LONG TERM MISSIONS AT THE SUN-EARTH LIBRATION POINT L1: ACE, SOHO, AND WIND

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Three heliophysics missions—the Solar Heliospheric Observatory (SOHO), the Advanced Composition Explorer (ACE), and the Global Geoscience WIND—have been orbiting the Sun-Earth interior libration point L1 continuously since 1996, 1997, and 2004, respectively. ACE and WIND (both NASA missions) and SOHO (an ESA-NASA joint mission) are all operated from the NASA Goddard Space Flight Center Flight Dynamics Facility. While ACE and SOHO have been dedicated libration point orbiters since their launches, WIND prior to 2004 flew a remarkable 10-year deep-space trajectory that featured 38 targeted lunar flybys. The L1 orbits and the mission histories of the three spacecraft are briefly reviewed, and the station-keeping techniques and orbit maneuver experience are discussed.

INTRODUCTION

Three heliophysics missions—the Solar Heliospheric Observatory (SOHO), the Advanced Composition Explorer (ACE), and the Global Geoscience International Physics Laboratory (universally referred to by its nickname, WIND)—have been orbiting the Sun-Earth interior libration point L1 continuously since 1997, 1996, and 2004, respectively.[†] ACE and WIND (both NASA missions) and SOHO (an ESA-NASA joint mission) all have their maneuver operations conducted from the NASA Goddard Space Flight Center (GSFC) Flight Dynamics Facility (FDF). While ACE and SOHO have been dedicated libration point orbiters since their launches, WIND has had also a remarkable 10-year career flying a deep-space, multiple lunar-flyby trajectory prior to 2004. That era featured 38 targeted lunar flybys during an initial Double-Lunar-Swingby (DLS) phase, a Distant Prograde Orbit (DPO) phase, and looping excursions to both the Sun-Earth L1 and L2 collinear points before its final insertion into an L1 orbit.

A prime scientific purpose of all three missions is the study of the heliosphere and the solar wind, making these missions similar to, and in many ways descended from, the first L1 orbiter called the International Sun-Earth Explorer-3 (ISEE-3) launched in 1978.[1] In addition, SOHO is the first mission to carry imaging instruments to L1for study of the Sun and its dynamics. This paper reviews the L1 orbits and the mission history of ACE, WIND, and SOHO, and describes the station-keeping techniques and orbit maneuver experience.[2-13] Also, the Lissajous orbit phase control that was performed for ACE during the period from 1999 to 2001 is briefly discussed.[7] Finally, the future for these ongoing missions is considered.

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[†] The Sun-Earth L1 point is approximately 1.5 million kilometers (0.01 AU) from Earth in the direction of the Sun.

