphere. Thus, there is an impressive fleet of spacecraft dedicated to solar observations and we predict that this era will become an extremely productive period in our understanding of our Sun and its connections to Earth.

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The STEREO Observatory

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Abstract The Solar Terrestrial Relations Observatory (STEREO) is the third mission in NASA's Solar Terrestrial Probes program. The mission is managed by the Goddard Space Flight Center (GSFC) and implemented by The Johns Hopkins University Applied Physics Laboratory (JHU/APL). This two-year mission provides a unique and revolutionary view of the Sun–Earth system. Consisting of two nearly identical observatories, one ahead of Earth in its orbit around the Sun and the other trailing behind the Earth, the spacecraft trace the flow of energy and matter from the Sun to Earth and reveal the three-dimensional structure of coronal mass ejections (CMEs) to help explain their genesis and propagation. From its unique side-viewing vantage point, STEREO also provides alerts for Earth-directed solar ejections. These alerts are broadcast at all times and received either by NASA's Deep Space Network (DSN) or by various space-weather partners.

Keywords STEREO · Coronal mass ejections · Solar-terrestrial relations · Heliocentric orbit · Heliospheric science

1 Introduction

The two Solar Terrestrial Relations Observatories (STEREO) were launched on a Boeing Delta II 7925-10L launch vehicle from the Cape Canaveral Air Force Station on October 26, 2006, at 00:52 UTC. Shown in the launch vehicle fairing in Fig. 1, the spacecraft were designated "Ahead" (A) and "Behind" (B) based on their relative position to the Earth while in their heliocentric orbits. To achieve their mission, observatory A, shown in Fig. 2 at the launch site integration facility, has a shorter orbital period than the Earth

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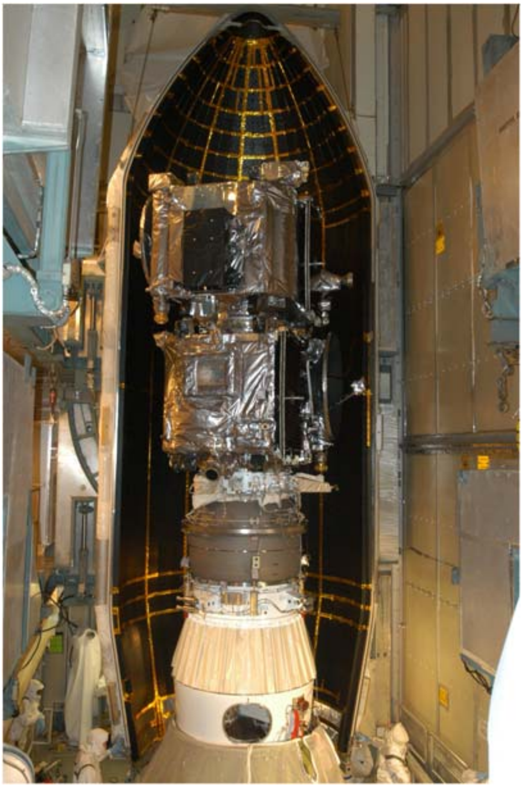

Fig. 1 The twin observatories stacked for launch on a Delta II 7925-10L launch vehicle. One fairing half is installed

and hence drifts ahead of the Earth at an average rate of approximately 22° per year. Correspondingly, observatory B has a longer orbital period than the Earth and thus lags the Earth with a similar drift rate. The actual drift rates achieved were +21.650° per year for Ahead and −21.999° per year for Behind. These drift rates were chosen as a compromise between in situ instrument science team members who desired both spacecraft to spend time within a single coronal mass ejection (CME) and imaging instrument science team members who wanted to quickly achieve the separation necessary to produce three-dimensional images.

To meet full mission success, each STEREO observatory is required to meet performance requirements for two years after both observatories reach heliocentric orbit. To achieve minimum mission success, both STEREO observatories are required to meet performance requirements for 150 days (after reaching heliocentric orbit), with either observatory meeting performance requirements for an additional 530 days. Each spacecraft bus is required to carry sufficient propellant to last five years.

