Available online at www.sciencedirect.com
SCIENCE DIRECT®
Advances in Space Research 36 (2005) 1483–1488
ADVANCES IN SPACE RESEARCH (a COSPAR publication)
www.elsevier.com/locate/asr

The STEREO mission: an overview

M.L. Kaiser *

NASA/Goddard Space Flight Center, Code 695, Greenbelt, MD 20771, USA

Received 25 October 2004; received in revised form 21 December 2004; accepted 21 December 2004

Abstract

In February 2006, NASA will launch the twin STEREO spacecraft 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 will use close flybys of the moon to escape into heliocentric orbits at 1 AU, with one spacecraft trailing Earth and the other leading Earth. As viewed from the Sun, the two spacecraft will separate at approximately 45° per year. The purposes of the STEREO Mission are to understand the causes and mechanisms of coronal mass ejection initiation and to follow the propagation of CMEs through the heliosphere. Additionally, STEREO will study the mechanisms and sites of energetic particle acceleration and develop 3D 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 will be equipped with a set of optical, radio and in situ particles and fields instruments. The SECCHI suite of instruments includes two white light coronagraphs covering the range from 1.4 to 15 solar radii, an extreme ultra violet imager covering the chromosphere and inner corona, and two heliospheric white light imagers covering the outer corona from 12 solar radii to 1 AU. The IMPACT suite of instruments will measure in situ solar wind electrons in the energy range from essentially 0 to 100 keV, energetic electrons to 6 MeV, and protons and heavier ions to 100 MeV/nucleon. IMPACT also contains a magnetometer to measure the in situ magnetic field strength and direction. The PLASTIC instrument will measure the composition of heavy ions as well as protons and alpha particles. The SWAVES instrument will use radio waves to track the location of CME-driven shocks and the 3D topology of open field lines along which energetic particles flow. Additionally, SWAVES will measure in situ plasma waves to provide an independent estimate of the local plasma density and temperature. Each of the four instruments will produce a small real-time stream of selected data for purposes of predicting space weather events at Earth, primarily for NOAA forecasters. In addition to the four instrument teams, there will be substantial participation by modeling and theory oriented teams. All STEREO data will be 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.
© 2005 Published by Elsevier Ltd on behalf of COSPAR.

Keywords: Solar; STEREO; Space weather

1. Introduction

The Solar TErrestrial RElations Observatory (STEREO) mission is the third in a coordinated sequence of science missions within the Solar Terrestrial Probes (STP) Program detailed in NASA's 1994 Strategic Plan. The STP Program focuses on understanding how the changing Sun affects the solar system and life on Earth.

STEREO is managed by NASA's Goddard Space Flight Center (GSFC) in Greenbelt, MD. GSFC provides science instrument management, systems engineering, mission assurance and reliability, science and data analysis, data archiving, and coordination of Education and Public Outreach (EPO) efforts. The Johns Hopkins University Applied Physics Laboratory (JHU/APL) in Laurel, MD is responsible for the design, construction,

* Tel.: +1 301 286 5461; fax: +1 301 1433.
E-mail address: michael.kaiser@nasa.gov.

0273-1177/$30 © 2005 Published by Elsevier Ltd on behalf of COSPAR.
doi:10.1016/j.asr.2004.12.066

integration, testing, and mission operations of the observatories, as well as the ground system. During its 2-year life, STEREO will provide a new perspective on the Sun by providing stereoscopic measurements of the Sun and coronal mass ejections (CMEs). Each of the two spacecraft carries a complement of imaging, remote-sensing and particle and fields instruments. STEREO will be the first mission to image CMEs continuously in 3D from the Sun to Earth.

The STEREO mission objectives are consistent with the goals of NASA's Strategic Plan, which include understanding the influence of both the Sun and human activities on Earth's atmosphere and accelerating the development of reliable space weather forecast techniques. The principal mission objective for STEREO is to understand the origin and consequences of CMEs, the most energetic eruptions on the Sun. 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 3D, time-dependent model of the magnetic topology, temperature, density, and velocity structure of the ambient solar wind.

Scientists have long known that Earth is affected by the Sun's dynamic behavior. Variations in the energy flow from the Sun can have considerable consequences on Earth's climate and environment which can have extensive economic impacts, making it vital to understand space weather. Major advances in global communications have resulted from satellite technology. The dynamic Sun can affect satellite tracking, reliability, and safety as well as communications and navigation equipment. With the construction of the International Space Station, an increased human presence in space will require knowledge of changing space habitats.