BACKGROUND AND MISSION ORBIT OVERVIEW

Figures 1 through 3 depict the orbits of the three spacecraft, showing projections of the orbits onto the YZ, XY and XZ planes of a solar rotating ecliptic reference frame, respectively. Throughout this paper, orbit diagram reference frames will be one of either two types of rotating frames common to libration point orbit (LPO) work: either a Geocentric Solar Ecliptic (GSE) frame or the similar Rotating Libration Point (RLP) L1-centered frame. For the Earth-centered GSE frame, the fundamental axis (X-axis) is formed by the Sun-to-Earth line, with X positive in the anti-Sunward direction. The X-axis for the RLP is similar, directed from the L1 point to the Earth-Moon barycenter. For both frames, the Z-axis is defined up toward the North Ecliptic Pole (NEP), and a Y-axis that is parallel to the ecliptic completes these two right-handed triads.
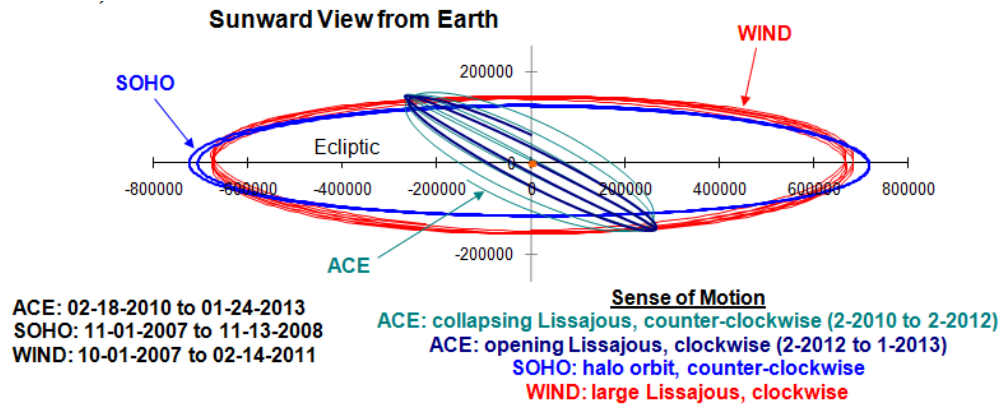
Figure 1. Sky Plane Perspective View of ACE, SOHO, and WIND Libration Point Orbits.
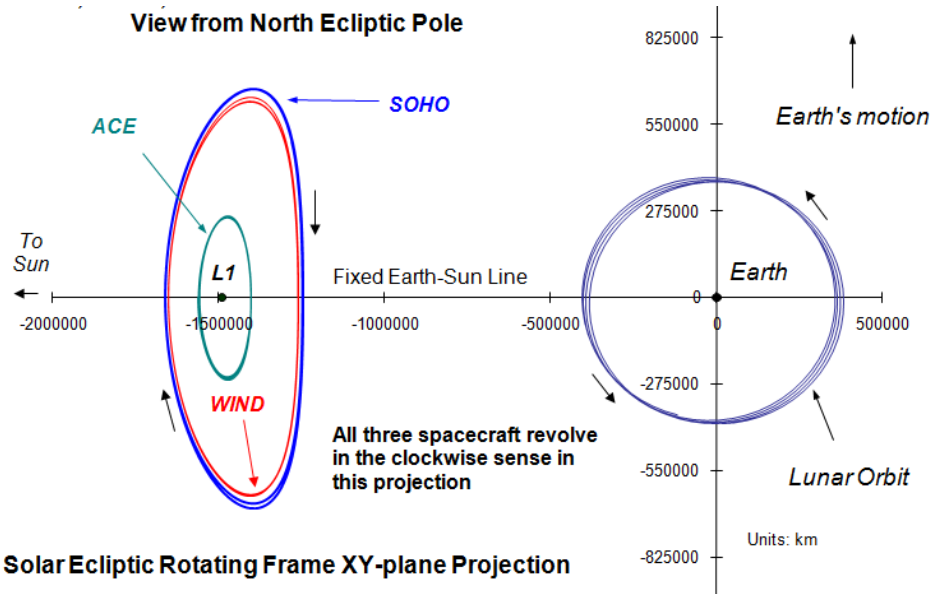
Figure 2. Ecliptic Plane Projection of ACE, SOHO, and WIND Libration Point Orbits.
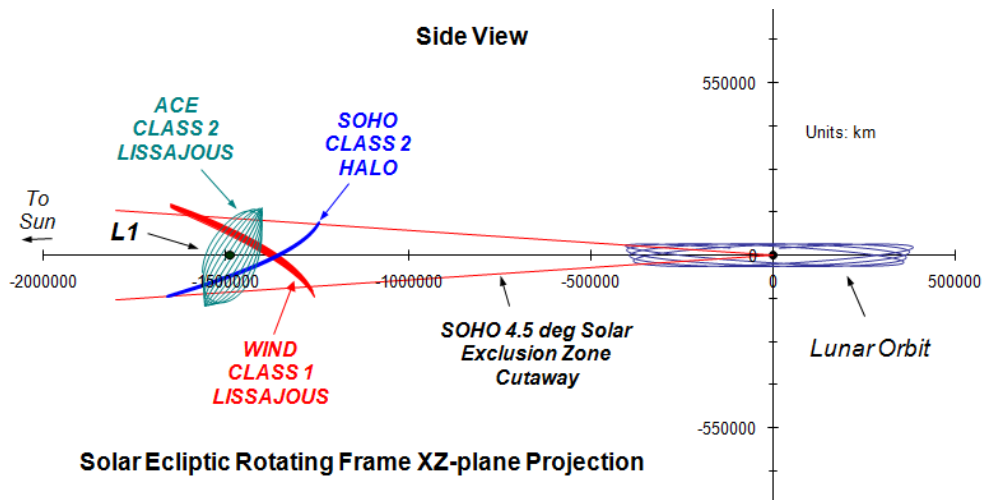
Figure 3. Side View of ACE, SOHO, and WIND Libration Point Orbits.

The SOHO orbit is a quasi-periodic halo orbit, where the frequencies of the in-plane and out-of-plane motions are practically equal. Such an orbit is seen to repeat itself with a period of approximately 178 days. For ACE and WIND, the frequencies of the in-plane and out-of-plane motions are unequal, giving rise to the characteristic Lissajous motion. ACE's orbit is considered to be of moderately small amplitude, whereas WIND's orbit is a large-amplitude Lissajous with dimensions close to those of the SOHO halo orbit. The WIND Lissajous evolves much more slowly over time than does the ACE Lissajous. For all three spacecraft, the selected size of the out-of-plane amplitude was governed by the associated Solar Exclusion Zone (SEZ) keep-out constraint required by the mission. The SEZ, shown for SOHO in Figure 3, is basically a right-circular cone of space with the Earth-Sun line for its axis, its vertex at Earth's center, and having a specific angular radius at the distance of L1. The SEZ constraint exists so spacecraft can avoid solar radio frequency background interference with their downlink transmissions. To determine whether the spacecraft trajectories are in fact staying clear of their mission SEZ, the Sun-Earth-Vehicle (SEV) angle is monitored continuously throughout the mission. An SEZ violation would occur if the SEV angles over a portion of an orbit fall below the SEZ angle limit.