2 Orbital Characteristics

The heliocentric orbit of the two STEREO observatories is shown in an inertial frame of reference in Fig. 3a; the geocentric solar ecliptic (GSE) frame is shown in Fig. 3b. These two views of the orbital dynamics of the spacecraft illustrate their relative motion within the

Fig. 2 Observatory A at Astrotech in Titusville, FL, shown prior to its final blanketing. The observatory's battery is shown at the top center of the image, and the star tracker aperture is shown at the bottom

Earth–Sun system that allows them to achieve the stereoscopic view of the Sun and CMEs at various scales and geometries. Specifically, the inertial frame shows the size differences of the semimajor axes that result in the relative movement of the two observatories with respect to the Earth and each other. The perihelion of observatory B is equivalent to the Earth's radius, whereas conversely the aphelion of observatory A is equivalent to the Earth's radius. This, combined with the eccentricity of the Earth's orbit, results in the variations in the drift rate throughout the year, as shown in the GSE coordinate system of Fig. 4. Also clearly illustrated by the GSE coordinate system view of the spacecraft in Fig. 3b is the relative location of the spacecraft with respect to the Earth while viewing the Sun. Figure 4 details the integrated Sun–Earth–Probe angle through the life of the mission based on the nominal prelaunch 22° per year drift rate for the spacecraft.

2.1 Phasing Orbit Characteristics

The mission design team at The Johns Hopkins University Applied Physics Laboratory (JHU/APL) developed an innovative orbit design with multiple lunar gravity assists to place

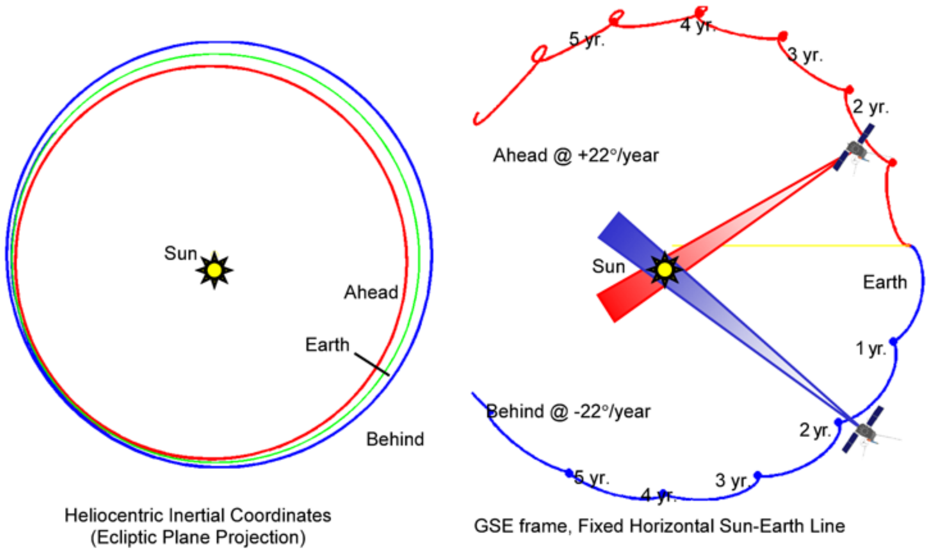

Fig. 3 (**a**) The two observatory orbits projected onto the ecliptic plane. The projection shows the relative eccentricities of the orbits. (**b**) The same projection is shown but with a fixed Earth–Sun line. This figure shows the evolution of the relative geometries over the life of the mission