The 2-year STEREO mission will provide a completely new perspective of the Sun by measuring in three dimensions the solar atmosphere and heliosphere from two functionally identical spacecraft simultaneously. STEREO will track disturbances from their onset at the Sun's surface to beyond Earth's orbit, measure energetic particles generated by CME disturbances, and sample fields and particles in the disturbances as they pass near Earth. The two spacecraft, one drifting ahead of Earth and one lagging behind, will obtain 3D measurements at gradually increasing angular separations. This unique vantage point for observing the Sun–Earth connection will provide optimum conditions for developing predictive capabilities. The STEREO scientific program does not depend on the 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 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, STEREO expects to observe at least 60 CMEs in remote sensing instruments and at least 24 interplanetary events in situ.

STEREO will greatly accelerate the development of reliable space weather forecast techniques. Measurements from STEREO will provide early warnings of solar eruptions, which are important for forecasting radiation at the space station, as well as having implications for communications and weather satellites and many other areas of human activity.

2. The Science teams

The STEREO science payload consists of four measurement packages, each of which has several components. Together, this suite of instruments will characterize the CME plasma from the solar surface to Earth's orbit. Using remote and local sensors to measure the physical characteristics of CMEs, they will determine the solar origins of CMEs, their propagation into the interplanetary medium, and their ultimate effects on Earth's magnetic field.

The STEREO observatory carries a complement of four scientific instruments (two instruments and two instrument suites, with a total of 13 instruments per observatory) as follows:

- Sun–Earth Connection Coronal and Heliospheric Investigation (SECCHI)
- In situ Measurements of PArticles and CME Transients (IMPACT)
- PLAsma and SupraThermal Ion Composition (PLASTIC)
- STEREO/WAVES (S/WAVES)

Fig. 1 shows the STEREO behind spacecraft with the various instruments indicated.

SECCHI encompasses a suite of remote sensing instruments designed to study the 3D evolution of CMEs from the Sun's surface through the corona and interplanetary medium to their eventual impact at Earth. The Naval Research Laboratory of Washington, DC is leading this investigation. SECCHI is composed of:

- Two White Light Coronagraphs (COR1, COR2) – exploring the region from $<1.4R_S$ to $15R_S$ (R_S is the radius of the Sun).

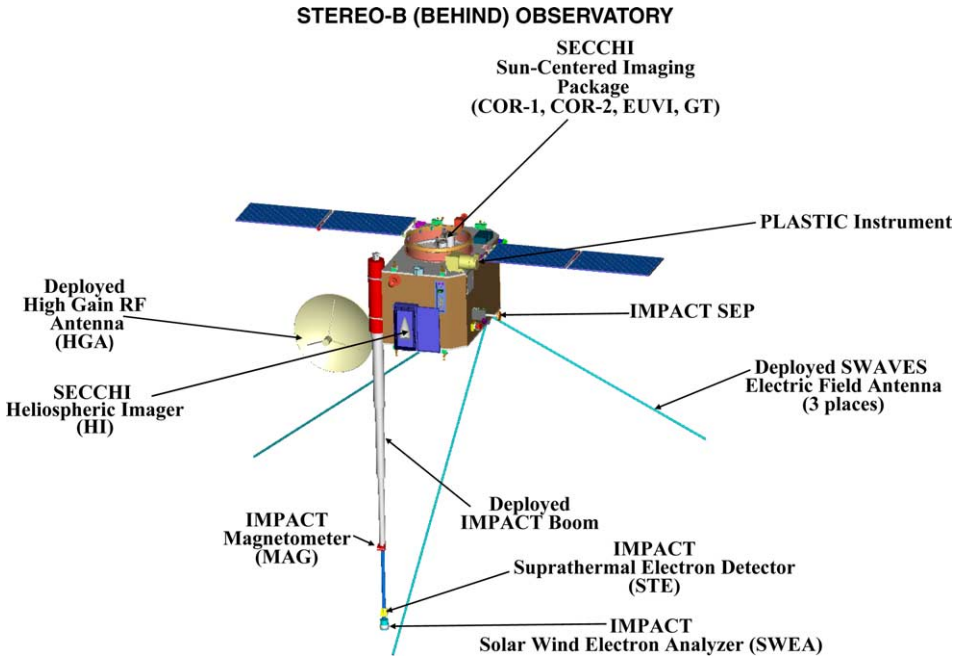


Fig. 1. An artists conception of the behind spacecraft (ahead spacecraft nearly identical except for placement of some body-mounted experiments) with the locations of the instruments shown. The SECCHI instruments point at the Sun and the IMPACT boom and SWAVES antennas are on the opposite end.

- Extreme Ultraviolet Imager (EUVI) – looks at the upper chromosphere and innermost corona.
- Heliospheric Imager (HI1, HI2) – observes CMEs from the Sun to Earth (12–215R_S).