As motion about the L1 point is inherently unstable, station-keeping maneuvers are necessary to prevent orbital decay and eventual escape from the L1 region. Although the three spacecraft are dissimilar (SOHO is a 3-axis stabilized Sun pointer, WIND is spin-stabilized with spin axis aligned with the ecliptic poles, and ACE is also spin-stabilized with its spin axis maintained close to Sun-pointing), the station-keeping technique for the three is fundamentally the same. In brief, this technique consists of correcting the energy of the orbit via a delta-V directed parallel or anti-parallel to the Spacecraft-to-Sun line.[3] Sunward thrust adds energy to the orbit, thereby preventing decay of the LPO back toward Earth. Alternatively, thrust directed anti-Sunward takes energy out of the L1 orbit, thereby preventing spacecraft escape from the grasp of the Earth-Moon system into an independent orbit around the Sun. Sun-pointing SOHO achieves a delta-V using thrusters oriented in line with the solar direction. WIND achieves the required delta-V direction from pulsing its radial thrusters as they rotate into alignment with the Sun. ACE uses its axial thrusters to apply delta-V with a cosine component along the ACE-Sun line that is in all situations 0.94 or better.

LPO station-keeping delta-V costs grow exponentially with time elapsed from the last maneuver performed. For these missions, the doubling time constant is approximately 16 days. To conserve fuel and limit the absolute magnitude of propulsion performance errors, station-keeping

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maneuvers should be performed before the delta-V grows too large; for our purposes 'too large' is presently considered to be greater than 0.5 m/sec. In practice, the typical interval between burns for this trio is about 90 days, and the typical delta-V is much smaller than 0.5 m/sec. In recent years, typical annual station-keeping costs have been around 1.0 m/sec for ACE and WIND, and much less than that for SOHO. All three spacecraft have ample fuel remaining; barring contingencies, all three could be maintained at L1 for decades to come.

Finally, for all three spacecraft, S-band tracking, telemetry, and command functions are supported by NASA's Deep Space Network (DSN) 34-meter sub-net, with the tracking and telemetry data forwarded to GSFC. Also for all three, all orbit and attitude maneuvers are designed, planned, commanded, and controlled from ground operations at GSFC.

THE SOLAR HELIOSPHERIC OBSERVATORY (SOHO) MISSION

The Solar and Heliospheric Observatory—a joint ESA and NASA deep space mission to study the Sun—is the second spacecraft to fly a Sun-Earth system Lagrange-point orbit.[2,3] Launched on December 2, 1995, SOHO is presently in a quasiperiodic halo orbit around the Sun-Earth point L1—a halo orbit of nearly identical dimensions to those of ISEE-3.[1] SOHO carries a suite of 12 scientific instruments including imaging sensors to study phenomena relating to the solar surface and atmosphere, solar dynamics, and the solar corona and solar wind, to better understand the Sun as a whole. The Sun-Earth L1 point region is the perfect location from which to conduct continuous, direct observation of the Sun and perform in situ measurements of the upstream solar wind.

This 3-axis stabilized spacecraft maintains one axis fixed upon the Sun's center at all times. This attitude keeps the suite of scientific instruments always trained upon the Sun with an accuracy of one arc-second for around-the-clock data gathering. The spacecraft was designed for attitude stabilization and pointing control via a closed-loop system. This system consists of an inertial reference unit including three roll gyroscopes, a four-wheel reaction wheel assembly for momentum management, a fixed-head star tracker, and two fine sun sensors—all under the control of an onboard computer (OBC). The onboard control system is supported by a variety of ground-based attitude determination and control functions including momentum wheel management.[*]

A large spacecraft, SOHO had a total mass of 1,863 kg at launch— of which 251 kg was hydrazine fuel. Electrical power is generated by two large solar cell array panels yielding 1,150 W. The solar panels, taken together with the main bus (Service Module) and payload (Instrument Module), give SOHO a deployed cross-sectional area of 21.9 m^2. The Service and Payload modules together give SOHO a boxy, rectangular look (see Figure 4), and it is parallel to the long axis that the body X-axis—the X_B, or roll, axis—is defined. The $+X_B$ direction is that along which the instrument bore-sights are intended to point at the Sun. The Z_B axis, or yaw axis, is orthogonal to X_B, and it is positive in an "up" sense that is intended to be parallel with the Sun's positive spin axis direction, i.e., its North Pole. The Z_B axis is also the axis of maximum inertia. The Y_B axis, or pitch axis, completes the right-handed triad.

The SOHO monopropellant blowdown propulsion system consists of a single large hydrazine fuel tank and a total of sixteen 4.5 N thrusters. The thrusters are divided into two branches of eight thrusters each, and are positioned around the spacecraft to provide for delta-V and roll, yaw, and pitch control. The primary branch (A-branch) is used for normal operations while the

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[*] All three gyroscopes failed by the end of 1998, precipitating a severe crisis (more about the contingency below).[3,4]

