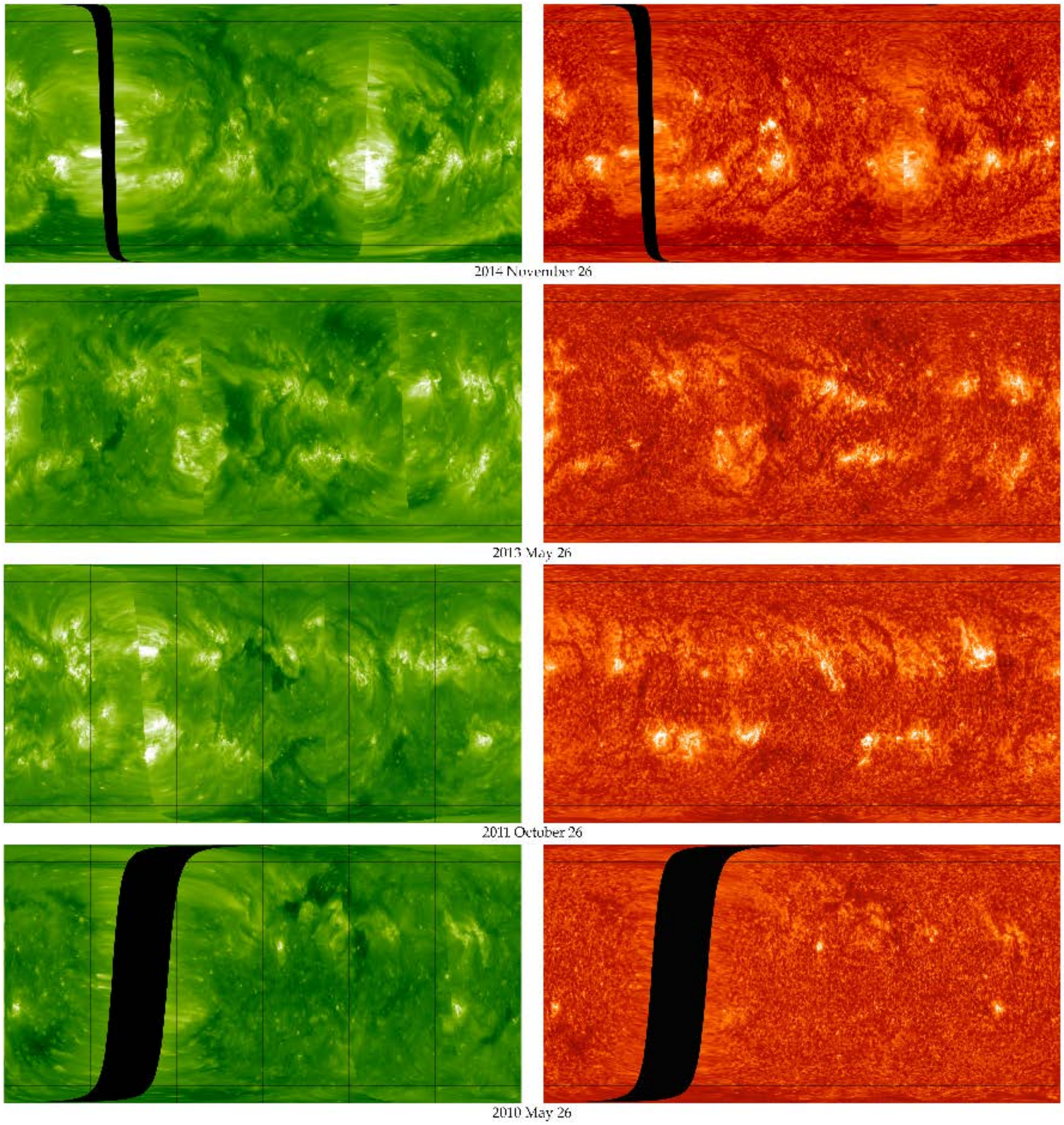
STEREO

A PROPOSAL TO THE SENIOR REVIEW OF HELIOPHYSICS OPERATING MISSIONS, 2015 MARCH.



STEREO + AIA synoptic or Carrington maps (cylindrical projections) of the entire solar surface in (left) Fe XII 193/195 Å and (right) He II 304 Å. The center of each image is the sub-earth longitude and information around it is derived from AIA images; all far-side information is from STEREO. The black areas represent lacunae in coverage due to the STEREO spacecraft not yet reaching opposition (2010) and the absence of STEREO Behind observations (2014). The progression in activity is what we can expect to sample, in reverse time order, during 2016 - 2020.

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Solar TErrestrial RElations Observatory (STEREO)

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I. Executive Summary

The STEREO mission has transformed the way both researchers and space weather forecasters work, by making possible observations of the Sun, the solar wind, and solar energetic particles from multiple longitudinal viewpoints near 1 AU. The STEREO observations from the far side of the Sun, in combination with the other assets in the Heliospheric Systems Observatory (HSO), have allowed an unprecedented global view of space weather throughout the inner heliosphere, as well as unique input for determining the conditions at the boundaries of the heliosphere.

The STEREO mission completed its prime phase in 2009 January, after nearly two years of heliocentric operations. Now, as it arrives at superior conjunction, it is a key part of research into the Sun and heliosphere, used by research groups all over the world. Data from the mission are being freely served by the STEREO Science Center and instrument team Websites, and, as of this writing, 936 STEREO publications have appeared in the refereed literature since 2006, including 168 in 2013 and 167 in 2014.

Our Prioritized Science Goals (PSGs) fall into three, broad categories: Characterizing space weather throughout the inner heliosphere, what we can learn from 360° coverage of the solar corona, and what we can learn from coverage of the full heliosphere. We have seen substantial progress in these science areas, including understanding the large-scale structures and physics of coronal mass ejections (CMEs) in the corona and interplanetary space and providing insight into the sources and propagation of solar energetic particles (SEPs). STEREO data are used to monitor and study space weather throughout the inner heliosphere, creating synergy with planetary missions such as MESSENGER and MAVEN. STEREO also contributes to the study of the outer boundaries of our solar system and the interstellar medium. Even in the event of the permanent loss of the STEREO-B spacecraft, STEREO-A, with its unique position in the solar system, would be able to make important contributions to our science goals.

Section II describes mission status, including operations near superior conjunction and loss of contact with the STEREO-B spacecraft. In Section III, we describe data accessibility and impact, and progress on and plans for our Prioritized Science Goals. Section IV provides an overview of the technical state of the mission, and Section V discusses budget issues. The mission archive plan is discussed in Appendix A. Additional appendices cover publications (B), spacecraft and instrument status (C), Roadmap research focus areas (D), and acronyms (E).

The following individuals were among those involved in the writing of this proposal on behalf of the STEREO Science Working Group: J. Luhmann (UCB), R. Mewaldt (Caltech), A. Galvin and C. Farrugia (UNH), A. Vourlidas (JHU/APL), W. Thompson (Adnet), R. MacDowall, T.A. Kucera, E. Christian, and J.B. Gurman (GSFC). Numerous members of the Principal Investigator (PI) teams submitted early drafts.

II. Mission Status

A. Launch, orbital design, and antenna thermal issue. The *STEREO* spacecraft were launched on a single Delta II vehicle on 2006 October 25 (October 26 UT) and inserted into heliocentric orbits in 2006 December (Ahead) and 2007 January (Behind) using lunar phasing orbits. Since the Behind spacecraft was placed in an orbit with semi-major axis slightly larger than the earth's, and Ahead in an orbit slightly smaller, each spacecraft appeared to drift away from the earth-Sun line by 22^o per year through opposition (2011 February), when each spacecraft was roughly 90° from the earth-Sun line, and then to approach the earth-Sun line on the far side of the Sun until superior conjunction (2015 January - July). The prime mission was designed for two years' operation starting with the Behind heliocentric orbit insertion, with engineering sufficient to sustain an extended mission of up to five years' duration — which we have exceeded.

The only major spacecraft subsystem failures in the eight years after launch were the loss of the primary inertial measurement unit (IMU) on the Ahead spacecraft on 2007 April 11 and the degradation of the primary IMU on Behind starting in 2012. The backup IMUs were put into service to replace each of the primaries., and the backup IMU on Behind failed on 2014 January 5. Since the common root cause was a well-known aging issue with ring laser gyros, the remaining IMUs could be expected to fail in the same manner, and the Mission Operations team at Johns Hopkins University Applied Physics Laboratory (APL) devised a method for maintaining pointing accuracy during scientific observations using the star tracker on each spacecraft for roll reference, and the SECCHI guide telescope for pitch and yaw. The IMUs would be powered on only in case of anomaly and for momentum managements; it was thought that would extend the usable lifetime of the remaining IMUs for some years to come.

In 2014 mid-April, the Mission Ops team noted a secular increase in the temperature of the high gain antenna (HGA) feed on both STEREO spacecraft; both HGA feeds rapidly exceeded their operational temperature limit of 85 C. It was quickly realized that this was due to focusing of solar radiation on the feed as the earth-Sun angle decreased, as seen from the spacecraft. Unfortunately, there is no efficient heat path out of the feed (indeed, the feed is clad in an insulated wrap), and modeling showed that for some months before and after the expected blackout periods for each spacecraft (2015 January - March for Behind, 2015 March - July for Ahead) due to low signal-to-solar-noise ratio, the temperature of the HGA feeds would exceed the measurement range and eventually rise to levels where the feed electronics would be damaged.

The Mission Ops team, already busy with planning for mission autonomy during the blackout periods, began to draw up plans for continuing science operations during the roughly seven months before and after superior conjunction blackout when earth pointing the HGA would be unsafe. Testing soon showed that scientific data and spacecraft housekeeping information could continue to be downlinked with the HGA offpointed to operate first off peak on its primary lobe, and then on its first and second sidelobes — at dramatically reduced bandwidth (see Table II-1) — using Deep Space Network (DSN) 70 meter antennas instead of the 34 m antennas more commonly used for STEREO downlink. During sidelobe operations, heavily subsampled telemetry from S/WAVES, PLASTIC, and IMPACT are being recorded on the solid-state recorder (SSR), and will be downlinked as soon as normal, primary lobe operations resume in late 2015.

Testing also showed that the very low rate "space weather beacon" transmission of heavily subsampled (and in the case of SECCHI, heavily and lossily compressed) data for near-realtime space weather applications could be acquired with DSN 34 m antennas. Since ~ 8 hours of 34 m downlink per spacecraft per day was required to achieve the nominal data return for this phase of the mission, we have asked DSN to schedule ~ 16 hours per day in order to keep at least space weather quality data coming down at all times except the superior conjunction blackout periods.

	Bandwidth (kbps)	Dates (Ahead)	Dates (Behind)
Primary lobe	120 - 160	< 2014/08/20, > 2015/11/19	< 2014/11/30, > 2016/01/05
First sidelobe	10 (7.4)	2014/08/20 - 2015/01/04; 2015/09/24 - 11/18	2014/12/01 - 2015/01/05; 2015/04/25 - 07/07; 2015/11/20 - 2016/01/04
Second sidelobe	3 (1.7)	2015/01/05 - 03/21; 2015/07/14 - 09/24	2015/01/06 - 01/20; 2015/03/30 - 04/24; 2015/07/08 - 11/19
Beacon mode	0.633	sidelobe periods	

Table II-1. Downlink bandwidths around 2 AU (surrounding superior conjunction) and planned dates. The figures in parentheses in the bandwidth column refer to scientific data packets; the remainder of the sidelobe bandwidth is used for spacecraft subsystem housekeeping packets. All sidelobe contacts assume DSN 70 meter antenna contacts; all other figures reflect normal science support (34 m antennas). The space weather beacon mode data is usually acquired by antenna partner sites with smaller dishes, but can also be acquired with 34 m antennas during the months when only sidelobe communication is possible.

B. Spacecraft autonomy during superior conjunction. Each STEREO spacecraft is hard-wired to put itself into safe mode, with power-positive attitude, in the event of ~ 70 hours' passing without contact from earth. It was determined that subsampled scientific observations could be carried out in this mode and recorded on each spacecraft's SSR, to be played back in 2016 January after return to nominal operations. Only the S/WAVES team decided to make use of this opportunity; the other instrument teams decided that issues with high voltage systems being repeatedly power cycled were to be avoided (IMPACT, PLASTIC) or that the data volume returned from such operations did not justify the operational risk (SECCHI).

C. Loss of contact with the Behind spacecraft. On 2014 October 1, the mission ops team was testing transition to spacecraft autonomy on the Behind spacecraft when dual single points of failure followed one another in quick succession. After the spacecraft reset, the star tracker failed to acquire a guide star in a timely fashion, so the onboard autonomy rules caused the remaining IMU to be powered on in order to maintain a power-positive attitude. Unfortunately, the IMU not only experienced the failure of a laser ring gyro, but the onboard monitoring and control software continued to regard the data coming from the IMU as still valid. Contact with the spacecraft was lost as the spacecraft was presumably commanded to correct for the invalid rate information, and has not been reestablished, despite many attempts to recover communications. These have recently been carried out during three DSN 70 m contacts per week, but are in abeyance while the Behind spacecraft is passing through three months of superior conjunction. NASA has established a Failure Review Board to examine the loss of control scenarios and make a best estimate of current spacecraft attitude and prospects for recovery, based in part on the partial telemetry frame acquired after loss of signal lock.

Since the status of Behind is still in doubt, the science, technical, and budget sections that follow all treat the cases of one- and two-spacecraft mission extensions. Per direction of the Heliophysics Mission Operations and Data Analysis Program Executive in 2014 October, we are including two proposed budgets, for one- and two-spacecraft operations respectively (see Section V).

III. Science and Science Implementation

IIIa. Data Accessibility and Impact

A Note on Hyperlinks: Rather than spelling out URL's, which tends to introduce awkward line breaks in the text, we provide a hyperlink (in blue and underlined) for each Internet-accessible resource mentioned in this proposal. The hyperlinks should be clickable in the PDF version of this document.

Research and space weather uptake. Data from STEREO have been incorporated into many scientific investigations, and some of the same services currently using observations from older assets of the Heliophysics System Observatory (HSO). Since the launch of STEREO in 2006 October, some 936 refereed publications have made use of STEREO data (see Appendix B), and there have been 27 Science Working Group meetings. An ACE / STEREO / WIND *In Situ* Science Workshop was held at Caltech in April 2014. The STEREO mission has also featured prominently in a number of general science meetings since the last Senior Review. Two of the eleven sessions in the Solar, Heliospheric and Interplanetary Environment (SHINE) conference in 2013 were heavily dependent on STEREO data, one on linking remote sensing and *in situ* data for solar energetic particle events, and another on the extreme CME of 23 July 2012. The 2014 SHINE conference also had two sessions involving STEREO, both on solar energetic particles. Using STEREO images for the 3D reconstruction of the solar corona was an important topic in both the Solar Image Processing workshops held during the period, SIPWork VI in Bozeman, MT in 2013, and SIPWork VII in La Roche en Ardennes, Belgium in 2014. The June 2013 Community of European Solar Radio Astronomers (CESRA) workshop in Prague, Czech Republic was devoted to the challenges posed by the new viewpoints from STEREO and Wind, combined with the upgraded capabilities of ground-based telescopes.

The services using STEREO data include the Solar Weather Browser from the Royal Observatory of Belgium, the SolarSoft Latest Events service maintained by the Lockheed-Martin Solar and Astrophysics Laboratory, the Integrated Space Weather Analysis System from NASA Goddard Space Flight Center. The NOAA Space Weather Prediction Center uses STEREO Beacon data on a regular basis, and serves them *via* a Website similar to that used for serving ACE realtime solar wind data. In China, University of Science and Technology's DREAMS Website includes a SECCHI EUVI 304 Å eruptive event database as well as a mirror of the STEREO Science Center (SSC) movie site. Also, the asteroid and comet-hunting communities have become avid users of the STEREO data, and even the variable star community has found the data valuable.

Accessibility. All STEREO science data are accessible on the Web through the STEREO Science Center (SSC) archive and Principal Investigator (PI) sites. The data in the SSC archive are identical to those on the PI sites, and are maintained by regular mirror processes running several times per day. ***The STEREO and SSC Websites together served ~56 Tbytes of data each year in the period 2013 - 2014.***

Adherence to standards has allowed STEREO data to be easily incorporated into a number of online browse tools. Interactive plots of *in situ* and radio data, together with the data themselves, are available through the CDAWeb. The Heliophysics Data Portal (formerly "VSPO") maintains an extensive list of STEREO-related services. STEREO image data are incorporated into the tools listed above, under "uptake."