IMPACT, which is being designed, built, and tested by an international team led by the University of California, Berkeley, will measure 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 are located on a 6-m deployable boom, with the others located on the main body of the spacecraft. The boom suite includes:

- Solar Wind Experiment (SWEA) – measures ~0.2–1 keV electrons with wide angle coverage.
- Suprathermal Electron Telescope (STE) – measures electrons from 5 to 100 keV with wide angle coverage.
- Magnetometer Experiment (MAG) – measures the vector magnetic fields in the ±512 nT range with 0.1 nT accuracy.

The Solar Energetic Particle (SEP) Experiment Suite includes:

- Suprathermal Ion Telescope (SIT)
- Solar Electron and Proton Telescope (SEPT)
- Low Energy Telescope (LET)
- High Energy Telescope (HET)

The PLASTIC experiment, built by an international consortium led by 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. PLASTIC incorporates three science sensor functions into one package:

- Solar Wind Sector (SWS) Proton Channel measures the distribution functions of solar wind protons and alphas, providing proton density, velocity, kinetic temperature and its anisotropy, and alpha to proton ratios with a time resolution up to about 1 min.
- Solar Wind Sector (SWS) Main (Composition) Channel measures the elemental composition, charge state distribution, kinetic temperature, and speed of the more abundant solar wind heavy ions (e.g., C, O, Mg, Si, and Fe) by using Electrostatic Analyzer (E/Q), Time-of-Flight (TOF), and Energy (E) measurement to determine Mass and M/Q. Typical time resolution for selected ions will be ~5 min.
- Wide-Angle Partition (WAP) measures distribution functions of suprathermal ions, including inter-planetary shock-accelerated (IPS) particles associated with CME-related SEP events, recurrent particle events associated with Co-rotating Interaction Regions (CIRs), and heliospheric pickup ions. Typical time resolution for selected ions will be several minutes to hours.

The S/WAVES instrument, being built by a team led by the Observatoire de Paris and the University of Minnesota, 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 will use three mutually orthogonal monopole antenna elements, each 6 m in length. The three monopoles, built by the University of California, Berkeley, will be deployed away from the Sun so that they remain out of the fields of view of Sun-facing instruments. The S/WAVES instrument includes:

- Radio receivers (HFR and LFRhi) that measure radio wave intensity, source direction, and angular size in the frequency range of 16 MHz to 40 kHz, corresponding to source distances of about $1R_S$ to 1 AU.
- Low Frequency Receivers (LFRlo) that make sensitive measurements of radio and plasma waves near the electron plasma frequency at 1 AU (2.5–40 kHz).
- A Fixed Frequency Receiver (FFR) that measures radio emissions at 32–34 MHz at high time resolution to complement ground-based radio-heliograph measurements.
- Time Domain Samplers (TDS) that simultaneously make wideband waveform measurements on three electric antennas at one of several commandable sample rates and bandwidths.

In addition to these four instrument teams, there are several groups devoted to global modeling with a goal of understanding the connection between the solar activity observed near the Sun by SECCHI and SWAVES and the in situ measurements taken by IMPACT, PLASTIC, and SWAVES when the disturbances finally reach the STEREO spacecraft.

3. The orbits and phases of the mission

To obtain unprecedented, 3D measurements of the Sun, the twin observatories will be placed into solar orbits near 1 AU and they will be separated from one another. One observatory will be placed "ahead" of Earth in its orbit and the other, "behind". For the first three months after launch, the observatories will fly in an orbit from a point close to Earth to one that extends just beyond the moon's orbit. Mission operations personnel will synchronize the orbits of the two spacecraft to encounter the Moon about two months after launch. At that point, one spacecraft will use the moon's gravity to redirect it to an orbit lagging "behind" Earth. About one month later, the second observatory will encounter the Moon again and be redirected to its orbit "ahead" of Earth. After both spacecraft have left the Earth–moon vicinity, they will be in heliocentric orbits at nearly 1 AU. The 'ahead' spacecraft will be in an orbit slightly closer to the Sun than Earth's orbit and the 'behind' spacecraft will be in a slightly larger orbit (left panel of Fig. 2). As viewed from the Sun, the two spacecraft will separate at an average of 45° per year, depicted in the right panel of Fig. 2.

The STEREO mission divides scientifically into three parts as shown in Fig. 3. During the first several months when the spacecraft are still fairly close together, the coronagraphs and EUVI instrument have good overlap of their plane-of-sky viewing areas so that 3D recon-