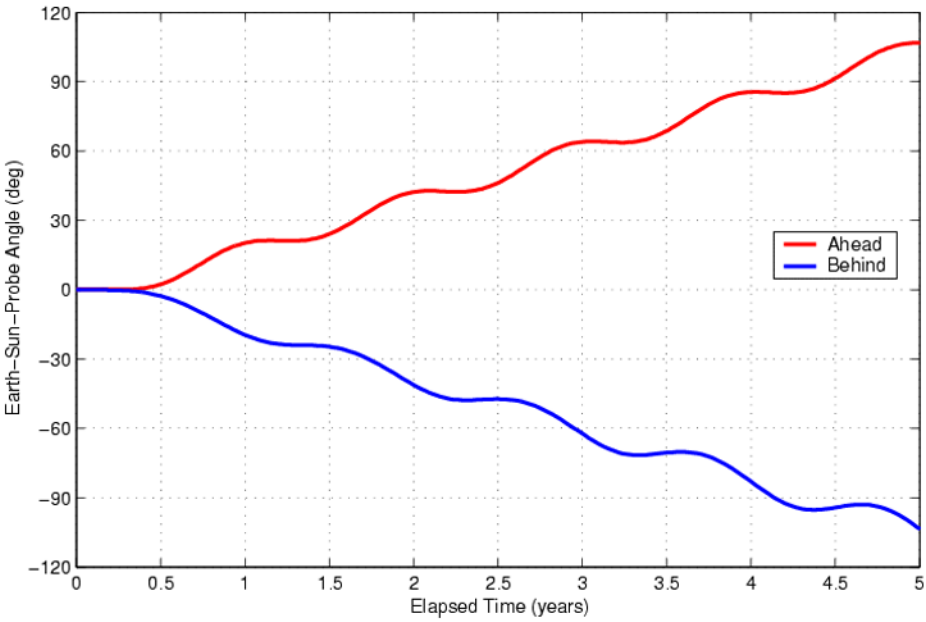

Fig. 4 The graph shows the relative drift rates of the two observatories based on the prelaunch drift rates of 22° per year for observatory A and −22° per year for observatory B

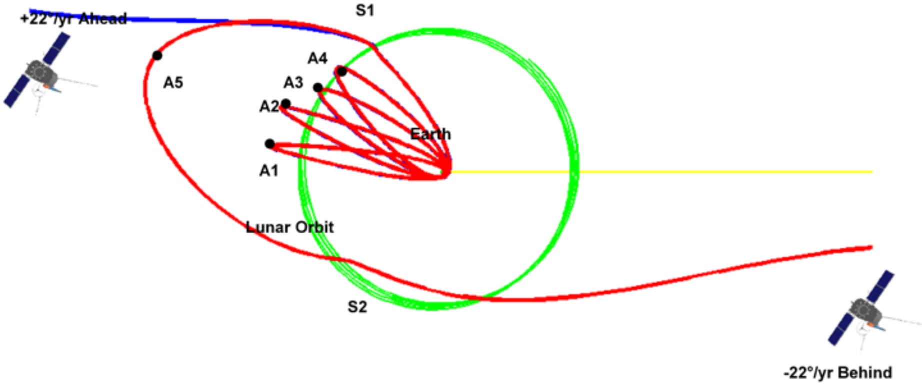

Fig. 5 Illustrated are the phasing orbits of the two observatories. Observatory A was ejected into heliocentric orbit after spending 52 days in Earth orbit. Observatory B re-encountered the Moon 38 days later and was ejected into a trailing orbit

both spacecraft in their respective heliocentric orbits. This unique design allowed the two observatories, which had drastically different orbital requirements, to be launched on a single launch vehicle. Figure 5 shows a series of phasing orbits in the GSE frame with apogees denoted as *A1–A4*. A series of propulsive maneuvers at events *A1*, *P1*, *A2*, *P2*, *A4*, *S1*+, and *A5*+ were used to adjust the trajectories to achieve the required lunar swing-by distances. These phasing orbits provided time to position the two observatories on slightly different trajectories at the first lunar swing-by (denoted as *S1* in Fig. 5). By virtue of the lunar swing-by, observatory A gained sufficient energy to be ejected from the Earth–Moon system and to achieve the required heliocentric orbit. The *S1* event imparted enough energy to observatory B to place it in a higher elliptical orbit, thus re-encountering the Moon for a second lunar swing-by (denoted as *S2* in Fig. 5) approximately 40 days after the *S1* event. The *S2* event ejected observatory B into a heliocentric orbit with a larger semimajor axis and therefore a drift rate lagging the Earth. A further propulsive maneuver was added after launch to refine the trajectory when it was realized that the Behind observatory trajectory could be positioned such that a lunar transit would occur on February 25, 2007. The lunar transit is used by the Extreme Ultra-Violet Imager (EUVI) in the Sun–Earth Connection Coronal and Heliospheric Investigation (SECCHI) suite as a means of understanding the stray-light performance of the instrument. The Moon essentially blocks out all light from the Sun, thus any UV light appearing on the area of the EUVI charge-coupled device that is occulted by the Moon is stray light. This knowledge is used to update the EUVI calibration data.