Although tools for accessibility are already in existence, a number of browse tools that enhance accessibility have been developed by the instrument teams. In addition to the NOAA beacon mode site noted above, a daily browse tool based on the SECCHI images and beacon *in situ* data is maintained on the SSC website. Customized browse pages are also available from the SECCHI, IMPACT, PLASTIC, and S/WAVES instrument sites. For example, daily Javascript movies from the SECCHI telescopes can be viewed at various resolutions at a SECCHI movies Webpage, and the IMPACT team combines STEREO and ACE realtime data to create displays emphasizing the solar system context of the multipoint measurements. Additional S/WAVES data are available from the Centre de Données de la Physique des Plasmas in France. The SECCHI/COR1, SECCHI/HI, and S/WAVES teams are providing higher-level data products (e.g. event catalogs) to direct researchers to the most interesting data sets. Additional event lists combine IMPACT and PLASTIC data on shocks, ICMEs, stream interactions, and SEP events, and another list of suprathermal events is provided by the PLASTIC team. These latter lists are archived on the SSC website as Level 3 data products. The STEREO Space Weather website at NRL, accessible through the SSC website, contains links to ancillary data for major events observed by many of the STEREO instruments.

Research access. The Virtual Solar Observatory (VSO; Hill *et al*., 2009) acts as the primary access point for all STEREO data, with the SSC as the data provider. This maximizes the use of existing resources without duplication, and enables collaborative data analysis with other solar observatories. The Virtual Heliospheric Observatory (VHO) serves PLASTIC solar wind, IMPACT magnetometer and particle data, and S/WAVES intensity spectra. The Heliophysics Data Portal provides access to STEREO data from many different sources, including the VSO and VHO. SPASE descriptions for most STEREO data products have been registered within the Space Physics Data Facility, and the few exceptions (mainly the newer products) are actively being pursued.

Data are available from the individual PI and Co-Investigator (Co-I) institutions, and in the case of some of the *in situ* and radio data at the CDAWeb website at the Space Physics Data Facility (SPDF). A list of all access sites is maintained on the STEREO Science Center Website.

The data products available from the STEREO project are now in a mature state. However, there are several new or improved data products which have become available since the last Senior Review. The SECCHI/HI Level 2 data are now available with full calibration applied, with the diffuse source correction applied, as well as in a form suitable for unresolved point sources. The IMPACT magnetic field and PLASTIC plasma parameters data product, previously available in ASCII format, is now also available as CDF files. **The remote sensing and *in situ* data being actively delivered to the SSC and SPDF form the major core of what will become the STEREO long term archive.**

Space weather. In addition to the normal science data provided by the instrument teams, STEREO also provides instantaneous beacon data to the space weather community. These data are used extensively by the NOAA Space Weather Prediction Center, as well as the NASA Goddard Space Weather Research Center. The Community Coordinated Modeling Center (CCMC) is modeling both the ambient solar wind and selected eruptive events in support of STEREO data interpretation. The Global Oscillation Network Group (GONG) is providing daily updated magnetograms, synoptic maps and potential field source surface models that can be used in analyzing prevailing coronal magnetic field geometry and solar wind sources on a near real-time basis. A number of space weather apps for smart phone and tablet devices now incorporate STEREO data, including 3D Sun developed with NASA support for the iPhone/iPad, and which combines STEREO and *SDO* imagery into a browsable map of the entire solar surface.

Publications. The SSC maintains a database of published journal articles and proceedings on the SSC Website; a standalone list is available as well. Many pre-publication works are made available by the authors through the Solar Physics E-Print Archive.

IIIb. Assessment of scientific progress, FY2013 - FY2015

In our 2013 Senior Review Proposal, we set out ten prioritized science goals (PSGs) organized into three goal sets for STEREO mission science in 2014-2018. Here we report on progress on the goals, including discussions of selected science results from some of the many STEREO related papers published in recent years, and discuss plans for addressing these goals in the future. We also discuss data needs and the effect of the possible loss of STEREO-B on the PSGs, which, although regrettable, would not prevent substantial progress. After each PSG name, we include in parentheses the Research Focus Area from the 2009 - 2030 Heliophysics Roadmap to which the science is relevant (see Appendix E for a list of focus areas).

Goal Set 1: Characterize space weather throughout the inner heliosphere

PSG1-1 Understand the Large Scale Structure of ICMEs (F2, J3, J4)

Statement of Goal. The classic picture of an ICME assumes an interplanetary flux rope, originating in the corona and still attached to the Sun while plowing outward through the ambient solar wind. Its propagation makes a preceding region of compressed solar wind 'sheath' and, if it is fast enough, a leading shock. This picture has been applied for decades to in-situ plasma and field measurements, heliospheric models, and geomagnetic storm predictions. However, earlier multi-spacecraft investigations hinted at the fact that this idealized description does not match most observations of the same event at different sites. Both the solar source(s) and interactions with the surroundings affect what is experienced. STEREO provides the opportunity to regularly observe ICMEs at ~1AU at separated locations with a full suite of key instruments, including multi-perspective images of the associated coronal eruptions at their source. Achieving this goal requires diagnosing these more complicated real structures and the physics that determines their multipoint in-situ attributes.

Progress and Science Highlights. Three major surveys have been carried out with STEREO data toward understanding the large scale structure of Interplanetary Coronal Mass Ejections (ICMEs) during the STEREO era – which so far spans the long cycle 23-24 solar minimum and the rising phase of cycle 24. Jian et al. (2013) found that compared to ICMEs observed during the previous solar minimum, the STEREO-era events had weaker maximum magnetic fields – consistent with the known reductions in both solar surface and ambient interplanetary fields over this period. These events were also found to be slightly slower and smaller. The Möstl et al. (2014) study of 22 individual cases of ICMEs investigated the relative accuracy of different models and the importance of multiple points of view in predicting speed, direction, and arrival times.

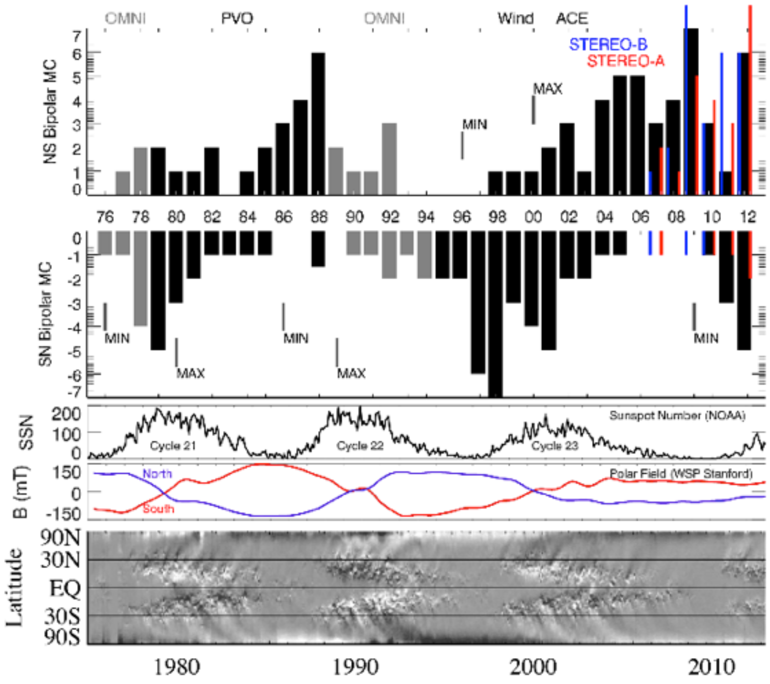


Fig. III-1: The north-south component of the heliospheric magnetic field (B_z) is the primary parameter influencing geomagnetic effects of ICMEs passing Earth. Li et al. (2014) study this parameter as seen from Earth/L1 and the broader perspective of the STEREO spacecraft. The thick black and grey bars in the top panels represent annual statistics of the two main ICME polarities measured at spacecraft other than STEREO, while STEREO-A and B observations are shown by the red and blue bars, respectively. The lower panels show the sunspot number and solar polar magnetic field strength. Although there are clear trends with solar cycle, exact B_z values vary significantly with location.

Li et al. (2014) track the properties of the most clearly defined ICME drivers, the magnetic clouds, during the STEREO era (Fig. III-1). The magnetic fields of these CME structures can generally be fit with flux rope models and often have bipolar signatures (rotating field direction) in their north-south, or B_z, components that exhibit a clear solar cycle trend. B_z is of particular interest because it is the primary parameter driving geomagnetic effects of ICMEs passing Earth. The predominant ICME magnetic cloud polarity is known to reverse around the time of the solar polar field reversal around solar maximum, with the predominant sign agreeing with what would be expected for a solar dipole field extending out to 1 AU. The STEREO-specific question of interest is whether this polarity pattern looks the same at different heliospheric locations. Li et al. find that the ICME occurrence rates differ at different locations 1 AU from the Sun. However, while details differ in the percentage of one B_Z polarity over the other, the phasing of the ICME polarity reversal with the start of the cycle 24 solar low-latitude field reversal in 2010 is clearly distinguishable everywhere. This work complements ongoing efforts to predict B_z in ICMEs (*e.g.* in NASA's LWS Program and at AFOSR) from observations of their solar source regions.

Future prospects. STEREO observations are now regularly used in conjunction with global heliospheric models of ICMEs toward sorting out which events are related, and how they are related. Realistic, 3D models of the solar wind structure such as ENLIL, SWMF, and CORHEL push the state of the art in injecting coronal disturbances with increasingly realistic attributes to simulate their global consequences at 1 AU. The availability of STEREO data with its well-separated (from L1) perspective continues to both motivate this work and provide an observational basis for its validation. The ultimate goal is sufficient understanding to reproduce, with models, the observed multipoint ICME attributes based on solar observations.

PSG 1-2 Physics of ICME interactions (F2).

Statement of Goal. Several studies have examined two aspects of the topic of ICME interactions over the last two years. One aspect concerns the manner in which ICME interaction with the ambient medium during propagation alters the properties of what arrives at 1 AU. The other concerns interactions between multiple ICMEs that occur in close spatial and temporal proximity and how such proximity factors in the nature of extreme space weather events.

Progress and Science Highlights. In the last two years solar activity approached a maximum. Under such circumstances, coronal mass ejections (CMEs) can occur in quick succession and the possibility of CMEs interacting in the inner heliosphere increases greatly. CME-CME interactions are important both because they affect CME/ICME propagation and evolution, and, from a space weather point of view, because the resulting geomagnetic effects can be drastically altered. STEREO studies of interacting CMEs take advantage of the combined Heliospheric Imager (HI) and *in situ* observations to understand their nature. Webb et al. (2013) use these to address the complicated structure of the inner heliosphere during a very active period in early August 2010, an interval that is also the subject of dedicated Workshops and associated publications. The authors reconstructed 3D heliospheric densities from the images and compared them with the timing and magnitude of *in situ* density structures at five spacecraft locations spread over 150 deg in ecliptic longitude and 0.4 to 1 AU in radial distance, together with modeled local flux rope structures. This work highlights the difficulties inherent in reliably diagnosing the kinematics and morphological evolution of ICMEs during periods of widespread activity.

The occurrence of an exceptionally fast and large CME seen as a halo event on STEREO-A when the spacecraft was about 120 degrees ahead of Earth on 2012 July 23 inspired multiple NASA media alerts and press activity. The excitement was in part due to its occurring during such a weak solar cycle, but also because its near-Sun speed, at upwards of ~2500 km/s was at the high end of observed CME speeds. The event also spawned an exceptionally intense Solar Energetic Particle (SEP) event detected by STEREO-A that was described by Russell et al. (2013), who noted that the leading shock of the ICME was likely eroded by the significant local pressure contribution of the large local density of SEPs. The question of how extreme space weather storms form and evolve, and how severe they can be when they reach Earth, was examined by Liu et al. (2014a), where the authors investigated this period using multi-point remote-sensing and *in situ* observations. At least three effects of CME-CME interactions were found to influence the observed event: a change in the propagation direction leading to a head-on impact with STEREO-A, the extreme enhancement of the ejecta magnetic fields to over 100 nT, and the exceptionally modest deceleration during Sun-STEREO-A transit. Together, these caused an unprecedented set of interplanetary field conditions, including an extended period of strong southward magnetic field ($-B_Z$) which, had it hit Earth, would have produced a record geomagnetic storm with a minimum Dst of order -1150 to -600 nT. The event would have been comparable to other Carrington Event class storms (see Freed et al. 2014). These results provide new insights on how an extreme space weather event can arise from a combination of solar eruptions.

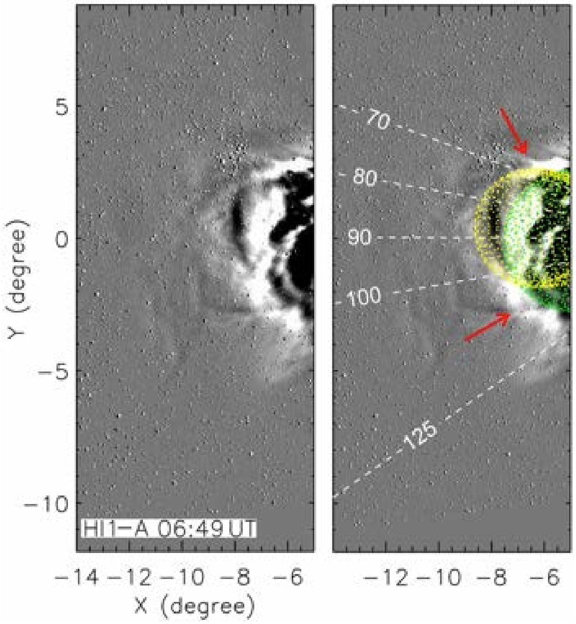


Fig. III-2: Study of interaction of two CMEs from 2011 Feb 16 using data from STEREO-A/HI (Temmer et al., 2014). The flux ropes modeling the two CMEs are shown in yellow and green, and the red arrows show the locations where the boundaries of both flux ropes are assumed to interact. Temmer et al. found that the interaction process strongly depends on the geometry of the situation. There were differences in the outcome for interacting ICME flanks versus apexes, with the central interaction showing the strongest changes in kinematics.

Several investigations examined the kinematics of ICME interactions to determine the manner in which they merge. Maricic et al. (2014) describe a chain of CME events in 2011 February 14-15 and found evidence for a gradual momentum transfer from the faster to the slower CME ahead. They infer that momentum transfer may result from alteration of the following events' shock propagation as they travel through the preceding events. Temmer et al. (2014) (Fig. III-2) present a detailed analysis of the interaction of two of these CMEs. It was found that the interaction process strongly depends on the geometry of the situation. There were differences in the outcome for interacting ICME flanks versus apexes, with the central interaction showing the strongest changes in kinematics. This topic was also addressed by Mishra and Srivastava (2014), who describe evidence in the *in situ* observations near 1 AU of acceleration, compression and heating of the leading ejecta. Shanmugaraju et al. (2014) examined the corresponding radio enhancement in detail using multi-wavelength data from SOHO LASCO, STEREO HI-1, and Wind/WAVES. A radio emission intensification was observed in the frequency range 1 MHz –

400 kHz. Kinematic modeling of the interacting event was used together with a density model to estimate the shock height for the radio enhancement, found to be 10-30 solar radii.

Several other periods of related interest, such as 2012 March with its 29 significant CMEs in a period of about 3 weeks, remain to be examined in more detail.

Future prospects. As interacting CME events are often responsible for enhanced space weather disturbances of many kinds, and also affect our ability to relate solar and interplanetary events for either research or forecast model purposes, they now occupy a prominent place in the set of overall challenges for heliophysics. The collective body of work so far tells us one typically cannot isolate events. As an example of ongoing activity in this area, two related projects under different PIs in the LWS Program are expecting to produce a quasi-continuous set of ENLIL runs with cone model CMEs for the STEREO years. These will provide global details such as shock connection mappings and first-order interacting CME information for a host of applications including STEREO data interpretations and model validations using STEREO data.

PSG 1-3: Understand how solar energetic particles are distributed so efficiently around the Sun (F2, H1, J1, J2, J3).

Statement of Goal. Early in its mission STEREO observations renewed the interest in the longitudinal extent of SEP events, and its physical determinants. This topic is of interest for understanding both heliophysical and astrophysical particle acceleration and transport, and for its importance in predicting space weather effects of SEPs.

Progress and Science Highlights. Just after solar activity began picking up in cycle 24 the STEREO spacecraft reached the far side of the Sun, providing our first 360° solar view and presenting a unique opportunity to use 3-point measurements (with near-Earth spacecraft) to investigate how solar energetic particles (SEPs) are distributed about the Sun. Several events early in the cycle showed that SEP longitudinal transport can be much more efficient than expected. For example, small, ^{3}He-rich flare-related events were expected to originate from compact regions with angular spreads of ±20°, but Wiedenbeck et al. (2013) found events observed over >50°, including the 3-spacecraft 7 Feb 2010 event spanning ≥159°. In contrast, Cohen et al. (2013) studied seven ^{3}He-rich events observed by a single spacecraft with upper limits at the other two. They suggested that a preceding Halo CME may have affected the SEP transport during the 7 Feb 2010 event. Bučík et al. (2014) identified several long-lasting ^{3}He emission sources successively observed by at least two among STEREO-B, ACE, and STEREO-A, implying ^{3}He emission processes are more continuous than previously thought. This is evidence for another mechanism which can produce broadened ^{3}He distributions.