redundant B-branch is used during autonomous fail-safe mode. A pair of primary branch thrusters (1A and 2A) on the Sun-facing side of this Sun-pointing spacecraft provide delta-V thrust in the body $-X_B$ direction (pointing anti-Sunward), while another pair (3A and 4A) on the rear side of SOHO provide thrust in the $+X_B$ direction, i.e., Sunward. It is these two pairs that are used for station-keeping (1A and 2A also provide pitch control while 3A and 4A provide yaw control). During delta-V maneuvers, another two thrusters from the roll set and the yaw or pitch set also provide intermittent thrusting to ensure overall roll, yaw, and pitch stability during the maneuver. At present, SOHO has approximately 129 kg of fuel remaining. This is sufficient fuel for station-keeping for more than a century to come, barring contingencies.
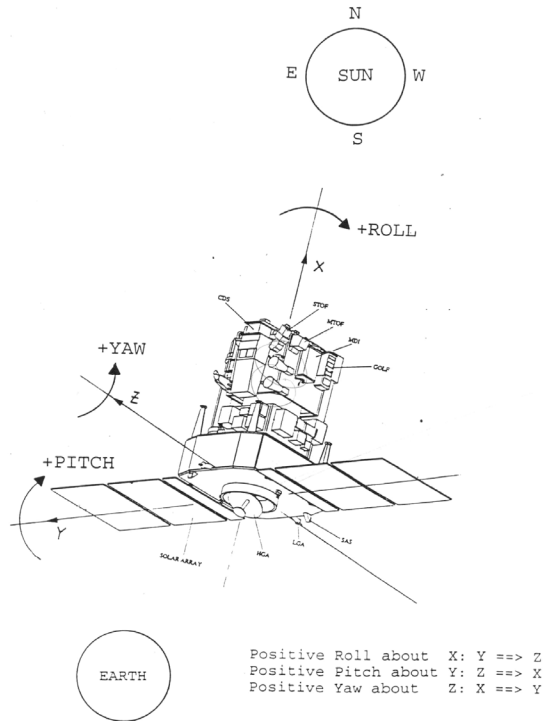

Figure 4. The Solar Heliospheric Observatory (SOHO) Spacecraft

The SOHO mission orbit is a Class 2-type halo orbit; one characteristic of the Class 2 is that its sense of revolution about L1—as it appears from Earth—is counterclockwise. The primary mission constraints placed on the halo orbit were: 1) that the minimum SEV angle never be less than 3.0 degrees (the SEZ constraint) and 2) that the maximum SEV angle never be greater than 32 degrees. The maximum SEV constraint derives from the HGA gimbal angle limits and was also germane to the design of the Earth to L1 transfer trajectory.[2]

The halo orbit selected for SOHO during the pre-launch mission design phase satisfied the mission constraints with plenty of margin. The design results showed that for the six-year antic-ipated life of SOHO the orbit comes no closer to the solar center than 4.5 degrees during the nearer, Earth-side crossing of the RLP XZ-plane, and is at about 5 degrees at the farther, Sun-side crossing. At the RLP extreme Y-axis points of the halo, the SEV angle is never more than ap-proximately 25.5 degrees.

The RLP-frame oscillation amplitudes corresponding to this 4.5-by-25.5 degree orbit—as specified during the pre-launch mission design phase—were as follows:

$$A_X = 206{,}448 \text{ km}$$

$$A_Y = 666{,}672 \text{ km}$$

$$A_Z = 120{,}000 \text{ km}$$

These amplitudes are nearly identical to those specified for the first LPO halo mission, ISEE-3. As noted above, the period of one full revolution around L1 for this orbit is approximately 178 days. SOHO's orbit is shown projected onto a solar rotating-frame XY-plane, XZ-plane, and YZ-plane, in Figures 1 through 3, respectively. As is seen in Figure 3, SOHO's orbit has a significant inclination to the Ecliptic plane. Another feature of the Class 2 halo orbit is that its northern-most point is nearest to Earth, and its southernmost point is furthest from Earth. The reverse would be true for a Class 1 orbit, as a Class 1 of the same A_Z amplitude as SOHO's would be seen to be a reflection of the Class 2 orbit about the GSE X-axis.

As is well known, orbits at the collinear libration points such as L1 are inherently unstable; hence, regular station-keeping maneuvers must be performed on some basis that makes sense for a mission's particular needs. Initially, the SOHO Project preferred that free-flight coasts be as long as possible, i.e., the time between maneuvers to be maximized, the better to minimize the operational impact to science. Yet with corrective delta-V costs for the halo orbit doubling every 16 days[4], it is prudent to stationkeep before such costs have grown "too large". During SOHO's first two years of flight, "too large" was considered to be any delta-V larger than about 0.75 m/sec, although a few station-keeping burns were over one meter per second. (Such cut-off guidelines, although subject to engineering judgment, are nevertheless driven by mission-determined considerations and concerns, such as fuel availability, delta-V error control, length of burn and duty cycling factors, science instrument sensitivity to propellant by-products, and impacts to attitude control, among others.)

Current orbital station-keeping practice for SOHO is tied operationally to other spacecraft functions, namely the need for regular momentum wheel management maneuvers and a quarter-annual need for a spacecraft roll inversion to maintain communications with Earth. The latter became a necessity when the gimbaled HGA dish became stuck in mid-2003.[*] Hence, all three functions are scheduled to occur together once every 90 days. This makes sense for station-keeping since the SOHO momentum wheel management maneuvers typically consist of a series of at least three burns (each using a single thruster only) that have the deleterious side effect of perturbing the orbit. So, doing the station-keeping the same day allows for the immediate negation of these unwanted perturbations. Prior to the stuck HGA problem of 2003, it was possible to coast longer than 90 days between station-keeping burns, with a maneuver opportunity scheduled to accommodate whichever of the momentum management or the station-keeping functions required it earliest.