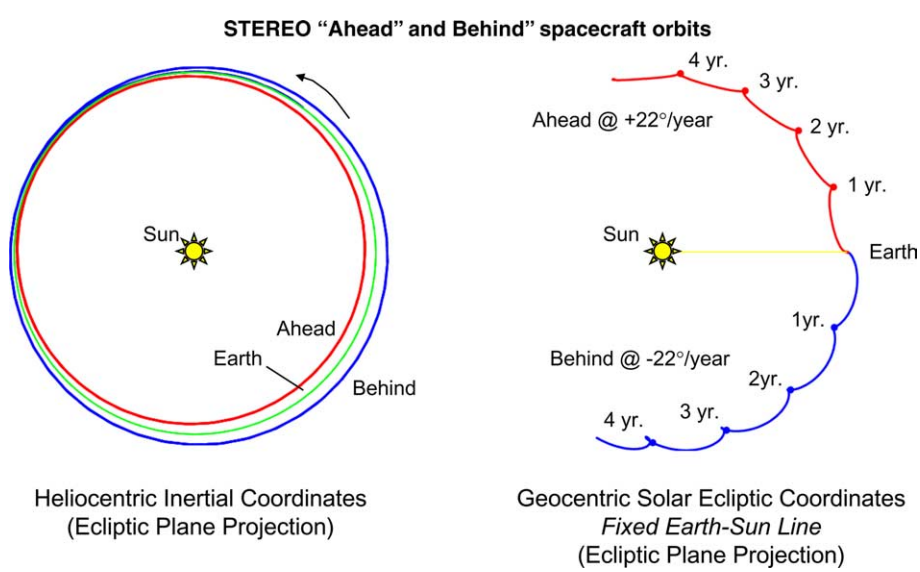


Fig. 2. Left panel shows the 'Ahead' and 'Behind' orbits relative to Earth's orbit. Ahead is in a slightly smaller orbit and Behind is in a slightly larger so that they orbit the Sun either faster or slower than Earth. Right panel shows the location of the spacecraft as a function of time relative to a fixed Sun–Earth line. As viewed from the Sun, the spacecraft separate from each other at approximately 45° per year.

STEREO Mission Phases

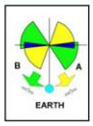
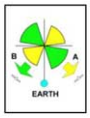
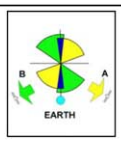
Mission Phase		Remote Sensing	In-Situ
Prime Stereo Science		•Stereo view of plane of sky CMEs and their propagation	•Multipoint observation of Earth directed CMEs
Multipoint Science		•Halo and limb CMEs and their propagation •SWAVES triangulation at its best	•Multipoint observation of Earth directed CMEs
LWS Precursor Science		•Stereo view of Earth directed CMEs	•STEREO-A at quadrature with STEREO-B

Fig. 3. The STEREO Mission naturally divides into three parts depending on the ability of the imaging instruments to make 3D images of plane of the sky or Earth directed CMEs. The coronagraphs are most sensitive to objects within 30° of the plane of the sky as depicted by the green and yellow wedges. During the early portion of the mission when the spacecraft are close together, the wedges overlap in the plane of sky perpendicular to the Earth–Sun line. Late in the mission, just the opposite is true; the overlap region is along the Earth–Sun line.

struction of observed features is performed. Also during this early phase of the mission, the likelihood of both spacecraft being immersed inside the same CME/magnetic cloud is increased. Furthermore, those in situ CMEs would be Earth-directed. At the opposite extreme late in the mission, the spacecraft are at quadrature so that remote viewing of Earth-directed CMEs is enhanced. This phase of the mission is thought of as a precursor to the Living With a Star missions to be launched later. In the intermediate interval, triangulation of radio bursts with SWAVES is best.

4. Space weather beacon

In addition to normal data collection, the two STEREO spacecraft also broadcast continuously a low rate (~600 bps) set of data consisting of typically 1-min summaries (or 5 min in the case of SECCHI) to be used for space weather forecasting, much like is currently done with the ACE and SOHO data. Several participating NOAA and international ground tracking stations will collect the data and send it electronically to the STEREO Science Center (see below) where it will be processed into useful physical quantities and place on the STEREO Web page. The goal is to have the processed data available within 5 min of receipt at the tracking stations.

5. The ground system

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. 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. Its Web site is: http://stereo-ssc.nascom.nasa.gov.

The STEREO mission operations approach allows for the direct control of scientific instruments by the PIs who are located at Payload Operations Centers (POCs) at their home institutions. Unlike many spacecraft, where requests for activities must be balanced against regular maintenance activities, STEREO is designed to allow the instruments to be operated independently of each other. The PIs at these POCs send instrument commands each day to the STEREO Mission Operation Center at JHU/APL where the commands are combined and up linked to the observatory once a day. This interdisciplinary approach allows data to be collected at low cost and data products to be distributed in an efficient manner.

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 be available within 24 h of ground receipt. Higher level data products will be made available as they are produced.

6. Summary

The STEREO mission will move space-based observations of the Sun to the next logical step, the ability to

make 3D 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 and the Solar-B spacecraft will also be launched the same year as STEREO (2006). Thus, there will be an impressive fleet of spacecraft dedicated to solar observations and I predict that this era will become an extremely productive period in our understanding of our Sun.