For large SEP events resulting from CME-driven shocks, both Lario et al. (2013) and Richardson et al. (2014) fit 3-spacecraft measurements of the peak intensities of >15 MeV protons with Gaussian distributions. Both studies found a mean width of sigma = 43°, somewhat larger than found by an earlier study using Helios and near Earth data. The widest events had sigma ≈ 85° (Richardson et al. 2014).

Progress was also made on the question of how source(s) versus transport affect the local characteristics of SEP events including onset and intensity. In a 2012 paper Rouillard et al. combined imaging of the coronal EUV 'wave' signature and in situ data to investigate whether the lateral expansion of the CME near the Sun can lead to rapid SEP acceleration up to ~90° from the related flare site. Their results indicated a positive relationship, with prospects for modeling and forecasting. Richardson et al. (2014) extended this work to 25 events and found that the onset delay observed by a spacecraft separated from the best connection point by $\Delta\Phi$ degrees in longitude is equal to $\Delta t = 53.5 exp(\Delta\Phi/64.9°)$ minutes, supporting the idea that particles are not observed on a given field line until the lateral expansion of the CME shock reaches that field line. Dresing et al. (2014) used SEP pitch-angle distributions from 19 multi-spacecraft events to distinguish whether efficient perpendicular transport or an extended source region at the Sun was responsible for wide-spread SEP events. They concluded that both effects were required. Dröge et al. (2014) also reached this conclusion using numerical solutions of a 3-dimensional particle propagation model (See Fig. III-3).

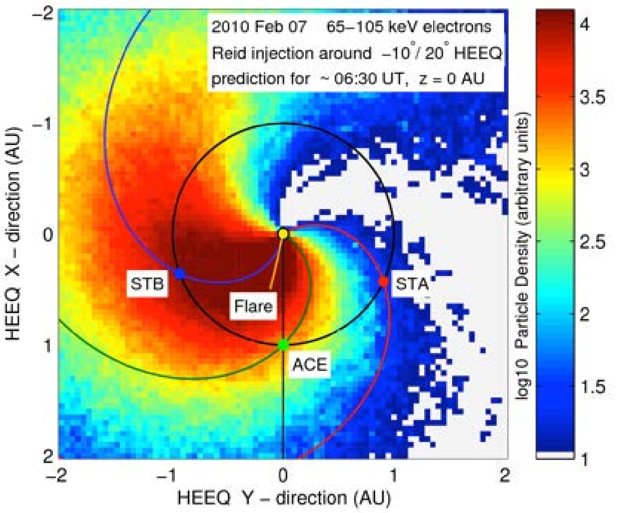
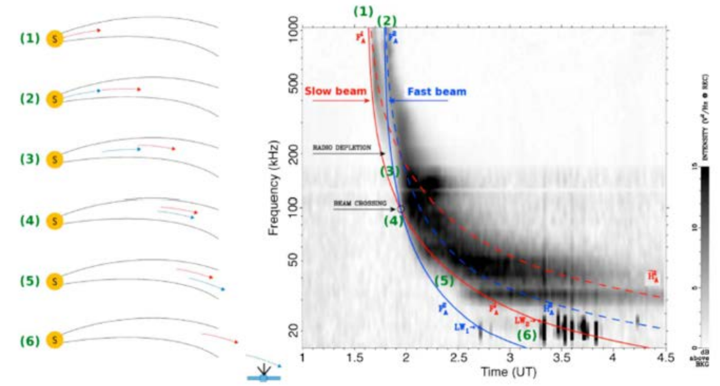


Fig III-3 Results of the three-dimensional modeling for the spatial distribution of near-relativistic electrons in the solar equatorial plane 4 hours after the injection following the flare on 2010 February 7 by Dröge et al. (2014). While the transport along the magnetic field lines is the fastest process the electrons also fill a broad longitudinal range of 180° at a distance of 1 AU. The authors conclude that this broad longitudinal spread of electrons took place partially close to the Sun and partially due to diffusion perpendicular to the average magnetic field in the interplanetary medium.

Future prospects. As in the case of the widespread activity analyses of ICMEs and their solar source connections (PSGs 1-1, 1-2), we have only scratched the surface of what can be learned from the distributed STEREO measurements in the SEP area. In particular, the realistic global heliospheric modeling now coming of age for the corona and heliosphere is starting to be applied to the development of consistent SEP and heliospheric models. The STEREO observations provide the basis for case studies for their validation. Moreover, the evolution of SEP activity as the current unusual solar cycle winds down is of interest in light of the STEREO-A major event detection in 2012 July. Indeed, a nearly comparable SEP event in December 2014 has been identified and awaits the downloading of onboard stored (SSR) data in late 2015 for a more complete analysis and documentation.

2013 PSG 1-4: Radio and in situ multi-spacecraft measurements of solar type III bursts (F2, J2, J3).

Statement of Goal. The radio burst signatures of solar flares are the fast-drifting type III radio bursts that extend from near the flare site outward beyond 1 AU. The radio emission is



generated by a plasma wave process, in which energetic, flare-accelerated electron beams traveling outward along open magnetic field lines cause the growth of plasma oscillations known as Langmuir waves. The specific mechanism by which Langmuir waves are converted into the observed type III radio emission is a puzzle that STEREO is helping to answer.

Progress and Science Highlights. Recent observations from STEREO have substantially advanced our understanding of the solar radio bursts that originate at flare sites and traverse the inner heliosphere (solar type III radio bursts). At least twelve publications in scientific journals address details of the complex process by which the flare-accelerated electrons produce electric field oscillations that are converted to radio waves.

Thejappa, MacDowall, and Bergamo (2013) found that STEREO WAVES (S/WAVES) data provide evidence for the role of strong turbulence and the so-called oscillating two-stream instability to generate the radio waves and stabilize the electron beam so that it can travel more than an AU through the inner heliosphere. The spectra of these bursts, obtained with the S/WAVES time domain sampler (TDS), may contain peaks at f_{pe}, $2f_{pe}$ and $3f_{pe}$ (f_{pe} is the electron plasma frequency), which is the first time these observations relevant to the conversion from electrostatic to electromagnetic waves have been convincingly observed for type III bursts.

It is likely that the above results only apply to intense electron beams, whereas a wide range of electron beam fluxes exists. Graham, Cairns, and Robinson (2013) have extended the investigation of electrostatic decay as the mechanism whereby the electron beam is stabilized and radio emission produced. They discovered that Langmuir waves have characteristics that may be explained by "snake-like" structures also seen in numerical simulations of the process. Graham and Cairns (2014) also divided the TDS events into six classes based on the waveform, power spectra, and field strength perpendicular to the local magnetic field. This classification allowed them to demonstrate that the electron beams, in conjunction with variations of the solar wind and magnetic field, likely produce electrostatic waves in several distinct ways.

The S/WAVES data have also provided other interesting results not directly related to the long-studied radio emission generation mechanisms. Briand, Henri, and Hoang (2014) have identified and analyzed in detail a type III burst where part of the burst is affected by the interaction of two separate electron beams produced at the same location- resulting in two separate radio bursts at high frequencies (close to the Sun). This analysis (see Fig. III-4) may help to explain variations that are seen in the time profiles of many of the type III bursts.

Figure III-4: (left) Schematic view of the two electron beams' positions corresponding to the radio observations. The numbers 1–6 are used to define several moments of the beam propagation. (right) Radio *spectrogram observed by STEREO-A on 18 July 2009 from 01:00 to 05:30 UT in the 15–1000 kHz range with the paths of the Type III bursts associated with the beams shown in red and blue (Briand et al, 2014).*

Future prospects. The results cited above indicate considerable progress in the theoretical study and scientific applications of solar type III bursts. Similar progress is being made in the modeling of solar type II radio bursts, produced by electrons accelerated at CME-driven shocks (Xie et al., 2013; Schmidt and Cairns, 2014). Both types of bursts are generated by similar plasma wave emission processes. Based on the STEREO and Wind results, we can foresee the theoretical understanding of the emission process reaching a point where there is common agreement among researchers. We hope to facilitate this improved understanding by arranging one or more workshops where the various researchers in the field will meet to compare data and summarize findings. Then, the application of the radio bursts for tracing magnetic field lines and shock propagation will be more accurate. This will be particularly interesting for type II and type III bursts observed in the future, where the improved modeling will be integrated into systems providing near real-time predictions of space weather.

PSG 1-5: Characterize space weather throughout the inner heliosphere (F2, J1, J3, J4).

Statement of Goal. Space Weather is usually associated with Earth's space environment, but it is in its broader definition solar system-wide. Solar activity's effects: the production of flares, ICMEs and SEPs affects each planet and solar system body in its own distinctive way. But almost all planetary missions capable of observing a planet's response cannot usually measure the inputs defined by the energetic photon flux on the face of the Sun seen from the planet or the external particles and fields it is exposed to.

Progress and Science Highlights. There has been substantial work on this PSG over the last two years made possible by the solar activity level and the availability of spacecraft at various locations in both radius and heliolongitude (MESSENGER at ~0.3 AU, Venus Express at ~0.7 AU, and at 1 AU Wind, ACE, SOHO, and of course STEREO with its dual, separated perspectives). In particular, the multipoint in-situ observations from 0.3 to 1 AU and multi-perspective images from 1 AU continue to be an essential link for interpreting the solar system-wide evolution and consequences of solar wind structure and CMEs. STEREO provides these inputs for the planetary missions, taking advantage of its unique longitudinal alignments.

Nieves-Chinchilla et al (2013) use the joint in-situ/imaging observations to study the 3D evolution of a 'stealth' CME in great detail. In Möstl et al. (2014), the examination of 22 events seen at the Sun and in heliospheric images, and then at various 1 AU locations, gave a new, more comprehensive empirical picture of how CMEs are affected as they propagate from the Sun. They both confirm the previously found deceleration of fast CMEs and also establish the limitations of in-situ arrival predictions based on certain proposed forecast models. An important finding was that the errors of hours, and sometimes days, in arrival times found for many sources are difficult to account for; possible factors include the history of interaction with ambient structure and the assumed shape of the propagating driver.

MESSENGER, with its SEP detection capability, provided opportunities to evaluate the radial dependence of peak SEP intensities for a selected set of events where MESSENGER lined up along the interplanetary spiral field with one of the distributed 1 AU spacecraft. Lario et al. (2013) studied the radial and longitudinal distribution of ~100 keV SEP electrons using Messenger, STEREO, and ACE data (See Fig. III-5). They found two events with a radial dependence of the peak intensity significantly greater than the R^{-3} dependence expected from standard diffusion theory. Both cases involved SEP events occurring in a complex interplanetary medium, providing additional support to the paradigm shift described above concerning the importance of the heliosphere-wide perspective during active times.

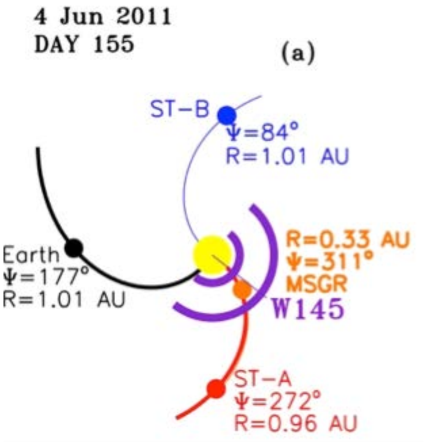


Fig. III-5: Lario et al. (2013) studied the radial and longitudinal distribution of ~100 keV SEP electrons using MESSENGER, STEREO, and ACE (Earth) data and found a radial dependence of the peak intensity significantly greater than the R^{-3} dependence expected from standard diffusion theory. Here the positions of Stereo A and B , MESSENGER and Earth are shown for one of the events. The spiral lines are the nominal interplanetary magnetic field lines attaching each the different spacecraft to the Sun. The purple semi-circles indicate the presence of interplanetary shocks.

The use of STEREO measurements to validate (WSA-)ENLIL also indirectly benefits MESSENGER analyses that use the model to assess external heliospheric conditions at MESSENGER, where in-situ solar wind information is limited (Baker et al. 2013).

Future prospects. The studies described here could not have been done without the availability of the distributed in-situ measurements and multi-perspective imaging provided by STEREO. In the next year a new inner heliosphere data set at another radial distance will be provided by the solar wind plasma, magnetic field, and SEP detectors on MAVEN at Mars at ~1.5 AU (Jakosky et al., 2015). With these new regular measurements at Mars, the continued STEREO observations take on a new importance for both contextual space environment information and for planning future human exploration of that planet. Solar Probe Plus is scheduled to get in to 0.18AU in 2018, where it will sample the SEP environment at an unprecedented proximity to the Sun. Together with eventual Solar Orbiter data around Mercury's orbit and at higher latitude, this will provide major new insights about the sources and evolution of the SEPs seen by STEREO and L1 spacecraft in their different locations at 1 AU. There is no greater advantage than these combined, radially, longitudinally and latitudinally separated measurements for constraining the newly developing global models of SEPs in the inner heliosphere.

Given this intense level activity and promise for its continuation, we are confident that this PSG as a whole will remain a main scientific driver not only for STEREO, but also for a significant part of the HSO.

With the STEREO mission it is also possible to experiment with concepts such as L5 or similarly one-sided perspectives (in addition to L1) to determine the extent to which a single side-looking spacecraft to the east will be adequate to characterize our future space weather. In the next few years STEREO-A will be heading into a position into the eastern sky and can act, for a time, as the ‘L5’ sentinel on which we will depend. It is a test of the L5 mission concept that may determine the direction of the space weather enterprise as a whole.

Goal Set 2: What Can We Learn from 360° Coverage of the Solar Corona?

PSG 2-1: Uncover the large-scale couplings in solar eruptive events (F1, F2, H1, J1, J2, J3)

Statement of Goal. STEREO far-side observations are combined with Earth-side observations of SDO and SOHO to provide essential views of the large scale, global properties of solar eruptions. This includes the connections between CMEs, flares, EUV waves, and shocks; interactions between different events; and the occurrence of sympathetic events in which one event appears to cause another and repeated homologous events.

Progress and Science Highlights. The multiple, interconnected CMEs on 2010 August 1 were studied in a series of papers (Webb et al 2013; Harrison et al. 2012; Liu et al. 2012; Möstl et al. 2012; Temmer et al. 2012; Titov et al. 2012). The role of expanding EUV waves in triggering activity in distant active regions was investigated by Shen et al (2013) while the 360° coverage of the corona allowed Olmedo et al (2012) to study wave reflection and transmission in coronal holes without the ambiguities of past studies. Overall, large-scale studies of EUV waves were greatly improved by the availability of 360° views of the corona and will probably remain an active research focus for the foreseeable future. The subject has been recently reviewed by Liu & Ofman (2014) and a recent paper by Kwon et al. (2014).

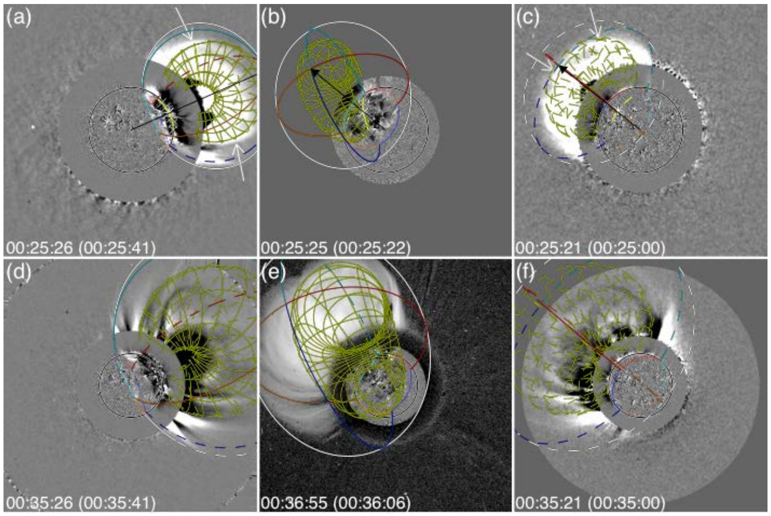


Figure III-6: 3D-reconstructed structures of the CME on 2012 March 7 at various times in running difference images. Green curves represent the CME ejecta with the GCS model (Thernesien at al 2006). Left, middle, and right panels show the composite images taken from STEREO Behind, SDO, and SOHO, and STEREO Ahead, respectively.