Briefly, the typical SOHO process for station-keeping maneuver targeting begins with numerically propagating the orbit from the epoch of an orbit determination solution state forward in time to a candidate maneuver epoch. From this point, a numerical differential correction targeting process iteratively determines the delta-V required to maintain the halo orbit. The targeting problem is constructed with a single independent variable and a single dependent variable, or

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[*] The SOHO stuck antenna problem was the impetus for exploring the idea of transferring SOHO to a LPO of new, smaller y-axis amplitude suitable for maintaining Earth coverage without the need for periodic roll inversions, the subject of a 2004 paper by the author.[4] Though feasible in principle, the LPO transfer option was not selected due mainly to SOHO's fragile condition making the rather large maneuvers needed too dangerous to attempt.

goal. The independent variable is the delta-V directed parallel (or anti-parallel) to the SOHO-to-Sun line.[*] The targeting goal is described as the x-component of velocity (V_X), in RLP-frame coordinates, specified to be zero km/sec (within some small tolerance) at the point where the trajectory crosses the RLP XZ-plane. So, the targeting proceeds with propagating the trajectory to first contact with the RLP-frame XZ-plane, where the V_X is evaluated. If V_X is not zero (within the tolerance value), the differential corrector will iteratively vary the delta-V until the trajectory reaches the XZ-plane meeting the RLP V_X = 0 km/sec condition. The targeting process is continued, and the delta-V is further refined, by targeting subsequent XZ-plane crossings (achieving one after the other in turn) with the same V_X = 0 goal. The process is generally stopped after two full revolutions (or about one year) in the halo are achieved; this amounts to the delta-V at the given maneuver epoch having been targeted on a total of four to five XZ-plane crossings (time-of-flight between crossings is about three months). This process is discussed further in References 3 through 5.

The history of SOHO halo orbit maintenance has been complex and not without drama. Following a 3-month transfer from Earth, the SOHO halo orbit was achieved in early March 1996. The very first SOHO station-keeping maneuver—a fairly modest burn of 0.31 m/sec—was performed on May 23, 1996. Over the next two years, a total of eight station-keeping maneuvers were performed. During this early period, emphasis was placed on maximizing time-of-flight between maneuvers, as the mission was fuel-rich and minimizing science observing interruptions was paramount. Therefore, when things were going well, the time between maneuvers was frequently above 100 days, and in some cases well above (the record was 146 days). However, there were times when this practice meant the correction delta-Vs would be relatively high (for instance, the cost was 1.89 m/sec following that 146 day coast).

With the emphasis on long coast times well over 100 days, the expectation would be that perhaps only two to three station-keeping maneuvers per year would be necessary, constrained as much by the frequency of momentum wheel management maneuvers as anything else. However this expectation was not realized entirely, due to sporadic attitude-related anomalies leading to failovers to a safe-hold mode. This SOHO safe-hold mode, called an Emergency Sun Re-acquisition (ESR) mode, would prove to be unhelpful to station-keeping.[†] The reason for that is, in ESR mode, the Sun-pointing attitude is maintained via autonomous thruster firing (using the B-branch thrusters in a hard-wired mode). This autonomous firing, while controlling the attitude, unfortunately imparts a net Sun-ward delta-V at a rate of nearly 0.5 m/sec/day, thereby adding energy to the orbit and pushing the spacecraft onto an escape trajectory. As it typically takes a minimum of eight hours (but it has often been longer) to recover the spacecraft from ESR mode, such events can introduce a considerable delta-V that must be corrected. Generally, a correction delta-V is planned and executed within one to two days or so following the ESR. Since accurate LPO orbit determination is not possible so soon after the ESR recovery, the ESR-imparted delta-V[‡] must be analyzed from the Doppler tracking data, and then modeled into the trajectory as an extended finite burn to update the trajectory knowledge prior to planning the post-ESR correction burn.

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[*] In more detail, a custom delta-V frame is constructed for targeting purposes as follows: the X-axis is formed from the SOHO-to-Sun line, a Z-axis is formed 90 degrees up from the X-axis in the direction of the North Ecliptic Pole, and a Y-axis completes the right-handed triad. For station keeping, the entire delta-V needed is along this frame's X-axis.

[†] SOHO ESRs would also become the progenitors of events that nearly destroyed the mission in 1998.

[‡] For SOHO, no thruster firing data is contained in the telemetry when in ESR mode; hence, the Doppler data provides the only insight as to what the imparted delta-V is.