To support the various maneuvers needed to properly position the spacecraft, an initial estimate of 180 m/s delta velocity (ΔV), equivalent to approximately 62 kg of hydrazine propellant, was used to determine the size of the propulsion system on each observatory. Driving the ΔV requirement was the need to support a monthly launch window of two weeks and a daily launch window of 15 minutes per day. Accommodating these launch windows and supporting the 3σ launch dispersions associated with the Delta II sized the ΔV requirement. The actual launch time occurred in the middle of the monthly launch window and at the end of the daily window. The launch vehicle dispersions were very low, thus each observatory achieved their heliocentric orbits with 43 kg of propellant.

2.2 Instrument Accommodations

The STEREO instrument suite initially was challenging to accommodate because it encompassed optical, particle, and electromagnetic wave instruments, each with their own set of unique requirements. For example, the optical instruments required very low jitter and extreme cleanliness, whereas the particle instruments required large unobstructed fields of view and electrostatic cleanliness, and the STEREO/Waves (SWAVES) instrument required extreme electromagnetic cleanliness. This section provides details on the primary drivers that the instruments imposed on the overall observatory design.

The instrument integration challenge is further illustrated by Table 1, which shows the fields of view and boresight of the various instruments. The final spacecraft and instrument payload design was a result of extensive technical trades. With the exception of some minor compromises, all field-of-view requirements were satisfied. An early instrument accommodation study resulted in dividing the Supra-Thermal Electron (STE) instrument into two: STE-Upstream (STE-U) mounted on the $+X$ (Sun-pointing) end of the boom and a STE-Downstream (STE-D) mounted toward the end of the boom. The High-Energy Telescope (HET), Low-Energy Telescope (LET), and Solar Electron Proton Telescope (SEPT) instruments are mounted in different orientations on the two spacecraft to allow their respective boresights to point in the direction of the Parker spiral. See Fig. 6 for illustration of the instrument configuration of spacecraft B.

The SECCHI Sun-Centered Imaging Package (SCIP) instruments have stringent pointing and jitter requirements. A detailed discussion of these requirements can be found in Sect. 4.2. The In-situ Measurements of Particles and CME Transients (IMPACT) booms, SWAVES antennae, and solar arrays all have fundamental frequencies that could affect the pointing and jitter requirements.

The combination of the particulate requirements from the coronagraphs and the condensable and hydrocarbon requirements from the EUVI instrument levied stringent contamination requirements on all the instruments, spacecraft, and processing facilities. The observatories' external surfaces had a specification of 300A at the time of launch, where "300" refers to the number of allowable particles of a given size per square foot and "A" refers to the amount of allowable nonvolatile residue deposited on a surface, with "A" being equal to one $\mu g/cm^2$ of deposition (Department of Defense 1994). The internal surfaces of the instruments had requirements ranging from 200A/3 to 100A/5. A contamination committee consisting of members from JHU/APL, the Naval Research Laboratory, University of California–Berkeley, University of New Hampshire, and the University of Minnesota met repeatedly throughout the program to plan and implement the contamination control plan. All of the spacecraft bus and instrument fabrication facilities were class 10,000, and any time the coronagraphs were opened to the environment was class 1,000. The facilities at JHU/APL, Goddard Space Flight Center (GSFC), Astrotech, and launch complex 17 were cleaned thoroughly and repeatedly during the integration and testing program. At the time of launch, the spacecraft external surfaces and internal surfaces had achieved their cleanliness requirements.

The Solar Wind Electron Analyzer (SWEA) instrument necessitated a requirement to have the spacecraft body at a uniform and low electrical potential with respect to the plasma. To meet this requirement, all observatory surfaces, with the exception of the solar arrays, were required to be conductive, less than 10^{-8} Ω/square. The Sun-facing surfaces of the spacecraft were covered with indium-tin-oxide (ITO)-coated silver Teflon thermal blankets. ITO has a surface conductivity of approximately 10^{-5} Ω/square, and its surface is perforated with small ITO-plated through-holes to the silver backing material. This design provided a robust connection between the delicate ITO on the front surface and the backing