The ability to separate CME and shock structures and then study their relative 3D evolution is crucial in many heliophysics fields, such as: solar energetic particle distributions and intensities throughout the inner heliosphere, the magnetic structure of the corona, and the force balance within the CME and with its surroundings. Kwon et al. (2014) use STEREO 360° coverage to address the 3D structure of CME-driven shocks and how they connect to EUV waves observed in the low corona and the CME front. They incorporated a simple geometric representation of a shock as a spheroid into a 3D forward modeling code to reconstruct simultaneously the shock and associated CME (as a flux rope) in March 7, 2012. The fits (Fig. III-6) describe very well the complex morphology of the eruptive events in all three coronagraph viewpoints. They clearly demonstrate that (1) the halo appearance of CMEs is mostly due to the shocks rather than the CME itself, and (2) the EUV wave is the low corona footprint of the expanding CME shock.

Most importantly, the knowledge of the location of the shock at any given time allows researchers to clarify the relation between SEPs and CME shock in multiple locations in the heliosphere as Lario et al (2014) have done using the Kwon methodology. This method paves the way towards a better understanding of the formation of shocks in the corona and their role in accelerating particles in the heliosphere, both long-standing issues in astrophysics.

Future prospects. This PSG reflects the unique achievement of NASA's Heliophysics Systems Observatory (HSO) to continuously observe the evolution of the solar corona over its full 360° extent. STEREO is the cornerstone for this accomplishment and remains so even without one of the spacecraft (see Section IIIc for a detailed discussion). As such, STEREO observations are still key to understanding the complete signatures of large scale eruptive events and remain a high priority for the STEREO mission during the period of performance of the current proposal. The SECCHI science team is pursuing these goals, closely coordinating with the operations team and other investigators. In particular there is currently a team studying the full longitudinal spread of energetic particles using reconstructions of 3D white light shocks.

PSG 2-2: Understand the lifetime of active regions, coronal holes, filaments, and filament channels (F1, F4, H1, H3, J1, J2)

Statement of Goal. Solar features including active regions, coronal holes, streamers, filaments and filament channels all evolve on time scales shorter than that of the solar rotation period. Thus, STEREO far-side coverage of the solar disk is vital to understanding the evolution of these features.

Progress and Science Highlights. Lowder et al. (2014) used the EUV observations to estimate the amount of open flux from coronal holes during Cycle 24. They found that data from SECCHI EUVI and SDO AIA allowed a more accurate assessment of the flux from equatorial coronal holes than had been possible using data from SOHO EIT or ground based sources.

Another important use of the 360° coverage was the derivation of an EUV proxy for the GOES soft X-ray (SXR) scale of flares by Nitta et al. (2013). This result allows researchers, especially in the SEP community, to compare and contrast analyses of far-side flares and associated SEP levels to work done in the past, which is tied to flare intensities based on the GOES scale.

The utility of GOES SXR observations of flares extends beyond simple monitoring to deriving plasma parameters and estimating the amount of energy release, especially for large events. These parameters, particularly the SXR classification of a flare event, have been used for years in joint analyses of flares, CMEs, and SEP production. However, while CMEs and SEPs originating beyond the Earth-facing solar disk are routinely observed with STEREO, their solar sources are not detectable by GOES or are heavily occulted resulting in spurious measurements. On the SEP side, the lack of a proper SXR scale for the far-side events made it difficult to correlate recent SEP analyses to pre-STEREO era work.

Fortunately, SECCHI EUVI coverage affords us a unique opportunity to expand our flare statistics without the need to launch a far-side X-ray monitor. Nitta et al (2013) have used the EUVI observations of far-side flares since 2010 to derive an EUV proxy at 195Å to the GOES SXR flux. The correlation coefficient is only 0.64 for the full sample but increases to an impressive 0.94 for flares above GOES M3 class (3×10^{-5} W m^{-2}). The scatter in the data is used to estimate an uncertainty for the proxy. Uncertainty in the EUV flux due to temporal variations during the event and range from 3% to 50%.

These results are very promising, given the significant differences in the origin of the EUV and SXR emission, and the simplicity of the single EUV wavelength approach. The high correlation for the more intense events is especially welcome since these are the events of most interest to the CME and SEP communities.

Future prospects. With its position on the farside of the Sun, STEREO continues to be in an excellent location to observe the full lifetime of coronal features. The SECCHI science team is pursuing these goals, closely coordinating with the operations team and other investigators. Studies are underway to study the full lifetime of active regions and coronal holes, and validate the new SDO HMI algorithm for far-side helioseismology using EUVI maps.

PSG Goal Set 3: What can we learn from coverage of the full heliosphere?

***PSG 3-1: Provide longitudinal coverage of the solar wind and transients that can affect the outer heliosphere* (F2, F4, J1).**

Statement of Goal. Coverage of the full heliosphere, including its outermost regions, requires the use of multiple assets in order to sample a range of different solar longitudes. At 1 AU, the near Earth solar and in-situ observatories, in particular SOHO, *Hinode*, SDO, Wind and ACE, provide the frontal view of the Sun and central meridian (solar longitude 0°) in-situ measurements. As the two STEREO observatories approach (and now recede from) superior conjunction (solar longitude 180°) from opposite sides, the STEREO provide unique and invaluable longitudinal coverage that has resulted in progress on this and the other PSGs in this section. Inner boundary conditions (solar wind and transients) affect the motion of the outer heliospheric boundaries, of particular interest to Voyager and IBEX observations. They also affect the generation and evolution of global merged interaction regions in the outer heliosphere.

Progress and Science Highlights. New observations of the outer heliosphere show that it is a dynamic region with both large-scale and small-scale changes in the interaction between the solar system and the interstellar medium. STEREO has given us better longitudinal understanding of the solar wind variability and solar transients, which is very important to understanding how the solar wind termination shock, heliopause, and energetic-neutral-atom (ENA) emission varies with location and time. Indeed, a recent review of the heliospheric magnetic field (Balogh and Erdos, 2013) mentions the importance of having STEREO A and B, with their extensive particle and field measurements, to the understanding of the dynamic evolution of solar wind and magnetic field structures.

Liu et al. (2014b) use STEREO and Wind observations of a series of CMEs in 2012 March as the input to an MHD model that propagates the disturbances out through the heliosphere. A merged interaction region (MIR) forms in their model, and that MIR reaches the heliopause on about 2013 April 22, which is consistent with Voyager 1 observations of radio emissions (Gurnett et al., 2013), a shock or pressure wave seen in the interstellar plasma (Burlaga et al. 2013), and similar in time to changes in the galactic cosmic ray fluxes (Krimigis et al., 2013). All of these effects are interpreted as the signature of solar transients propagating out into nearby interstellar space.

Future prospects. Over the next few years, STEREO will continue to be an important component in the understanding of the outer heliosphere and its interaction with interstellar space, especially as Voyager 2 traverses the heliosheath towards the heliopause. The community will continue to try and resolve disagreements in the observations of inflowing interstellar neutrals (see Progress on PSG 3-2), and to understand the structure and evolution of the still-puzzling IBEX ribbon of ENAs.

PSG 3-2: Pickup Ions (F2, F3, J1)

Statement of Goal. Pickup ions (PUIs) at 1 AU are studied with the PLASTIC and IMPACT sensors on STEREO. Interstellar PUIs originate from the penetration of the neutral component of the local interstellar medium (LISM), while solar system sources include neutrals from the so-called "inner source", planetary magnetospheres, and comets. A portion of these neutral populations is ionized by charge exchange with the solar wind and/or by interaction with the solar ultraviolet radiation. Direct measurements of interstellar pickup ions provide information on our solar system's passage through the LISM and the processing of neutrals as they pass through the solar system. As a counter point, inner source pickup ions provide information on solar wind – dust interactions in the inner heliosphere.

Progress and Science Highlights. Drews et al. (2012) used STEREO longitudinal surveys of He+, O+, and Ne+ to determine the flow direction and speed of interstellar neutrals. These observations are a direct benefit of the unique STEREO longitudinal trajectory and the large geometrical factor of the PLASTIC instrument. STEREO observations have established corresponding focusing cones and pickup ion crescent distributions related to the longitudinal distribution of interstellar neutrals aligned along the inflow direction of the LISM, which in turn can be used to infer the temperature of interstellar neutral helium, oxygen and neon (Drews, 2013). These studies also have important consequences to the structure of the galactic/heliospheric interaction (PSG 3-1), such as the location and strength of the possible bow shock in front of the solar system. The parameterization of the interstellar flow is currently controversial (Lallement and Bertaux, 2014), with implications for inner and outer heliospheric studies.

Another PUI survey by Drews et al. (2013) measured the velocity distribution functions of He+ pickup ions (Figure III-7), a task particularly suited to the directional measurement capabilities of the PLASTIC instrument on STEREO, which exceed the capabilities of previous missions due to the instrument's combining the use of position sensing detectors and electrostatic deflectors (similar detection techniques are now being incorporated in the Solar Orbiter composition instrument). Changes in spectral shape and reductions in the flux of He+ during radial magnetic fields have been previously reported by Ulysses, SOHO, ACE, and AMPTE, and attributed to inefficient scattering across the 90^{o} pitch angle by isotropic distributions. The pitch angle measurements by STEREO PLASTIC and IMPACT revealed a highly isotropic population of cooled PUIs, but superimposed on this population, an almost scatter-free PUI population was observed, following a strict gyro motion perpendicular to the magnetic field direction. The interpretation is that this is due to the injection of freshly ionized interstellar helium into the solar wind. This shows that the interstellar pickup ions are not fully isotropic and instead show distinct anisotropies resulting from the pickup process.

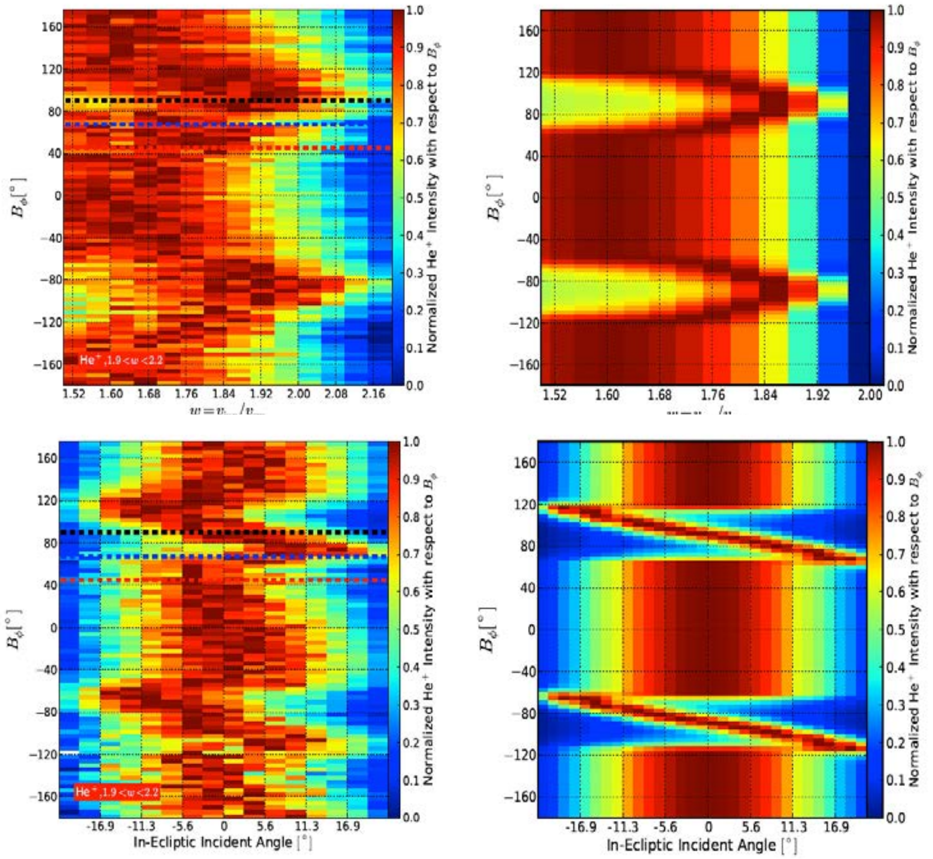


Figure III-7. STEREO Ahead measurements (left) and model results (right) of Drews et al. (2013) for interstellar He+ w-spectra (top), where w = ion speed / solar wind speed, and angle of incidence (bottom), measured as a function of the in-ecliptic pitch angle. The STEREO measurements reveal a highly isotropic population of cooled PUIs and also an almost scatter-free PUI population.

Future prospects. Pickup ion fluxes are subject to solar cycle influences, such as the cycle variations in the ultraviolet flux and proton flux that affect ionization rates. The interplanetary large-scale structures (e.g., ICME shocks, SIR compression regions) that accelerate pickup ions also vary with the solar cycle. He+ is a key pickup ion species due to its relatively high abundance at 1 AU and is often used as a tracer species in ion acceleration studies. PLASTIC currently provides the only continuous public data set for He+ fluxes in the lower suprathermal energy range, covering the past solar minimum conditions through mid 2014. Pickup ion data from mid 2014 to late 2015 will be unavailable due to the lower telemetry rates near superior conjunction, however once the nominal telemetry rate returns, the pickup ion measurements will be resumed to continue the study of pickup ion generation, focus cones, and acceleration processes seen during the declining phase. Continued data accumulation also enhance statistics for other sources of pickup ions, such as the inner source, and serendipitous sources, such as comets. For the studies of the focus cone and crescents and the inward flow directions of the local interstellar medium, the operation of one spacecraft will still cover the entire sky within a year's orbit. If STEREO B continues to be unavailable, it will be more difficult to distinguish transient effects and location effects in studying pickup ions and their acceleration.

PSG 3-3: Improve our understanding of dust in the inner heliosphere.

Statement of Goal. Dust detection plays a key role in understanding the evolution of the dust flux with time and increasing distance from the Earth, with applications for heliophysics and astrophysics.

Progress and Science Highlights. Additional S/WAVES dust observations over the past two years have significantly improved our understanding of dust in the inner heliosphere. The observations of interplanetary dust by STEREO are important because researchers believe that nanometer dust (nanodust) may be a significant contributor to the total mass of interplanetary space (Le Chat et al, 2013). Le Chat et al (2013) provide a new analysis of the nanodust based on a recent analysis of the last five years of S/WAVES Low Frequency Receiver (LFR) data. The statistical results show that the nanodust flux on STEREO A has decreased with time (See Fig. III-8). Because geometrical effects (such as projection effects including the flow direction of the dust and the orientation of the spacecraft) on dust detection are not fully understood at this time, it is not possible to determine the origin of the large difference in the dust measurements from one year to another. The LFR on STEREO B is not sensitive to dust because neither the X-antenna nor the Y-antenna, which feed the LFR, are close enough to the preferred impact zone of fast nanometer grains.

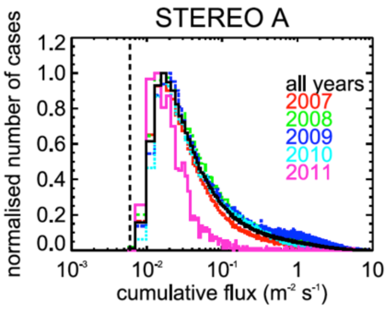


Figure III-8. Histograms of the cumulative flux of particles of mass greater than 10^{-20} kg measured by STEREO-A for all data (black solid line) and year by year (Le Chat et al 2013).

Mann et al. (2014) discuss the formation of nanodust and the likelihood that part of the population remains trapped inside 1 AU. This trapping suggests a possible explanation for the large time variations of the nanodust flux. Le Chat et al. (2015) carried out a study of the correlations between the nanodust flux as measured by S/WAVES LFR and the occurrence of interplanetary shocks. Some cases seem to show an interaction (a possible trapping) between the nanodust and the perturbed interplanetary magnetic field. In the same work, the nanodust flux is shown to exhibit periodicities close to Mercury and Venus orbital periods. Meyer-Vernet et al (2014) have explained the higher levels of nanodust detected by STEREO, compared to other missions, such as Wind, by the difference between detection rates for monopole and dipole antennas, and proposed a new mechanism for micro-dust detection with dipole antennas. Based on S/WAVES TDS data, a theoretical model has been built by Zaslavsky (2015) to predict the shape of the voltage pulses generated by dust of micron size. This model provides a basis for the development of future radio receivers optimized to facilitate dust detection, such as Solar Probe Plus and Solar Orbiter, and for the interpretation of impact signatures on different missions. Studies are also being carried out to better understand the charge yield for the materials used on the exteriors of the STEREO spacecraft (Collette et al, 2014).

Future Prospects. It is important to continue the STEREO-A dust detections, to better understand the results described by Le Chat et al (2013) and to observe the changes that take place when STEREO-A is flipped to maintain the HGA downlink to Earth. Both nanodust and micron-sized dust detections are likely to be influenced by the spacecraft flip, which will provide a new constraint on understanding details of the STEREO dust observations. Additional data will also be useful in refining the correlations and periodicities in the dust flux reported by Le Chat et al (2015).