In the discussion to follow, post-ESR recovery burns will be regarded as equivalent to station-keeping burns, even though the case can be made that they should be treated as special post-contingency recovery burns distinct from regular station-keeping burns. Therefore, we have grouped all maneuvers together as station-keeping maneuvers in Figure 6, which shows 63 maneuvers performed between 23 May 1996 and 19 July 2011. In Figure 6, the blue trace (diamond markers) show the first eight station-keeping maneuvers discussed above. Only 20 days separate the sixth and seventh maneuvers, as the seventh maneuver was actually a post-ESR recovery maneuver. Following the eighth burn is a one year gap. The story that goes with this gap—starting in June 1998—is one of the most amazing of any in the history of space flight.
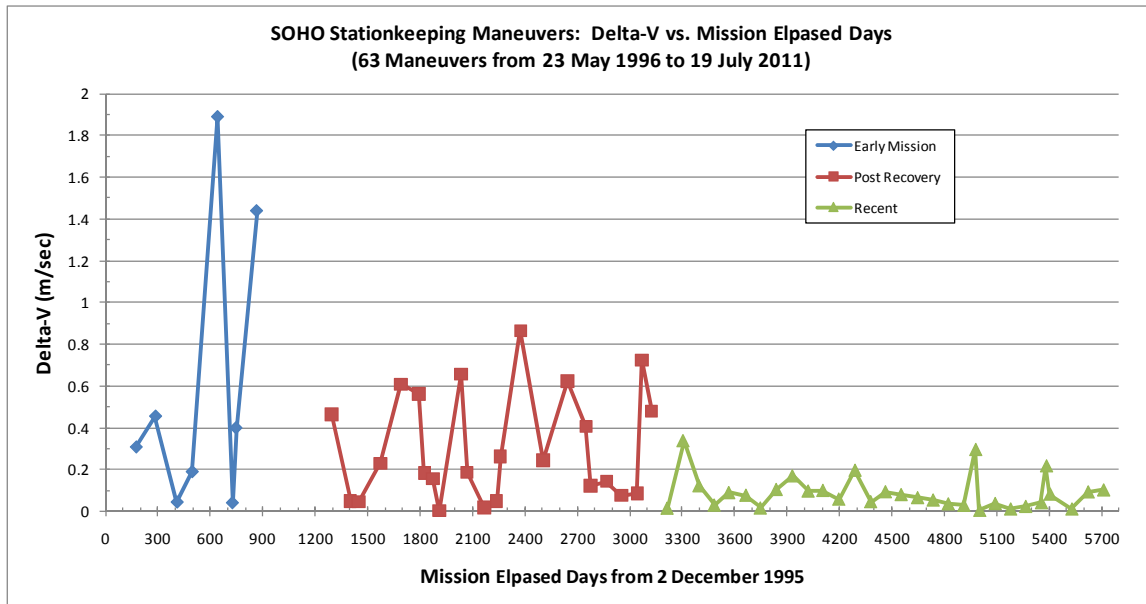

Figure 6. SOHO L1 Halo Orbit Station-keeping Maneuvers

On June 24th, 1998, the recovery from an ESR contingency went awry, SOHO went into a tumble, and all contact was lost for over five weeks. Not until early August was contact with the de-powered, frozen, slowly spinning SOHO re-established, and a long, arduous campaign to recover the spacecraft began. By late fall 1998, SOHO had been fully recovered and, amazingly, was a fully functioning observatory again. However, just before Christmas, the lone surviving gyro died, plunging SOHO once again into a grave crisis. SOHO would be in ESR mode for 40 long days with no way to return to normal control mode and with the delta-V build-up threatening escape into solar orbit. What transpired was a frenzied campaign by large teams of engineers on two continents to re-invent the spacecraft, including, among much else, a re-write of the on-board flight software for control on reaction-wheels only, and figuring out how to do orbit maneuvers with a badly crippled spacecraft. (It was critical to resume orbit maneuvers as soon as possible to counter the ESR thruster firing.) The full story of the two recoveries is long and complex, and well beyond the scope of this paper. (The author has written an extensive account of the struggle to save the halo orbit in Reference 3 and a longer, particularly detailed account in Reference 4.) However, it will suffice here to mention that eight recovery maneuvers were designed and executed between September 1998 and March 1999. For completeness these maneuvers are summarized in Table 1.

Table 1. SOHO Recovery Maneuvers.

Burn #	Date	Days since Prior Burn	Delta-V (m/sec)
RM-01	9/25/98	161	−6.21
RM-02	10/16/98	21	+1.92
RM-03	11/13/98	28	+2.29
RM-04	1/07/99	55	−8.08
RM-05	1/19/99	12	−8.64
RM-06	1/26/99	7	−3.95
RM-07	2/1/99	6	+0.32
RM-08	3/5/99	32	−0.12

Note: − anti-Sunward; + Sunward

Referring to Figure 6, station-keeping maneuvers pick up again following the year of contingencies and their recoveries. The five year period between June 1999 and June 2004 is represented by the square markers (red trace). During this period, the goal was to return to the practice of extending coast periods for as long as possible. However, this was also an era of frequent, unpredictable ESR events, caused at least in part by bugs in the new onboard flight software that needed to be ironed out. As a consequence, a number of these burns were larger than 0.5 m/sec (although none greater than 0.87 m/sec). Nevertheless, many of these burns were at or below the 0.2 m/sec mark, with the average over the entire period being 0.30 m/sec. By the middle of 2003, the failure of the HGA gimbal mechanism led to a change in the frequency of station-keeping maneuvers, one that would also prove to lower the average annual costs.