Table 1 Instrument field-of-view accommodations

STEREO Science Instrument	Field of View (FOV)	Component boresight orientation
SECCHI		
SCIP	8° Cone (w/180° Clear FOV)	Sun-Pointing
HI*	85° Cone (w/183° Clear FOV Tilted 1.5° Along $-Z$ Axis)	90° to Sun–Earth Line
IMPACT		
SWEA	130° × 360° Annular Shape	Boom-Mounted, Anti-Sun
STE	80° × 80° Fan Shape into Ecliptic (East & West)	Boom-Mounted, Anti-Sun
MAG	N/A	Boom-Mounted, Anti-Sun
SEP		
LET		
Earth Behind Observatory	100° × 30° Fan Shape into Ecliptic (East & West)	50° to Sun–Spacecraft Line
	130° × 30° Fan Shape into Ecliptic (East & West) Goal	
Earth Ahead Observatory	100° × 30° Fan Shape into Ecliptic (East & West)	50° to Sun–Spacecraft Line
	130° × 30° Fan Shape into Ecliptic (East & West) Goal	
HET		
Earth Behind Observatory	50° Full Cone into Ecliptic (East & West)	45° to Sun–Spacecraft Line
	60° Full Cone into Ecliptic (East & West) Goal	
Earth Ahead Observatory	50° Full Cone into Ecliptic (East & West)	45° to Sun–Spacecraft Line
	60° Cone into Ecliptic (East & West) Goal	
SEPT-E		
Earth Behind Observatory	45° Full Cone in Ecliptic (East & West)	45° to Sun–Spacecraft Line
	52° Cone into Ecliptic (East & West) Goal	
Earth Ahead Observatory	45° Full Cone in Ecliptic (East & West)	45° to Sun–Spacecraft Line
	52° Cone into Ecliptic (East & West) Goal	
SEPT-NS		
Earth Behind Observatory	52° Cone Perpendicular to Ecliptic (North & South)	90° to Sun–Spacecraft Line
Earth Ahead Observatory	52° Cone Perpendicular to Ecliptic (North & South)	90° to Sun–Spacecraft Line
SIT		
Earth Behind Observatory	44° × 17° Rectangular Shape into Ecliptic (West)	45° to Sun–Spacecraft Line
Earth Ahead Observatory	44° × 17° Rectangular Shape into Ecliptic (West)	45° to Sun–Spacecraft Line

Table 1 (*Continued*)

STEREO Science Instrument	Field of View (FOV)	Component boresight orientation
PLASTIC		
Solar Wind Sector Main	$55° \times \pm 20°$ Fan Shape (clear FOV)	Sun-Pointing
Solar Wind Sector Proton	$55° \times \pm 20°$ Fan Shape	Sun-Pointing
Wide-Angle Partition	$250° \times \pm 7°$ Fan Shape	In Ecliptic Non-Sunward
SWAVES	Three Mutually Orthogonal Antenna Elements	Anti-Sun