IIIc. Scientific Impact of a One Spacecraft Mission

All PSGs can be achieved with regular STEREO synoptic data. The somewhat limited data stream available during the far-side sidelobe operations (see Section II) will inhibit the study of pick-up ions (PSG 3-2), but these studies will resume with regular operations by the end of 2015.

The loss of STEREO-B affects the science return from STEREO but is neither mission-crippling nor impossible to mitigate. Until about February 2016 the two STEREO spacecraft will be very close to each other and in opposition with earth, viewing highly overlapping-areas of the solar fair side disk and sampling similar in situ conditions. The loss of one spacecraft will not greatly affect the science return of the SECCHI instruments during this time. Im particular, the combination of SDO and SECCHI will continue to provide views of nearly the entire Sun in EUV and enable active region diagnostics while the evaluation of far side CMEs and SEP events continues.

From 2016 February to about 2018 October, the angular separation of the STEREO spacecraft from the earth-Sun line will decrease from 160° to 120°. The most severe impact of the absence of STEREO-B SECCHI data is the loss of EUV coverage of the western limb, as viewed from Earth, and an increased uncertainty in the 3D fitting of CMEs propagating in the far-side sector. However, the imagers on STEREO-A will cover all CMEs propagating along the earth-Sun line and 3D estimates of their size, direction, and speed will still be possible, provided the LASCO coronagraphs are operational. Similarly, although in-situ measurements from both STEREO spacecraft are clearly preferable, STEREO objectives can still be achieved with a combination of STEREO-A and other spacecraft near Earth (ACE, Wind, SOHO) and at other planets (MAVEN). After 2018, instrumentation on Solar Orbiter and Solar Probe Plus will, roughly half the time, cover the solar far side.

One exception to this is that the temporary loss of STEREO-B prevented the planned determination of the longitudinal extent of type III burst-producing electron beams that would be made possible by the varying proximity of the two spacecraft, relevant to PSG 1-4. The next opportunity to perform such a study will occur when STEREO-A approaches the earth-Sun line and the Wind spacecraft in 2023. In general, the study and application of solar radio bursts utilizing multiple perspectives can still be conducted effectively using the similar data products from STEREO-A S/WAVES and Wind Waves.

IIId. Scientific Productivity and Vitality

In the last two years, STEREO scientific productivity has reached unprecedented levels, as measured by papers in refereed journals, theses, and recognition of young researchers employing STEREO data to advance our understanding of solar and heliospheric phenomena. More theses and papers published in refereed journals appeared in 2013 and 2014 than in any other two-year period in the mission's eight years (cf. Appendix B, below). At least ten theses using STEREO data were accepted in fulfillment of Ph.D. and master's degrees at universities in the US and Europe. In addition, three young scientists received recognition in the form of prestigious awards for their work with STEREO data:

Dr. Neel Savani received the SCOSTEP Distinguished Scientist Award for 2014 for his work on CME eccentricity (full citation available online.). Dr. Alexis Rouillard received both the European Geophysical Union's 2013 Arne Richter Award for Outstanding Young Scientists and the American Astronomical Society Solar Physics Division's 2014 Karen Harvey Prize for "contributions to the understanding of the sources and heliospheric evolution of corotating interaction regions, small scale transients, coronal mass ejections, and solar energetic particle events." Dr. Noé Lugaz received the European Geophysical Union's 2014 Arne Richter Award for Outstanding Young Scientists "for his innovative contributions to the understanding of coronal mass ejections." He is now working at the University of New Hampshire and is supported in part by the STEREO PLASTIC team.

IIIe. Prioritized Science Goals, FY2016 - FY2020

Our scientific goals are the same as proposed in 2013 for the FY2014 - FY2018 period. Since the individual goals are described in detail in Section IIb, above, and at even greater length in our 2013 proposal, we simply list them here, grouped in goal sets addressing related scientific questions, and discuss novel opportunities for the FY2016 - FY2020 period:

Goal Set 1: Characterize space weather throughout the Inner Heliosphere

PSG 1-1: Understand the large-scale structure of ICMEs Understand the physics of ICME interactions

PSG 1-2: Understand how solar energetic particles are distributed so efficiently around the Sun

PSG 1-3: Radio and in situ, multispacecraft measurements of Type III bursts

PSG 1-4: Characterize space weather using multiple viewpoints

Goal Set 2: What can we learn from 360° coverage of the solar corona?

PSG 2-1: Uncover the large-scale couplings in solar eruptive events

PSG 2-2: Understand the lifetime of active regions, coronal holes, filaments, and filament channels

Goal Set 3: What can we learn from coverage of the full heliosphere?

PSG 3-1: Provide longitudinal coverage of the solar wind and transients that can affect the outer heliosphere

PSG 3-2: Pickup ions

PSG 3-3: Improve our understanding of dust in the inner heliosphere

***Opportunity:* Activity.** The PSGs in Goal Sets 1 and 2 address multiple facets of solar and heliospheric activity. Cycle 24 has been unusual (for the space age, at least) in its late onset and low level of activity proxies such as sunspot "number" and 10.7 cm flux. Will there be more active regions like AR 12192 (2014 October - November) that produce X-flares without CMEs? Will the usual trend of large events in the declining phase persist? The proposal period, which corresponds to that decline, presents a unique opportunity to sample an extended heliolongitudinal range, and thus duration, of solar active regions and their activity.

Opportunity: L5 testbed. A currently popular concept for a space weather early warning mission features a spacecraft with imaging and in situ measurement capabilities parked at the L5 Lagrange point, 60^o east of the earth-Sun line. That vantage allows seeing active regions for several days before they rotate onto the hemisphere visible from earth, as well as giving a "side" view that allows more accurate measurement of earth-directed ICME propagation speed than can be inferred from a single, earth-Sun line view. From mid-2018, the Ahead-earth angle will be within 45^o of that separation, closing to zero by the summer of 2020, and should provide measurements that both address Goal Set 1 PSGs' science and determine whether an L5 view can provide improved space weather forecasting.

Opportunity: The expanding Heliospheric System Observatory. MAVEN, now in orbit about Mars with a full suite of in-situ instrumentation to sample particles and fields at 1.5 AU, will provide numerous alignments (both radial and Parker spiral) with Ahead during the years of the proposed extension that will allow us to pursue the goals of PSG 1-4. Similarly, the ESA Solar Orbiter and NASA Solar Probe Plus missions will provide numerous periods of solar far-side coverage after their launches in 2018, and sample multiple distances from the Sun closer than 1 AU (as close as 0.30 and 0.05 AU, respectively). In order to maximize scientific return from those missions' limited high-rate telemetry intervals, knowledge of the 3-dimensional state of the inner heliospheric is required for careful planning, and STEREO will play a unique role in providing such information from ~ 1 AU but well separated from the Earth-Sun line.

IIIf. Implementation

Implementation of the STEREO scientific goals for FY2016 - FY2020 is straightforward: We plan to continue the synoptic (essentially the same from day to day) measurements we have been obtaining since the spacecraft achieved heliocentric orbit in 2006 and 2007, while taking advantage of periods of higher than normal telemetry bandwidth to improve on temporal sampling, energy domain, polar angle range, and imaging spatial resolution and lossiness of compression as possible. If we are only able to use the Ahead spacecraft for these measurements but are able to retain the DSN contact time previously allocated to the two STEREO spacecraft, we can achieve those improvements earlier in the proposed extension period than the closing of the spacecraft-earth distance alone would allow — perhaps as soon as early CY2016 (see Table IV-1, below).

Occasionally, STEREO has deviated from the synoptic plan for some hours per day for a limited time to capture unique scientific opportunities, such as imaging comets to search for disconnection events, but such campaigns are limited in duration to prevent disruption of the synoptic observations, and only carried out when operational risk is well understood and kept at a minimal level.

The PI team science operations staffing necessary to achieve these goals is minimal: the only expected changes are in the telemetry/sampling domain, as noted above, and occur infrequently. Pipeline processing is well understood and requires only fractional full-time equivalent support. The PI team budgets are balanced between operational requirements and enough data analysis to insure both a healthy interest in STEREO data in the larger community, and the validation of the pipeline data products.

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IV. Technical Implementation

A. Mission management

STEREO mission operations are carried out by a dedicated STEREO team at the Johns Hopkins University Applied Physics Laboratory (APL), via a task on a contract between NASA Headquarters and APL. The Space Science Mission Operations (SSMO) office at NASA Goddard provides management and engineering oversight for contract operations, as well as DSN scheduling, flight dynamics (orbit), and NASA-rented tail circuits for communication with APL. The Project Scientist is the funds manager for STEREO, as well as providing scientific and Communications (the activities formerly known as public affairs) leadership for the mission; he is assisted in that work by two Deputy Project Scientists. All NASA personnel on STEREO, including a small number of Co-Investigators still funded for data processing and data-validating scientific research, charge only fractional FTEs to the project.

B. Science operations

Science commanding is carried out by the PI teams from workstations at their home institutions that communicate securely with the Mission Operations Center (MOC) at APL. Downlinked telemetry is flowed to the PI teams, as well as to the STEREO Science Center (SSC) at Goddard. The raw telemetry and the scientifically useful files reformatted by the PI teams are archived at the SSC, which also receives and rapidly publishes on the Web the space weather beacon data usually obtained by antenna partner sites organized though NOAA's Space Weather Prediction Center (SWPC). The SSC also provides the primary means of joint science planning and can act as single point of contact with the APL MOC for the science team. See Appendix A, below, for the Mission Archive Plan.

Science coordination is achieved through Science Working Team (SWT) meetings held either by telecon or in conjunction with scientific conferences. While the SWT meetings in the early years of the mission included scientific sessions as well, the feeling of the science team is that scientific progress is now better achieved through interaction with the larger scientific community, through workshops co-sponsored with other missions (*e.g.* the In-situ Science workshops in 2010, 2012, and 2014, the Sun 360 Workshop in 2011) and general scientific conferences (AGU, Cosmic Ray, SPD, &c.).

C. Technical Risk

In our 2013 proposal we considered the following areas of technical risk: telemetry, spacecraft subsystem and ground system aging, and budget. These are still the primary areas of risk to be managed.

Rate (kbps)	Ahead	Behind	Daily Telemetry Volume (Gbit) per spacecraft, prime lobe	Pass duration (hr)	Ahead only Volume (Gbit)	Hours of 34 m support to achieve Ahead only volume
720	2007/01	2007/01	5	4		
480	2008/10	2008/09	5	5		
360	2009/05	2009/06	5	6		
240	2010/04	2009/12	4	7		
160	2011/06	2011/07	2.7	8		

Rate (kbps)	Ahead	Behind	Daily Telemetry Volume (Gbit) per spacecraft, prime lobe	Pass duration (hr)	Ahead only Volume (Gbit)	Hours of 34 m support to achieve Ahead only volume
120	2013/05	2012/11	2.1	8	4.2	16
160	2017/07	2017/07	2.7	8	5.4	16
240	2019/03	2019/04	5	7	10	14
360	2020/06	2020/05	5	6	10	12
480	2020/09	2020/06	5	5	10	10

Table IV-1. The different maximum rates achievable for 34 meter antenna supports during different phases of the STEREO orbit, from heliocentric orbit insertion through the end of the proposal period (2020 September), assuming HGA main lobe operations had remained possible throughout. The fourth column shows the daily telemetry volume ***per spacecraft*** *with two spacecraft and the fifth column, the number of hours of 34 m support* ***per spacecraft*** *necessary to achieve that volume. The last two columns show the daily volume achievable with the Ahead spacecraft alone, and the number of 34 m contact hours to achieve those figures, respectively. Occasional 70 m contacts and 34 m contacts with high spacecraft elevation enable high rates and shorter data accumulation times.*

Telemetry. During the proposal period (2016 October 1 - 2020 September 30), the spacecrafts' orbits will be carrying them ever closer to the earth, so that higher data rates will be possible than immediately around superior conjunction. Table IV-1 addresses the rates; if we are unable to recover the Behind spacecraft, we plan to use all 34 m contacts for Behind on Ahead in order to step up the telemetry volume returned until the downlink bandwidth becomes high enough to allow fewer contact hours per day to achieve the same daily volume.

If Behind is not recovered during the proposal period, we could therefore obtain measurements with higher sample rates and, in the case of SECCHI imaging observations, higher spatial resolution and/or lower compression lossiness. Since the 120 kbps rate limited the SECCHI suites to infrequent images in any wavelength other than 195 Å, for instance, the doubled rate for a single spacecraft could lead to better determinations of eruptive event initiations.

Spacecraft. As noted in Appendix C, the only known spacecraft degradation issues are in the Inertial Measurement Units (see also Section II, above) and the star trackers. The onboard software in Ahead has been patched to recognize situations in which *any* ring laser is faulty and react by marking data from the entire IMU as invalid; this would protect the spacecraft against anomalies of the kind that resulted in the loss of contact with Behind. Obviously, if Behind is recovered, its software would be patched as well.

The star trackers have slowly developed noise levels similar to the signal levels of fainter stars, often making for slow acquisition of guide stars; to counteract that, the mission ops team has commanded the operational temperature of the Ahead star tracker to a setting 10 C lower than previously, and the noise appears to have been reduced. Thorough verification of improved star acquisition times would take several forced resets, however, and out of prudence, the mission ops team has decided against that. Starting in 2013, the spacecraft were transitioned to an attitude control law that depends on the star tracker (for roll attitude information) and the SECCHI guide telescope (for pitch and yaw).

Ground system. Several components of the MOC ground system have been refreshed over the last two years, and more will be replaced over the next five years, as needed. Similarly, the PI teams pipeline processing and commanding systems have been refreshed as needed (infrequently). The servers that process the raw, reformatted, and beacon mode telemetry at the STEREO Science Center, as well as those serving the STEREO public and SSC (data) Websites average over five years in age, and will have to be replaced in the proposal period. Fortunately, small servers such as Mac minis or Intel Next Units of Computing (NUCs) are adequate for some of the tasks, and can be procured at extremely low cost.

Budget. For a discussion of the STEREO budget in one- and two-spacecraft scenarios, see Section V.

D. One and two spacecraft scenarios

At the time of writing, it is unclear whether and when communications can be restored with the Behind spacecraft, and if so, to what extent the instrument suite will be able to resume its scientific operations. We therefore examine two extreme cases for the proposed mission extension: a single spacecraft (Ahead) and two spacecraft, the latter assuming a full return of the Behind spacecraft and all its instruments to service before the start of the proposed extension period (2015 October 1).

Two spacecraft mission. This scenario would replicate the mission phase before the HGA thermal issue and superior conjunction, so we have a good baseline for planning. Costs for the PI teams and project management are unchanged except for inflation. In general, the scientific research carried out by the PI teams is sufficient to validate the continued quality of the data, and PI team members are focused on science operations, data pipeline processing, and validation of higher level data products as well as sufficient science analysis to make substantive progress toward the Prioritized Science Goals. Mission operations support will be less costly than in the two years before superior conjunction, when additional engineering support was needed to plan for superior conjunction operations, which involved contingencies not anticipated during the prime mission and first mission extension (2010).

We would propose to operate the two STEREO spacecraft in the same way we did prior to superior conjunction and the HGA thermal issue, with increasing data bandwidth and correspondingly higher daily data volume as the spacecraft-earth distance decreases (see Table IV-1, above). The higher telemetry would allow a return to higher sampling rates for the in situ instruments, a greater range of frequencies sample by S/WAVES, and more frequent images with less lossy compression for SECCHI.

Single spacecraft mission. This scenario envisions an unrecoverable Behind spacecraft, or a recovery beyond the scope of this proposal (*e.g.* around inferior conjunction in 2022). In this scenario, we could use the same number of hours of 34 m contact time we enjoyed per day for two spacecraft to double the contact time for a single spacecraft, or as close to that as is consistent with DSN loading. That would significantly accelerate the dates on which we could achieve higher data return (Table IV-1, above, last two columns), and by 2017, we would be exceeding the maximum data return using 34 m stations in the earliest parts of the STEREO mission — but only for the Ahead spacecraft. By the spring of 2019, we could be achieving double that figure, as we did during a few weeks of the heliocentric phase of the mission in 2007, when we had dedicated 70 m support and 720 kbps downlink rates for true stereoscopic observations of the lower corona.

With the additional telemetry, all the data originally provided by the instruments can be restored. For IMPACT, the primary effect of this on science would be the full return of full resolution (32 Hz) MAG burst data for high frequency waves and turbulence studies, and the collection of multiple bursts per day, as was done early in the mission. Other diagnostic products, such as burst criteria, and onboard pitch angle distributions (PADs) and moments products, which had been dropped to accommodate the lower telemetry rates, would be restored. The PLASTIC solar wind and pickup ion composition data, solar wind proton moments, and suprathermal rates would be restored, and the remaining ion rates, including solar wind protons, would be returned to their original cadence. PLASTIC would also recover housekeeping information used in tables. S/WAVES time and frequency resolutions would no longer be halved. By far the biggest impact of any increased telemetry volume would be on the SECCHI images, with significant improvements both in image quality from the use of lower compression ratios, but also in the image cadence needed to properly study solar activity. Only during two short "SECCHI campaign" periods early in the mission were such telemetry volumes achieved.