The implementation of a fixed (roughly) 90-day cadence for station-keeping has resulted in an overall lowering of annual station-keeping costs over the period from mid-2003 to mid-2011. This trend, which is seen primarily from September 2004 onward, is represented in Figure 6 by the triangular markers (green trace). Since that time, station-keeping delta-Vs have averaged just 0.09 m/sec, with many considerably smaller than that. A combination of consistent, accurate thruster calibration, reasonable thruster repeatability, and short, small burns has led to driving down the absolute magnitudes of the burn performance errors.   With a fixed time between maneuvers, the exponential growth factor for the subsequent station-keeping maneuver is fixed; hence, the smaller the absolute error for a given burn, the smaller will be the magnitude of the follow-on burn.[*] By way of example, in a 90-day span there are 5.625 sixteen-day doubling periods. Hence, the correction delta-V growth factor over 90 days is $2^{5.625} \cong 49$. So if your maneuver error was 0.1 cm/sec, you could expect that your next SK burn 90 days later would require 4.9 cm/sec. If your error was 1 cm/sec, the next burn 90 days later would be approximately 49

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[*] That is, everything else being equal; other factors can come into play to disrupt such an outcome, with often the foremost being variability in orbit knowledge accuracy.

cm/sec, and so on. This fairly simple rule of thumb approach can be surprisingly accurate, although it can be thrown off if there are other error sources present of uncertain origin, magnitude and direction. In any case, it is never sufficient for planning; numerical targeting is always necessary for full delta-V accuracy.

THE ADVANCED COMPOSITION EXPLOER (ACE) MISSION

The Advanced Composition Explorer (ACE) is the third NASA spacecraft to fly a libration point orbit, and like ISEE-3 and SOHO before it, it is orbiting the Sun-Earth L1 point. Launched on August 25, 1997, the ACE mission is to study the composition of both the solar wind and the galactic cosmic rays.   ACE is a spin-stabilized spacecraft with a required spin rate of 5.0 ± 0.1 revolutions per minute (rpm). With a dry mass of 785 kg, ACE at launch had 195 kg of hydrazine fuel and a delta-V capability of approximately 445 m/sec. The ACE bus is a squat structure of octagonal shape measuring approximately 1.6 meters across and 1 meter high (see Figure 7).
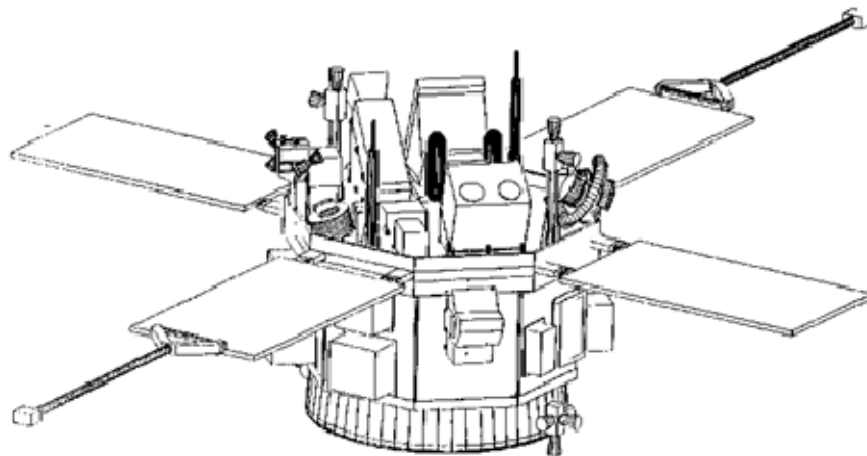

Figure 7. The Advanced Composition Explorer (ACE) Spacecraft

Extending from four of the 8 side faces are fixed solar cell array panels generating 464 watts of power. The solar panel configuration gives ACE somewhat the appearance of a windmill in space. The deployed configuration has a Sun-facing area of approximately 7.2 m^2. The nine science instruments are all mounted on or around the top, Sun-facing deck. The attitude sensor suite consists of two digital sun sensors and a single star tracker. ACE does not possess autonomous attitude determination or control capability, and therefore attitude determination is performed on the ground. A parabolic High Gain Antenna is in a fixed mounting on the aft end for Earth pointing.

The ACE blowdown propulsion system consists of four monopropellant hydrazine fuel tanks and a total of ten 1-lbf thrusters. Two thrusters on both the top deck and the bottom deck are used in a continuous firing mode to provide axial delta-V. Two triads of radial thrusters are arrayed on opposite side faces, with one thruster of the triad on the face midline above a solar panel (top group) and the remaining two forming the base of the triad mounted astride the midline and beneath a solar panel (bottom group). The radials are fired in a pulsed mode to provide either radial delta-V (using all six thrusters with each triad firing once per spin) or spin-axis reorientation (using three radials, one top group thruster and two bottom group thrusters from the opposite face). Thruster on/off pulsing is controlled via once per spin cycle Sun detection and on-board clock-

tick timing. Offset pairs of radials are also used in a continuous firing mode for spin rate changes. As of mid-2011, ACE has 58.1 kg of fuel remaining.

ACE is required at all times to have its spin axis (body +Z-axis) oriented such that the spin-axis-to-Sun angle (β-angle) is no fewer than 4 degrees and no more than 20 degrees. Another attitude constraint imposed by the Earth-pointing requirements for the High Gain Antenna is that the body −Z-axis must always point within a cone of radius 8.0 degrees about the ACE-to-Earth line.[*] Thus the inertial spin-axis attitude selected for ACE at any given time must satisfy both of those constraints simultaneously. Since the Earth-Moon system revolves around the Sun at about 1 deg/day, however, no single inertial attitude can satisfy these two constraints indefinitely. There-fore fairly frequent spin axis re-orientations are necessary—an average of about once every two weeks and, when ACE is moving retrograde relative to Earth, as frequently as once every week. More than 570 of these spin axis re-orientations plus an additional 23 spin rate change maneuvers have been carried out since launch through June 2011.