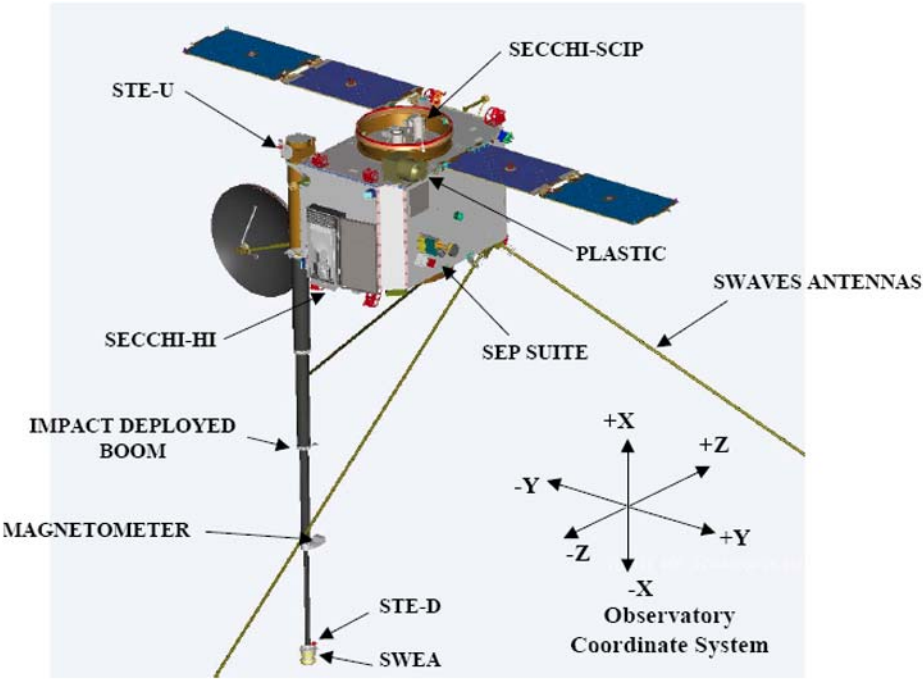

Fig. 6 Illustration of spacecraft B in its deployed configuration. For scale, the large vertical boom (IMPACT boom) is approximately 6 m long

material, which is connected to the spacecraft structure with redundant wires. After a design analysis, it was determined that the solar array cover-glass did not need to be conductive. The electrostatics of the observatory, including the solar array, were modeled. It was found that, due to the deposition of photoelectrons and the distance of the most sensitive electron instruments, the buildup of charge on the solar array was acceptable. With small exceptions (optical apertures and star tracker lens), the remainder of the spacecraft's outer surface was covered with conductive black Kapton thermal blanket, with a conductivity of less than $10^8\ \Omega/\text{square}$. Special attention was paid to shaded surfaces, which could not be discharged by photoelectrons. For example, with the exception of apertures, no nonconducting surfaces were allowed on shaded portions of the spacecraft.

The SWAVES instrument drove the observatory electromagnetic compatibility (EMC) requirements. An EMC committee with members from all the critical institutions was chartered early in the program to generate design and test requirements for all flight hardware. The approach to controlling electromagnetic emissions had several facets, including shielding, twisted-pair wiring, use of differential circuits, and control of primary and secondary grounds. Even with stringent controls, it was understood early that the largest source of noise on the observatories would be the switching power supplies found in almost every electronics box. Rather than try to (overly) control the conducted and radiated noise from these supplies (a costly effort), control instead was placed over the switching frequency. Power supplies were required to switch at a frequency of 50 kHz (±1 part in 10,000) or a harmonic thereof. This novel approach limited the bulk of the electromagnetic noise to narrow bands, which allowed the SWAVES instrument to tune its receiver bands (starting at 100 kHz) in between the "noisy" bands. In addition to control, a stringent test program was put in place that ensured compliance with the radiated and conducted emissions requirements, which in some places were 20 dB below MIL-STD-461 requirements (Department of Defense 1999). All observatory hardware was screened individually. Once the hardware was integrated into an observatory, each observatory went through radiated and conducted compatibility testing. Compatibility testing was used rather than standard emissions testing because the SWAVES instruments were, in general, more sensitive than the receivers used to conduct the emissions testing.

2.3 Instrument Data Volume

Each observatory has five imaging instruments: EUVI, Coronagraph 1 (COR1), Coronagraph 2 (COR2), Heliospheric Imager 1 (HI-1), and Heliospheric Imager 2 (HI-2). These imagers are capable of producing images at a rate that would be impossible to bring to the ground, which when coupled with the Earth–observatory distances approaching 0.8 AU generated a series of early trade studies aimed at maximizing the data volume brought down to the ground via the Deep Space Network (DSN). The trade studies were used to size the spacecraft's communications system, the level of image compression, the size of ground antennas used, the duration of ground tracks, the size of the onboard solid-state recorder (SSR), the interfaces between the imagers and the spacecraft bus, and the software used to communicate between the two. The resulting requirement was to bring down 5 Gbits of data per day averaged over a 12-month period. To account for normal outage (e.g., DSN station outages), the system was designed to bring down 6.2 Gbits per day. Table 2 shows the baseline design.

Table 2 Instrument downlink data rates and resulting average daily volumes

Instrument	Average data rate (kbps)[a]			Average daily data volume (Mbits)		
	Months 0–14	Months 15–18	Months 19–24	Months 0–14	Months 15–18	Months 19–24
SECCHI	54.888	50.727	46.239	4,742	4,383	3,995
IMPACT	3.274	3.590	3.274	283	310	283
SWAVES	2.074	2.272	2.074	179	196	179
PLASTIC	3.274	3.590	3.274	283	310	283

[a]Including space-weather data and packet primary and secondary header overhead