The increased telemetry would allow SECCHI to focus on 3D studies of the early phases of erupting events, such as the tantalizing evidence for a super-expansion phase (Patsourakos et al. 2010). They can reveal essential information for the 3D morphology of the erupting structures (e.g. Patsourakos et al. (2013) for an example) and will become increasingly important as STEREO-A nears quadrature configuration with SDO in 2018-19. Beyond 2019, the 'campaign'-level telemetry opens up a whole new world of science objectives such as 3D studies of jets, and spicules (w/ SDO & IRIS) and the possibility to trace the origin of the solar wind via small-scale outflows from the inner to the outer corona---an important support for SO and SPP. These studies rely on high cadence, multi-view observations from SDO AIA and STEREO EUVI and detailed kinematic profiles from the COR1/COR2 telescopes.

V. Budget

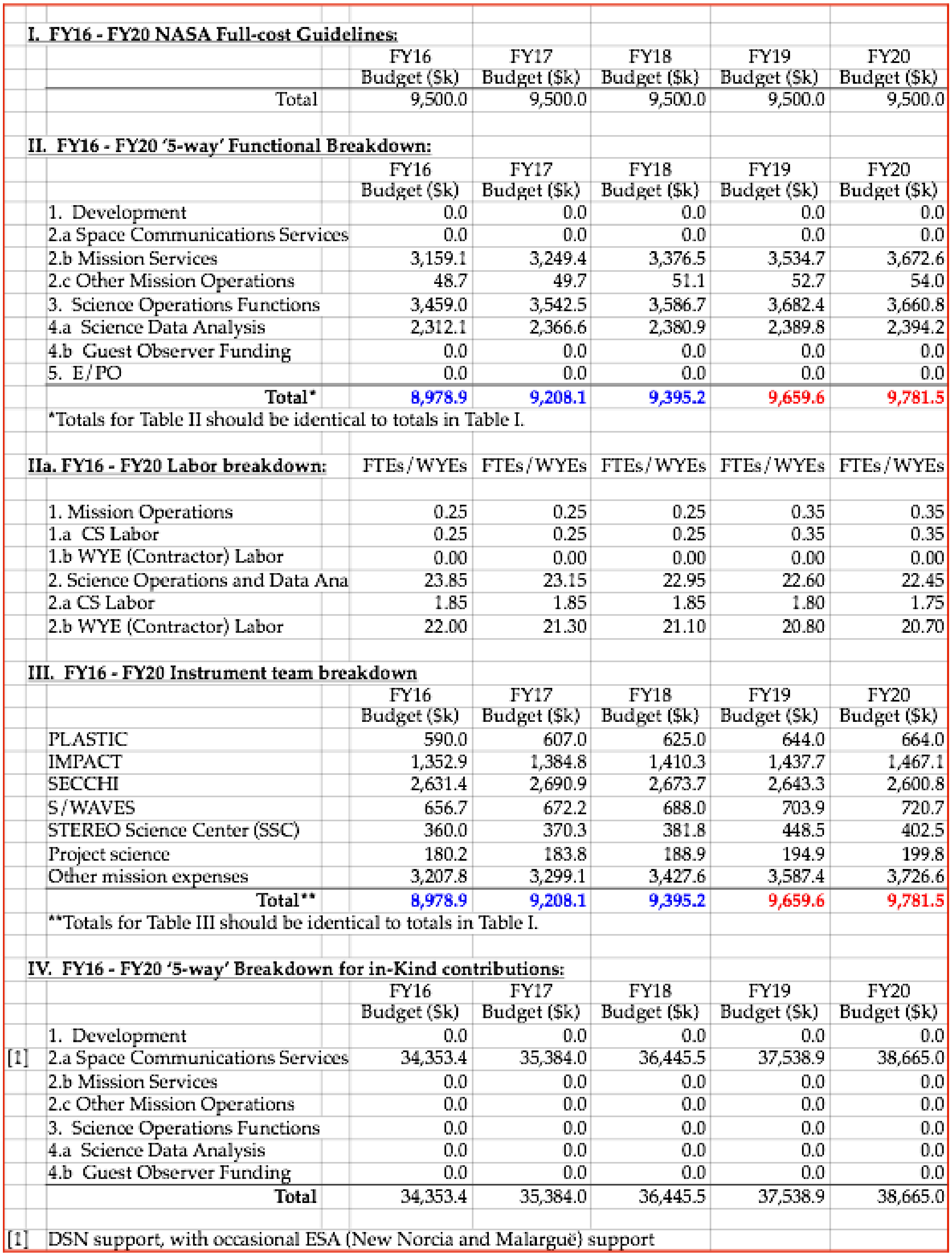
At the time of writing, it is unclear whether and when communications can be restored with the Behind spacecraft, and if so, to what extent the instrument suite will be able to resume its scientific operations. We therefore, and ***at the request of Heliophysics MO&DA management***, examine two extreme cases for the proposed mission extension: a single spacecraft (Ahead) and two spacecraft, the latter assuming return to service and full scientific operation of all instruments before the start of the proposed extension period (2015 October 1).

Two spacecraft mission. This scenario would replicate the mission phase before the HGA thermal issue and superior conjunction, so we have a good baseline for planning. Costs for the PI teams and project management are unchanged except for inflation. In general, the scientific research carried out by the PI teams is sufficient to validate the continued quality of the data, and PI team members are focused on science operations, data pipeline processing, and validation of higher level data products. Mission operations support will be less costly than in the two years before superior conjunction, when additional engineering support was required to design, implement, and test new board software and ground procedures for superior conjunction operations. That additional support was also used to deal with the HGA thermal issue and to modify the onboard anomaly response to prevent a repetition of the loss of communication with the Behind spacecraft on Ahead. By contrast, barring new spacecraft hardware issues, we expect a much more familiar operational environment in the years FY2016 - FY2020. Even the changing downlink bandwidths and time to download the nominal data return volumes will simply mirror our experience before superior conjunction, with rates increasing and download times — and DSN contact requirements — correspondingly decreasing. ***The decrease in mission operations costs allows us to propose an underguide budget for FY2016 - FY2018, though inflation causes us to exceed the guidelines for FY2019 and FY2020, despite holding the higher PI team budgets below inflation.***

The budget for a two spacecraft mission can be found in Table V-1.

Single spacecraft mission. The PI and mission ops teams were asked to examine potential cost savings in a single spacecraft mission extension. Since data pipeline operations are extensively automated, and instrument planning and commanding involves little or no additional work for two spacecraft as opposed to one, none of the PI teams was able to identify significant cost savings for single spacecraft operations. (In fact, there is some marginal additional cost associated with integrating the data to be recovered from the spacecraft solid state recorder (SSR) when nominal mission operation resumes on the prime HGA lobe in 2015 November into the existing data set.

The APL mission ops team, however, was able to project significant cost savings for single-spacecraft operations, as can be seen in Table V-2, where the single-spacecraft budget is presented. ***The decrease in mission operations costs allows us to propose an underguide budget throughout the proposed extension years.***



I. FY16 - FY20 NASA Full-cost Guidelines:

	FY16 Budget ($k)	FY17 Budget ($k)	FY18 Budget ($k)	FY19 Budget ($k)	FY20 Budget ($k)
Total	9,500.0	9,500.0	9,500.0	9,500.0	9,500.0

II. FY16 - FY20 '5-way' Functional Breakdown:

	FY16 Budget ($k)	FY17 Budget ($k)	FY18 Budget ($k)	FY19 Budget ($k)	FY20 Budget ($k)
1. Development	0.0	0.0	0.0	0.0	0.0
2.a Space Communications Services	0.0	0.0	0.0	0.0	0.0
2.b Mission Services	3,159.1	3,249.4	3,376.5	3,534.7	3,672.6
2.c Other Mission Operations	48.7	49.7	51.1	52.7	54.0
3. Science Operations Functions	3,459.0	3,542.5	3,586.7	3,682.4	3,660.8
4.a Science Data Analysis	2,312.1	2,366.6	2,380.9	2,389.8	2,394.2
4.b Guest Observer Funding	0.0	0.0	0.0	0.0	0.0
5. E/PO	0.0	0.0	0.0	0.0	0.0
Total*	**8,978.9**	**9,208.1**	**9,395.2**	**9,659.6**	**9,781.5**

*Totals for Table II should be identical to totals in Table I.

IIa. FY16 - FY20 Labor breakdown:	FTEs/WYEs	FTEs/WYEs	FTEs/WYEs	FTEs/WYEs	FTEs/WYEs
1. Mission Operations	0.25	0.25	0.25	0.35	0.35
1.a CS Labor	0.25	0.25	0.25	0.35	0.35
1.b WYE (Contractor) Labor	0.00	0.00	0.00	0.00	0.00
2. Science Operations and Data Ana	23.85	23.15	22.95	22.60	22.45
2.a CS Labor	1.85	1.85	1.85	1.80	1.75
2.b WYE (Contractor) Labor	22.00	21.30	21.10	20.80	20.70

III. FY16 - FY20 Instrument team breakdown

	FY16 Budget ($k)	FY17 Budget ($k)	FY18 Budget ($k)	FY19 Budget ($k)	FY20 Budget ($k)
PLASTIC	590.0	607.0	625.0	644.0	664.0
IMPACT	1,352.9	1,384.8	1,410.3	1,437.7	1,467.1
SECCHI	2,631.4	2,690.9	2,673.7	2,643.3	2,600.8
S/WAVES	656.7	672.2	688.0	703.9	720.7
STEREO Science Center (SSC)	360.0	370.3	381.8	448.5	402.5
Project science	180.2	183.8	188.9	194.9	199.8
Other mission expenses	3,207.8	3,299.1	3,427.6	3,587.4	3,726.6
Total**	**8,978.9**	**9,208.1**	**9,395.2**	**9,659.6**	**9,781.5**

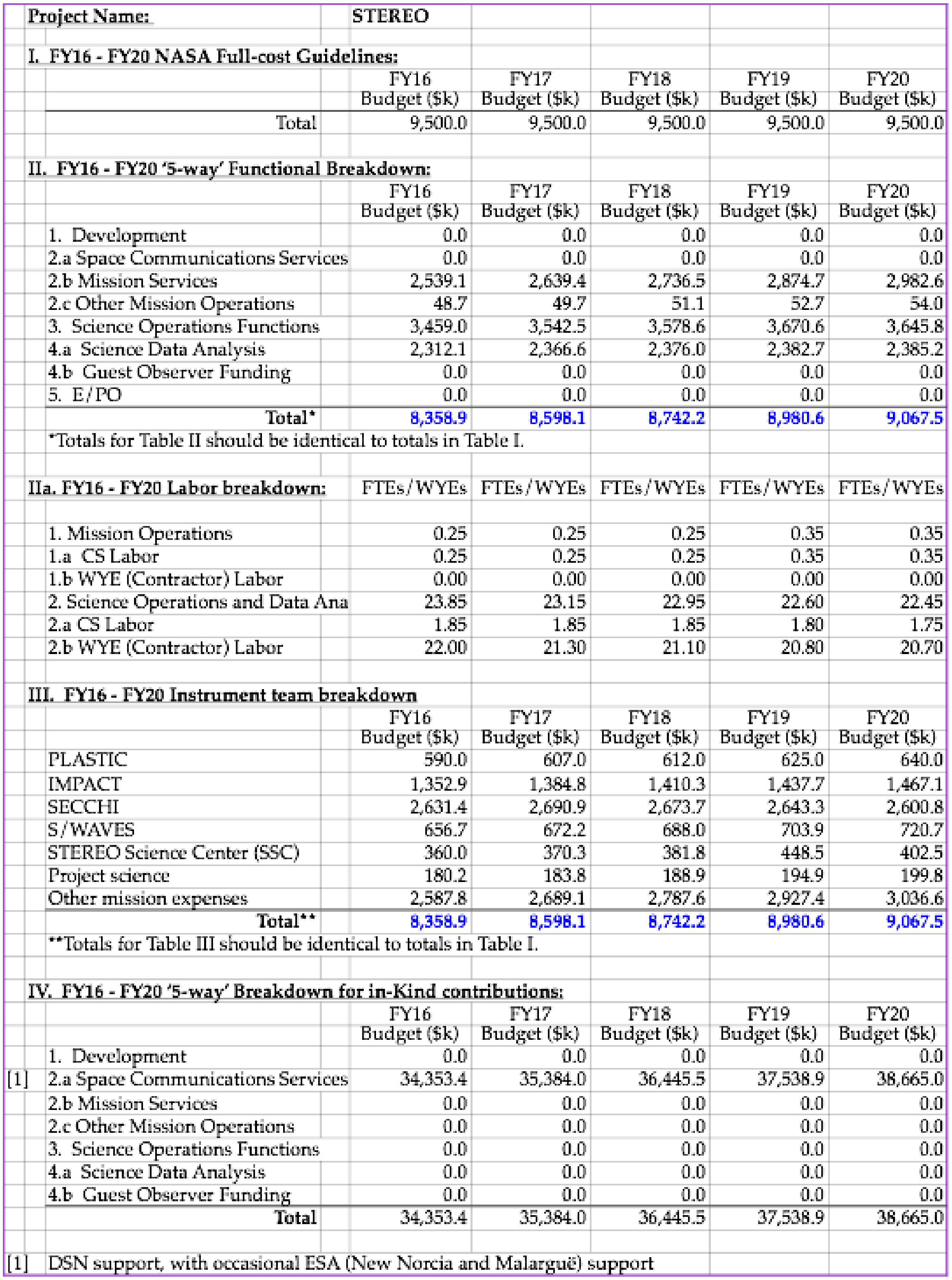
**Totals for Table III should be identical to totals in Table I.

IV. FY16 - FY20 '5-way' Breakdown for in-Kind contributions:

	FY16 Budget ($k)	FY17 Budget ($k)	FY18 Budget ($k)	FY19 Budget ($k)	FY20 Budget ($k)
1. Development	0.0	0.0	0.0	0.0	0.0
[1] 2.a Space Communications Services	34,353.4	35,384.0	36,445.5	37,538.9	38,665.0
2.b Mission Services	0.0	0.0	0.0	0.0	0.0
2.c Other Mission Operations	0.0	0.0	0.0	0.0	0.0
3. Science Operations Functions	0.0	0.0	0.0	0.0	0.0
4.a Science Data Analysis	0.0	0.0	0.0	0.0	0.0
4.b Guest Observer Funding	0.0	0.0	0.0	0.0	0.0
Total	34,353.4	35,384.0	36,445.5	37,538.9	38,665.0

[1] DSN support, with occasional ESA (New Norcia and Malarguë) support

Table VI-1. STEREO budget for a two-spacecraft mission. The budget is underguide for FY2016 - 2018, and overguide for FY2019 and FY2020; overall, the total budget for five years is $476.6K underguide.



	Project Name:	**STEREO**				
	I. FY16 - FY20 NASA Full-cost Guidelines:					
		FY16 Budget ($k)	FY17 Budget ($k)	FY18 Budget ($k)	FY19 Budget ($k)	FY20 Budget ($k)
	Total	9,500.0	9,500.0	9,500.0	9,500.0	9,500.0
	II. FY16 - FY20 '5-way' Functional Breakdown:					
		FY16 Budget ($k)	FY17 Budget ($k)	FY18 Budget ($k)	FY19 Budget ($k)	FY20 Budget ($k)
	1. Development	0.0	0.0	0.0	0.0	0.0
	2.a Space Communications Services	0.0	0.0	0.0	0.0	0.0
	2.b Mission Services	2,539.1	2,639.4	2,736.5	2,874.7	2,982.6
	2.c Other Mission Operations	48.7	49.7	51.1	52.7	54.0
	3. Science Operations Functions	3,459.0	3,542.5	3,578.6	3,670.6	3,645.8
	4.a Science Data Analysis	2,312.1	2,366.6	2,376.0	2,382.7	2,385.2
	4.b Guest Observer Funding	0.0	0.0	0.0	0.0	0.0
	5. E/PO	0.0	0.0	0.0	0.0	0.0
	Total*	**8,358.9**	**8,598.1**	**8,742.2**	**8,980.6**	**9,067.5**
	*Totals for Table II should be identical to totals in Table I.					
	IIa. FY16 - FY20 Labor breakdown:	FTEs/WYEs	FTEs/WYEs	FTEs/WYEs	FTEs/WYEs	FTEs/WYEs
	1. Mission Operations	0.25	0.25	0.25	0.35	0.35
	1.a CS Labor	0.25	0.25	0.25	0.35	0.35
	1.b WYE (Contractor) Labor	0.00	0.00	0.00	0.00	0.00
	2. Science Operations and Data Ana	23.85	23.15	22.95	22.60	22.45
	2.a CS Labor	1.85	1.85	1.85	1.80	1.75
	2.b WYE (Contractor) Labor	22.00	21.30	21.10	20.80	20.70
	III. FY16 - FY20 Instrument team breakdown					
		FY16 Budget ($k)	FY17 Budget ($k)	FY18 Budget ($k)	FY19 Budget ($k)	FY20 Budget ($k)
	PLASTIC	590.0	607.0	612.0	625.0	640.0
	IMPACT	1,352.9	1,384.8	1,410.3	1,437.7	1,467.1
	SECCHI	2,631.4	2,690.9	2,673.7	2,643.3	2,600.8
	S/WAVES	656.7	672.2	688.0	703.9	720.7
	STEREO Science Center (SSC)	360.0	370.3	381.8	448.5	402.5
	Project science	180.2	183.8	188.9	194.9	199.8
	Other mission expenses	2,587.8	2,689.1	2,787.6	2,927.4	3,036.6
	Total**	**8,358.9**	**8,598.1**	**8,742.2**	**8,980.6**	**9,067.5**
	**Totals for Table III should be identical to totals in Table I.					
	IV. FY16 - FY20 '5-way' Breakdown for in-Kind contributions:					
		FY16 Budget ($k)	FY17 Budget ($k)	FY18 Budget ($k)	FY19 Budget ($k)	FY20 Budget ($k)
	1. Development	0.0	0.0	0.0	0.0	0.0
[1]	2.a Space Communications Services	34,353.4	35,384.0	36,445.5	37,538.9	38,665.0
	2.b Mission Services	0.0	0.0	0.0	0.0	0.0
	2.c Other Mission Operations	0.0	0.0	0.0	0.0	0.0
	3. Science Operations Functions	0.0	0.0	0.0	0.0	0.0
	4.a Science Data Analysis	0.0	0.0	0.0	0.0	0.0
	4.b Guest Observer Funding	0.0	0.0	0.0	0.0	0.0
	Total	34,353.4	35,384.0	36,445.5	37,538.9	38,665.0
[1]	DSN support, with occasional ESA (New Norcia and Malarguë) support					

Table VI-12. STEREO budget for a one-spacecraft mission. The budget is underguide in all years.

VI. Appendices

A. Mission Archive Plan

Mission-wide Data and Software

The STEREO Science Center (SSC), located at NASA Goddard, serves as the main archive for all STEREO data. The primary source of ancillary data products for the STEREO mission is the STEREO Data Server (SDS) maintained as part of the Mission Operations Center at the Johns Hopkins University Applied Physics Laboratory. These data, which include all operational and engineering data and reports shared between the operations and instrument teams, are mirrored over to the SSC several times per day for archiving. All the ancillary data products are made available online except for the telemetry dictionaries which are archived separately for security reasons, and the DSN Schedule Change reports which are not made public because they include email addresses. The DSN Schedule Change reports are not archived because the information in them is included in the subsequent DSN schedule files. Event lists maintained by the PI teams and others are available at the SSC Website.

Telemetry, Ephemerides, and Attitude History. Final level-0 telemetry files are archived by the SSC for each of the instruments and spacecraft subsystems. All STEREO ephemerides and attitude history files are provided as SPICE kernels. SPICE is a standard ephemeris package provided by the Jet Propulsion Laboratory's Navigation and Ancillary Information Facility (NAIF), and used by many interplanetary and heliospheric missions. Information about SPICE and the SPICE software package can be obtained from the NAIF Website. The SPICE kernels archived by the SSC are in ASCII transfer format, which can then be compiled into machine-readable form for any supported platform.

SolarSoft. Data analysis software is distributed as part of the Solar Software Library, also known as SolarSoft. This multi-mission software library is used extensively within the solar physics community, and enables cross-mission data analysis. The primary emphasis is on Interactive Data Language (IDL) software, but source code for other languages is also distributed using the SolarSoft mechanism. Together with the large generic library supplied with SolarSoft, each instrument team provides software for analyzing their own data. Also provided are the most current ephemeris and attitude history files for the entire mission, and software to manipulate them in a large variety of standard coordinate systems.

Instrument resources. Resource pages are available for each of the STEREO instruments, using a standardized format first developed for the SOHO mission, and are accessible from the SSC Website.

Mission Documentation. A special issue (Volume 136) of Space Science Reviews (SSR) is devoted to the STEREO mission. In that issue are extensive descriptions of the spacecraft, instruments, and ground systems.

Data Distribution. The SSC resides within the Solar Data Analysis Center (SDAC) at the Goddard Space Flight Center. The SDAC is a multi-mission Resident Archive with extensive experience distributing data for a number of missions, including SOHO, TRACE, RHESSI, Hinode, SDO, and others, as well as archiving data for older missions such as the Solar Maximum Mission. The SDAC will act as the active Resident Archive for the lifetime of the mission and beyond. Ultimately, the data will be delivered to the Permanent Archive designated by NASA Heliophysics MO&DA management.

The remote sensing and *in situ* data being actively delivered to the SSC form the major core of what will become the STEREO long term archive, and many of the *in situ* data products are also being actively delivered to the Space Physics Data Facility (SPDF). SECCHI Level 1 and Level 2 products will be generated from the current Level 0.5 files using already existing software, after final validation of the calibration. The various levels of data from the IMPACT and PLASTIC instruments are already in archivable format, as are the CDF versions of the S/WAVES data in the SPDF, and only require revalidation of the calibration and completion of the most recent data. At the end of the STEREO mission, an additional year of work will be needed from the instrument teams to perform a last validation of the calibrations, and to complete any remaining data processing.

The Virtual Solar Observatory (VSO) acts as the primary access point for all STEREO data, with the SSC as the data provider. This maximizes the use of existing resources without duplication, and enables collaborative data analysis with other solar observatories. IMPACT magnetometer and particle data, as well as S/WAVES intensity spectra, are also available through the Virtual Heliospheric Observatory (VHO). An extensive list of all access sites, including those at the individual PI and Co-I institutions, is maintained on the SSC Website.

IMPACT

Scientific Data Products. The IMPACT investigation provides several levels of science data products. The primary, "Level 1" science products include all science data at highest time resolution and in scientific units and coordinates. These products are produced at UC-Berkeley upon transfer of the Level 0 telemetry files from the SSC and validated by the IMPACT Co-Investigators within one month of generation. Once validated, these files are made publicly available (see below). Level 1 data files are in ISTP-compliant CDF format and intended to be self-documenting. The full complement of ISTP-required metadata are included within these files. All IMPACT Level 1 files are archived within the SSC. Appropriate metadata have been developed for each Level 1 data product, and incorporated into the VHO.

Level 2 data are a merged data set, including data from the IMPACT and PLASTIC investigations, and averaged to ensure identical time cadences (1-minute, 1-hour and 1-day). These data are intended for quick browsing and are integrated with an online plotting and ASCII listing service hosted at UCLA. The same data in CDF format will also be available by the time of the Senior Review. Level 3 data are list-type data such as event lists compiled by the IMPACT team. They are in PDF and Excel formats. Appropriate metadata have been incorporated into the VHO to enable searching on the data.

Currently, the IMPACT investigation provides Level 1 data for all instruments. Level 2 data including MAG and PLASTIC moments are being served at UCLA in ASCII format, and are archived within the SSC as CDF files. Level 2 data in ASCII format are also available for the SEP suite instruments through the Caltech and Kiel sites, with links for the latter on the UCLA site. CDF versions of these data are under active development. Level 3 event lists are served by UCLA, and archived within the SSC.

Documentation. The SSR special issue includes complete information regarding the IMPACT instruments and data products. In addition, documentation is served online through the IMPACT instrument resource page. Information about calibrations and software versions used in the production of Level 1 data products are listed on this website and included in the internal documentation of the CDF files themselves.

Analysis Tools. The IMPACT investigation provides data products in ISTP-compliant CDF and ASCII formats to ensure easy integration with users' native analysis environments. In addition, the IMPACT team provides custom software through the instrument resource page based on the UC-Berkeley TPLOT library. This is an IDL-based set of analysis routines designed specifically for *in situ* measurements.

Online browsers and plotters hosted by UCLA, UC-Berkeley, the University of Kiel, and the Institut de Recherche en Astrophysique et Planétologie (IRAP) provide tools on the web. At UC-Berkeley, a traditional browse-type, static plot tool is available. This tool links IMPACT and ACE plots and data with images and models. A real-time space weather has also been developed at UC-Berkeley which integrates STEREO Beacon, SDO and ACE plots.

Data Distribution. The IMPACT data sets are available through the main IMPACT UC-Berkeley instrument resource web site listed above. In addition, all data are mirrored by the SSC and available there. Data are also mirrored and available through CDAWeb. IMPACT data are being included in the VHO interface. Space Physics Archive Search and Extract (SPASE) descriptions of the IMPACT Level 1 data products have been written.

Together with the above, Caltech hosts a site specific to the Solar Energetic Particle (SEP) suite. This site provides SEP and some ancillary data (notably, orbit and attitude information) in ASCII format. A site hosted by the IRAP includes additional data products and analysis tools for the SWEA instrument.

PLASTIC

Scientific Data Products. Level 1 data are the highest-resolution, complete data set. They have the epoch time and instrument section decommutated, counts decompressed, and entries separated into meaningful products (solar wind proton moment array, reduced proton and alpha distributions, heavy ion species count rate arrays, pulse height data, housekeeping, etc.), but are not fully converted into physical units (such as flux) that require the incorporation of detection efficiencies which may change over the life of the mission (due to gain changes in the detectors). Level 1 data products are produced at UNH within 24 hours of receipt of Level 0 telemetry files. Software and calibration/efficiency files to convert the data into physical units, along with appropriate documentation, are delivered electronically to the SSC archive. Level 1 data products are in ISTP-compliant CDF files.

Level 2 data products include the most frequently used quantities from PLASTIC in physical units. These data products are accessible on the PLASTIC Website (menu link to "Resources") and include both browse quality (typically available within 1 day of Level 1) and validated (updated monthly) products. Validated Level 2 products currently available on the UNH site as ASCII files include solar wind protons, alphas, selected minor ions, and helium pickup ions. Selected key parameters (such as solar wind bulk parameters, ion charge state distributions, and He+ intensities) are also provided on the UNH-hosted PLASTIC online browser as daily and/or monthly time series plots. Verified and validated products undergo both automatic and science personnel quality checks. These archival quality data are added to ISTP-compliant Level 2 CDFs and mirrored at the SSC. The validated PLASTIC proton moments are also included as a merged plasma plus magnetic field product courtesy of the IMPACT/MAG site at UCLA.

Production of Level 2 products that involve compositional information (species, charge states) and suprathermal rates are subject to the available telemetry. These products will be resumed as the telemetry returns to nominal values. Calibration files will need to be updated after the spacecraft flip, as different sections of the detectors will become exposed in the direction of the aberration angle. Level 3 data products typically result from directed scientific analysis, and include specific intervals (such as identified ICMEs) and other value-added products. A list of early mission suprathermal event periods is available through the SSC website, as are daily averaged He+ pickup ion spectra (processed yearly, using long duration efficiency curves), both in ASCII format.

Documentation. Full descriptions of the PLASTIC instruments and the Level 1 data products can be accessed through the Instrument Resource webpage at the UNH website. Metadata relevant to particular data products are also available within the CDF files. ASCII products either have the product information contained within the file header, or else a Readme file is provided. The instrument and data products are fully described in the PLASTIC instrument paper in the SSR special issue. This paper is available online, free-of-charge to the public, and is linked through the PLASTIC Resource page.

Analysis Tools. PLASTIC data are available in ISTP-compliant CDFs such that they can be easily integrated into existing analysis and search tools, such as the VHO and SolarSoft. In addition, the PLASTIC team has extended the UC-Berkeley TPLOT library, (see IMPACT section, above), into the IDL-based SPLAT (Stereo PLastic Analysis Tool) that further enables integration of data sets. SPLAT and other IDL programs, including those that support composition analysis and those that create specialized ASCII files from the CDF files, are distributed through the SolarSoft library.

Data Distribution. PLASTIC Levels 1 and validated Level 2 data are available both via the UNH-hosted Website and at the mirrored SSC instrument data site. PLASTIC archival data is also available at the CDAWeb, the VSO, the VHO, and the Heliophysics Data Portal.

SECCHI

Scientific data products. All SECCHI image telemetry data are converted to FITS files upon receipt of version 02 of the Level-0 telemetry files, about 2 days from the date of observation. This processing is done at the SECCHI Payload Operations Center (POC), located at NRL. The FITS headers contain all instrument parameter and spacecraft pointing information. The images have been oriented to put the spacecraft north, which usually corresponds to ecliptic north, at the top of the image, but no interpolations are done at this Level-0.5 stage. The images may be converted to Level-1 by the user using a SolarSoft IDL procedure, SECCHI_PREP, which performs all of the calibration functions using the latest calibrations. Image header metadata are available in a database, accessible from the SECCHI Website, which can be also used to download specific FITS files. In addition to the FITS data, the SECCHI Website serves a large number of Level-2+ data products for science and public use. These products currently include: (1) Browse images in PNG format (2) Javascript movies for user-defined intervals (1-36 hours) and (1-9 days). (3) Synoptic browse movies (individual or combined, 1, 2 or 4 weeks) in MPEG format. (4) PNG anaglyphs and stereo pairs of all EUVI data suitable for stereo viewing, (5) synoptic maps of EUVI, COR1, COR2 accessible in a variety of forms, (6) auto-generated CACTus CME lists for SECCHI, and (8) EUVI synchronic 360° maps in Carrington coordinates (195Å, 284Å, 304Å). Additional Level-2+ data products are readily available by request: (1) EUVI wavelet-enhanced dual-wavelength combined movies, (2) EUVI wavelet-enhanced images for the full mission, (3) EUVI+SDO synchronic maps in cos-lat projection, (4) COR2 total brightness and % polarization FITS files. New products on the SECCHI Website since the last Senior Review include: (1) Time-elongation plots ("J-maps"), (2) cosmic-ray scrubbing results. In the near term, preprocessed EUVI wavelet-enhanced images, and a list of images affected by debris or other problems will also be added to the website. A CME list with 3D properties is available from the University of Göttingen. Another COR2 list which will be more similar to the LASCO CDAW list will be available on the SECCHI Website by January 2016.

Calibration activities for the SECCHI telescopes are now complete. Pointing and flat-fielding (including vignetting) calibrations have been established for all telescopes. Geometric distortion corrections have been implemented for all applicable telescopes (COR2, HI1, and HI2), as have the shutterless readout corrections for HI1 and HI2. Photometric calibrations have been implemented for all telescopes.

Housekeeping. Selected SECCHI instrument housekeeping telemetry is also available via web interface to a database at NRL. Plots may be extracted from this database of various engineering parameters such as temperatures, currents, voltages, door position, guide telescope pointing and HK events. Table definitions and table structure are described on the SECCHI web site.

Documentation. The SECCHI Website serves: Science (FSW) Operations Manual, FSW documentation, image telemetry completeness data, instrument status, image scheduling details, various instrument and operations event logs, software user's guides, SECCHI FITS Keyword Definition, and the SECCHI Data Management Plan. A description of the instrument is given in the SSR special issue. SECCHI operations and data documentation is maintained in a wiki site. The wiki pages are updated as information becomes available.

Analysis Tools. SECCHI analysis tools, and most of the pipeline software, are freely available through SolarSoft. The following tools are currently available via SolarSoft: data browsers, data calibration, movie generation and display, image enhancement and visualization, polarized image processing, star-removal, height-time plots, ray-tracing, CME detection, tomography. As these tools are improved and future tools developed, they will be added to the SolarSoft library. In addition, there are some stereographic visualization tools which currently require specialized hardware. At NRL all software is under Concurrent Versions System management.

Final Data Set. The SECCHI Level-0.5 data is "final" after the FITS files have been updated with any additional telemetry received in the final (+30-day) Level-0 telemetry from APL. Currently, the Level-1 (calibrated) product is the combination of the Level-0.5 FITS images and the SECCHI_PREP IDL routine and data files available in Solar- Soft. This allows the user to take advantage of the evolving calibration of the various telescopes. At the end of the mission, the calibration files and parameters that are used in this package will be revalidated to ensure that they are up to date and able to generate Level-1 FITS files of calibrated images, polarized brightness, and brightness images. Calibration will include corrections for instrumental artifacts such as stray light, vignetting, shutterless readout, and conversion to physical units. (Geometric distortion is described by header keywords together with the World Coordinate System standard algorithms.) Complete documentation, transparent software code, and non-proprietary data formats ensure that calibration can be properly applied to Level-0.5 data into the foreseeable future. The final archive will contain both the calibrated Level-1 files and the original Level-0.5 files.

Data availability. The primary site for storage of Level-0.5 FITS image data is the NRL Solar Physics Branch (PI home institution). The primary means of querying data for analysis is by utilizing summary flat-files which are read by SolarSoft tools. Besides being available on-site, the data is freely available (in relatively small quantities) from NRL via database query at the SECCHI website. All of the data are also synchronized hourly to the SSC. In addition, other partner institutions – LMSAL (California), RAL (UK), IAS (France), MPS (Germany) – mirror STEREO data. These all serve as backups for the complete data set.

Virtual Observatory Access. The SSC is now serving SECCHI data through the VSO at GSFC/SDAC, which is intended to be the gateway to other Virtual Observatories. The SECCHI data are fully accessible to the wider VO community. VSO is committed to community interoperability efforts, such as the SPASE data model.

S/WAVES

Scientific Data products. The S/WAVES investigation provides several levels of science data products. Access to the Level 0 data is achieved through a processing system called TMlib, based on a similar system (WindLib) successfully used since the early 1990s for the Wind/WAVES (W/WAVES) data. The TMlib can be downloaded from the University of Minnesota (send request to goetz@umn.edu).

Daily summary plots showing all frequency-domain receivers and summaries of the time domain receivers are available from the SSC and S/WAVES Webpage. Both of these sources also serve 1-minute averages in both ASCII and IDL save format of all frequency-domain receivers. These 1-minute averages are also served by the CDAWeb. The CDAWeb site includes customized plotting capabilities. Both the daily summary plots and the 1-minute averages are produced automatically upon receipt of the data, so are available usually within 24-hours of real-time.

The French IRAP Plasma Physics Data Center (CDPP) also serves daily summary plots of the frequency domain receivers in a different format than those from the U.S sites. CDPP will also serve in the future the higher level S/WAVES products associated with direction finding and wave polarization capability. This site requires a password (due to French security regulations), but this is freely given upon request.

Additional higher level data includes the Type II/IV catalog maintained by the Wind/WAVES team and now including S/WAVES data. This site has been in existence since the late 1990s and is a valuable resource for solar researchers. The years covering the STEREO mission are archived on the SSC website.

Documentation. Three papers of importance to S/WAVES data processing are in the SSR special issue, one providing a complete description of the S/WAVES instrument, another discussing the antennas, and a third describing the direction finding technique used by S/WAVES. Pointers to these articles as well as to a description of the 1-minute average data are on the S/WAVES instrument resource page referenced by the SSC. The direction finding and wave polarization parameters, when available, will be documented on the CDPP Web site mentioned above.

Analysis tools. The customized plotting capability available at the CDAWeb is based on the same program used by the S/WAVES team. This original IDL program is available from the instrument resource site at the SSC. Future customized plots of polarization and direction of arrival will be available from the CDPP Web site.

Data Distribution. S/WAVES data, as mentioned above, are available directly from the team's US Web site, from the SSC, from CDAWeb, and from CDPP. The S/WAVES event lists can be obtained from the Type II/IV catalog Web site, from the SSC website, and through interface with the VSO.

B. STEREO Publication Record, 2013 - 2015

STEREO refereed journal (not conference proceedings) rates through the first few weeks of calendar year 2015 can be found in Table B-1.

Calendar Year	Refereed Journals and Theses Only
2006	1
2007	12
2008	56
2009	128
2010	107
2011	121
2012	161
2013	168
2014	167
2015 through February 28	15
Total	936

Table B-1. STEREO refereed papers and theses. Source: Astrophysics Data System.

Here, a "STEREO paper" is taken to mean any paper using STEREO data, or concerning models or theoretical interpretations of STEREO measurements.

Publication rate. 2013 and 2014 yielded the highest two-year, refereed publication rate over the lifetime of the STEREO mission. In each of the two most recent full years, the refereed publication rate exceeded the rate during 2012, which included the special issue of *Solar Physics* (Volume 281, Issue 1) on The Sun 360 that includes 29 papers.

Theses. Since the beginning of 2013, STEREO data have been used for eight theses (6 PhD, 1 Masters, 1 undergraduate).

Bibliography. A reverse time-ordered list of STEREO publications accessible by the NASA Astrophysics Data System (ADS) is available here. A standalone list is available as well. A searchable STEREO publication database is also available.

C. Spacecraft and Instrument Status as of 2015 March 1

SPACECRAFT

Contact with the Behind spacecraft has been lost. Depending on the recommendations of the NASA failure review board, attempts to recover the spacecraft may or may not continue. The Mission Ops team has made a number of changes to the spacecraft autonomy rules on Ahead to prevent a similar loss of attitude control. Among other changes, if even a single gyro within the IMU is producing bad data, only the solar presence detectors on all sides of the spacecraft will be used for attitude determination.

The Ahead spacecraft is healthy, aside from the loss of the primary IMU and the degradation of the backup IMU. The HGA feed is the only part of the spacecraft with a thermal issue, and its temperature is expected to return to nominal range by the beginning of CY2016. All four reaction wheels and the sun sensors are nominal, and the propulsion system still retains ~ 50 years of fuel for momentum management. Solar panel performance remains nominal.

A Mission Operations Center (MOC) hardware refresh was carried out in 2013.

IMPACT

Flight hardware. In 2014 a major operational change was driven by the HGA feed temperature issue and the related move to sidelobe operations. A software patch was formulated and uplinked to allows IMPACT IDPU to decimate science packets to lower data rates for the spacecraft offpoint conjunction modes. In addition, SWEA and STE-D were shut off upon entering the first sidelobe phase. This saved a large fraction of the available telemetry for the other IMPACT instruments, and more importantly minimized concerns about monitoring either instrument's state of health while we are not getting full instrument housekeeping. (Both SWEA and STE-D have had occasional SEUs that sometimes require intervention.) IMPACT boom suite instruments have otherwise been functioning nominally, with MAG obtaining low rate data through the sidelobe period for both reduced real time transmissions and continuous recording to the SSR. The SEP LET, SIT, and HET sensors continue normal operations when in contact. For the sidelobe periods a flexible packet decimation scheme was designed that provides broad energy and composition coverage (with reduced temporal resolution) based on in-flight particle identification, supplemented by limited pulse-height data. In-ecliptic particle flows are also monitored. The SEP-SEPT sensor dropped the N-S telescope data transmission as of the second sidelobe phase, leaving the ecliptic (E-W) telescope data intact. As of early February four large SEP events had been identified during the STA sidelobe period.

GSE. The aging, low-cost Windows PCs used to command the IMPACT instruments from its POCs have been replaced by new, low-cost machines.

PLASTIC

Post-launch analysis determined that the design of the contributed entrance system did not meet specifications, resulting a polar angle dependent instrument response (cross-calibrated post launch against Wind) and in faster than anticipated decreases in the gain of the microchannel plates (currently restored by bias increases). The gain affect will be greatly ameliorated by the spacecraft flipping in 2015, as the exposure to the high-flux solar wind aberration direction will shift to a different, “fresher” section of the detector array. As the instruments will be off during the superior conjunction blackout, re-commissioning will include a determination of any changes in the instrument response function in the new orientation.

Otherwise, the instruments are operating nominally, with the exception of a modest current increase recently observed in one power supply on STEREO A. In September 2014, during an SEP event, one of two polar deflection power supplies began showing a gradual increase in its current draw, while maintaining its commanded voltage value. A yellow flag alert occurred in December 2014. The power supply retained full operational capability (that is, an examination of the data shows the polar angle measurement remains nominal). While this anomaly is still under active investigation, it is planned that the table entries that set the deflection voltages at suprathermal energies will be lowered, to reduce potential stress on the parts.

During the reduced telemetry periods, not all data products are available, and other remaining products have reduced temporal resolution.

SECCHI

“Watchdog” resets (23 on Behind, 36 on Ahead over the course of the mission) generated in the SECCHI Electronics Boxes (SEBs) each result in a few hours’ of lost observing time. Anomalies in the EUVI quadrant selector on Ahead were corrected by adjusting the encode timing delay in 2011 October. The COR1 polarizer wheel on Behind began to show some jitter at the end of 2012; so-far successful mitigation efforts have focused on adjusting the mechanism delay settings.

S/WAVES

The S/WAVES instrument on STEREO-A continues to function nominally, albeit with a reduced telemetry rate. We expect that S/WAVES on STEREO-B is also capable of functioning as it was previously. The STEREO-A S/WAVES instrument will be on throughout the solar conjunction period with a small volume of data being recorded on the spacecraft solid state recorder. Playback of the S/C SSR at the end of 2015 will allow reasonable coverage of the entire period., though with lower time and frequency resolution than typical for most of the mission. Loss of the STEREO-B data has a significant effect on S/WAVES science but can be mitigated in the years to come with the use of the Wind/WAVES instrument for 3-D direction finding.

D. Research Focus Areas, NASA Heliophysics Roadmap, 2009 - 2030

Research Focus Areas

- **F1** Magnetic reconnection
- **F2** Particle acceleration and transport
- **F3** Ion-neutral interactions
- **F4** Creation and variability of magnetic dynamos

Open the Frontier to Space Environmental Prediction

The Sun, our solar system, and the universe consist primarily of plasma. Plasmas are more complex than solids, liquids, and gases because the motions of electrons and ions produce both electric and magnetic fields. The electric fields accelerate particles, sometimes to very high energies, and the magnetic fields guide their motions. This results in a rich set of interacting physical processes, including intricate exchanges with the neutral gas in planetary atmospheres.

Although physicists know the laws governing the interaction of electrically charged particles, the collective behavior of the plasma state leads to complex and often surprising physical phenomena. As the foundation for our long-term research program, we will develop a comprehensive scientific understanding of the fundamental physical processes that control our space environment.

The processes of interest occur in many locations, though with vastly different magnitudes of energy, size, and time. By quantitatively examining similar phenomena occurring in different regimes with a variety of techniques, we can identify the important controlling mechanisms and rigorously test our developing knowledge. Both remote sensing and in situ observations will be utilized to provide the complementary three-dimensional, large-scale perspective and the detailed small-scale microphysics view necessary to see the complete picture.

Research Focus Areas

- **H1** Causes and evolution of solar activity
- **H2** Earth's magnetosphere, ionosphere, and upper atmosphere
- **H3** Role of the Sun in driving change in the Earth's atmosphere
- **H4** Apply our knowledge to understand other regions

Understand the Nature of Our Home in Space

Humankind does not live in isolation; we are intimately coupled with the space environment through our technological needs, the solar system bodies we plan to explore, and ultimately the fate of our Earth itself. We regularly experience how variability in the near-Earth space environment affects the activities that underpin our society. We are living with a star.

We plan to better understand our place in the solar system by investigating the interaction of the space environment with the Earth and the effect of this interaction on humankind. We plan to characterize and develop a knowledge of the impact of the space environment on our planet, technology, and society. Our goal is to understand the web of linked physical processes connecting Earth with the space environment.

Even a casual scan of the solar system is sufficient to discover that habitability, particularly for humankind, requires a rare confluence of many factors. At least some of these factors, especially the role of magnetic fields in shielding planetary atmospheres, are subjects of immense interest to heliophysics. Lessons learned in the study of planetary environments can be applied to our home on Earth, and vise versa, the study of our own atmosphere supports the exploration of other planets.

Research Focus Areas

- **J1** Variability, extremes, and boundary conditions
- **J2** Capability to predict the origin, onset, and level of solar activity
- **J3** Capability to predict the propagation and evolution of solar disturbances
- **J4** Effects on and within planetary environments

Safeguard the Journey of Exploration

NASA's robotic spacecraft continue to explore the Earth's neighborhood and other targets in the heliosphere. Humans are expected once again to venture onto the surface of the Moon and one day onto the surface of Mars. This exploration brings challenges and hazards. We plan to help safeguard these space journeys by developing predictive and forecasting strategies for space environmental hazards.

This work will aid in the optimization of habitats, spacecraft, and instrumentation, and for planning mission operation scenarios, ultimately increasing mission productivity. We will analyze the complex influence of the Sun and the space environment, from origin to the destination, on critical conditions at and in the vicinity of human and robotic spacecraft. Collaborations between heliophysics scientists and those preparing for human and robotic exploration will be fostered through interdisciplinary research programs and the common use of NASA research assets in space.

E. Acronyms

ACE	Advanced Composition Explorer
AFOSR	Air Force Office of Scientific Research
AMPTE	Active Magnetospheric Particle Tracer Explorer
APL	Johns Hopkins University Applied Physics Laboratory
ASCII	American Standard Code for Information Interchange
AU	Astronomical Unit
CACTUS	Computer Aided CME Tracking
CCMC	Community Coordinated Modeling Center
CDAWeb	Coordinated Data Analysis
CDF	Common Data Format
CDPP	Centre de Données de la Physique des Plasmas (France)
CME	Coronal Mass Ejection
Co-I	Co-Investigator
COR1	SECCHI Inner Coronagraph
COR2	SECHHI Outer Coronagraph
DSN	Deep Space Network
ENA	Energetic Neutral Atom
EUV	Extreme UltraViolet
EUVI	SECCHI Extreme UltraViolet Imager
FITS	Flexible Image Transport System
FY	Fiscal Year
GCS	Graduated Cylindrical Shell
GOES	Geostationary Operational Environmental Satellite
GONG	Global Oscillation Network Group
GSE	Ground support equipment
GSFC	Goddard Space Flight Center
HET	IMPACT High Energy Telescope
HGA	High Gain Antenna
HI	SECCHI Heliospheric Imager
HSO	Heliophysics System Observatory
IAS	Institut d'Astrophysique Spatiale (France)
IBEX	Interstellar Boundary Explorer
ICME	Interplanetary coronal mass ejection
IDL	Interactive Data Language™
IMPACT	In-situ Measurements of Particles and CME Transients Investigation
IMU	Inertial Measurement Unit
IRIS	Interface region Imaging Spectrograph
ISTP	International Solar Terrestrial Physics program
kbps	Kilobits per second
L1	First Lagrangian Point
LASCO	SOHO Large Angle and Spectrometric Coronagraph
LET	IMPACT Low Energy Telescope
LFR	S/WAVES Low Frequency Receiver

LISM	Local Interstellar Medium
LMSAL	Lockheed Martin Solar and Astrophysics Laboratory
LWS	Living With a Star
MAG	IMPACT Magnetometer
MAVEN	Mars Atmosphere and Volatile EvolutioN
MESSENGER	MErcury Surface, Space ENvironment, GEochemistry, and Ranging
MHD	Magnetohydrodynamics
MIR	Merged Interaction Region
MO&DA	Mission Operations and Data Analysis
MOC	Mission Operations Center
MPS	Max Planck Institut für Sonnensystemforschung (Germany)
NAIF	Navigation and Ancillary Information Facility
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
NRL	Naval Research Laboratory
NUC	Next Unit of Computing
PAD	Pitch Angle Distributiom
PI	Principal Investigator
POC	Payload Operations Center
PSG	Prioritized Science Goal
PLASTIC	PLAsma and SupraThermal Ion Composition Investigation
PUI	Pickup Ion
RAL	Rutherford Appleton Laboratory
RF	Radio frequency
RHESSI	Reuven Ramaty High Energy Solar Spectroscopic Imager
SCOSTEP	Scientific Committee On Solar-terrestrial Physics
SDAC	Solar Data Analysis Center
SDO	Solar Dynamics Observatory
SDS	STEREO Data Server
SECCHI	Sun Earth Connection Coronal and Heliospheric Investigation
SEP	Solar Energetic Particle
SEPT	IMPACT Solar Electron Proton Telescope
SEU	Single Event Upset
SIT	IMPACT Suprathermal Ion Telescope
SO	Solar Orbiter
SOHO	Solar and Heliospheric Observatory
SPASE	Space Physics Archive Search and Extract
SPDF	NASA Space Physics Data Facility
SPICE	Spacecraft, Planet, Instrument, C-Matrix, Events
SPLAT	STEREO PLASTIC Analysis Tool
SPP	Solar Probe Plus
SSC	STEREO Science Center
SSR	Solid State Recorder
STA	STEREO-Ahead
STB	STEREO-Behind
STE	IMPACT Suprathermal Electron Telescope
STEREO	Solar TErrestrial RElations Observatory

S/WAVES	STEREO Waves Investigation
SWEA	IMPACT Solar Wind Electron Analyzer
SXR	Soft X-Ray
TDS	S/WAVES Time Domain Sampler
TRACE	Transition Region and Coronal Explorer
UCB	University of California, Berkeley
UNH	University of New Hampshire
URL	Uniform Resource Locator
VHO	Virtual Heliospheric Observatory
VSO	Virtual Solar Observatory
VSPO	Virtual Space Physics Observatory (now the Heliophysics Data Portal)

STEREO instrument and instrument subsystem names are in blue.