Launched in late August 1997, the maneuvers that inserted ACE into its L1 orbit after a 110-day transfer from Earth were completed in mid-December 1997. The ACE orbit is a Lissajous orbit of relatively small RLP X-axis and Y-axis amplitudes.[†] The design amplitudes chosen for the ACE Lissajous were as follows:

$$A_X = 81,755 \text{ km}$$

$$A_Y = 264,071 \text{ km}$$

$$A_Z = 157,406 \text{ km}$$

These amplitudes correspond to angular dimensions of approximately six degrees out-of-plane and 10 degrees in-plane (Y-axis). The 10-degree Y-axis amplitude was mandated by science and spacecraft-specific requirements, while the 6-degree Z-axis amplitude was designed to keep the orbit from crossing the SEZ for the first two years of on-orbit flight. The mission design specifi-cation for the SEZ was an angular radius of 5.0 degrees (although later during flight this was re-laxed slightly to 4.75 degrees). Following that 2-year period, it was planned that periodic Z-axis control maneuvers would be used to keep the Lissajous orbit out of the SEZ for the remainder of the mission.[7] The natural evolution of the Lissajous orbit over its full 14-year cycle can be seen in Figures 8 and 9. Figure 8 shows the RLP YZ planar projection, essentially the view from Earth looking Sunward. Figure 9 shows the same orbit projected on the XZ plane, essentially the view from the side looking in the direction of the Earth's motion. Figure 9 also indicates the original Class 1 orientation of the orbit when it was first established in 1997. The XY-plane projection of the Lissajous appears as it does in Figure 2 throughout the 14-year cycle.

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[*] At the beginning of the mission, this requirement specified a HGA pointing constraint of just three degrees radius, necessitating very frequent spin axis reorientations. Subsequent flight experience showed that this constraint was un-necessarily tight; hence, the constraint has been gradually relaxed, over time, to its current value of 8.0 degrees, thereby relieving the frequency and intensity of maneuver operations.

[†] Of course, innumerable families of Lissajous orbits exist which may span a very wide range of amplitudes, with many being much smaller than the ACE Lissajous. When originally conceived, however, the proposed y-amplitude for ACE was much smaller than that of the only previous L1 orbiters, the halo missions ISEE-3 and SOHO.
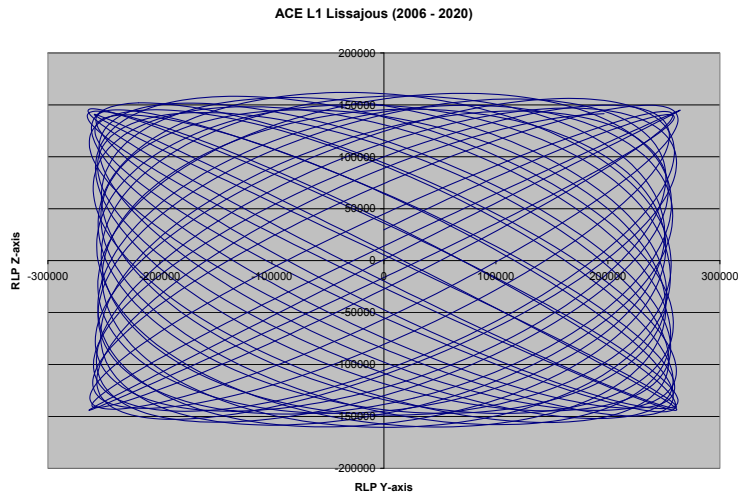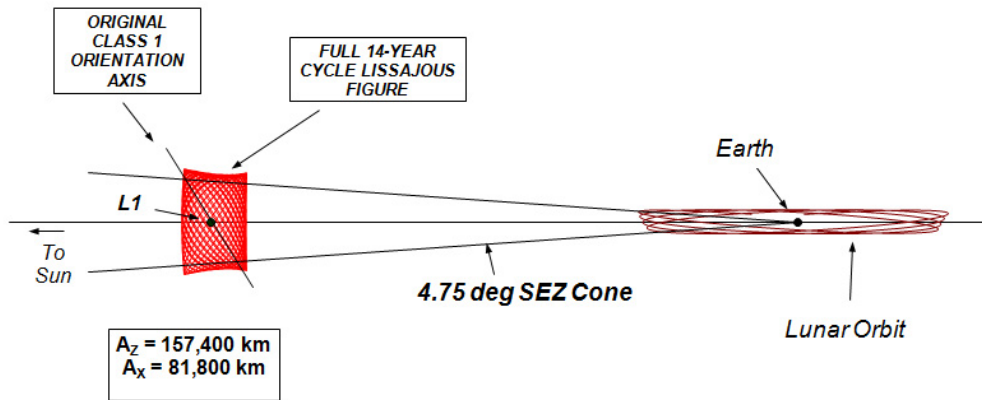
ACE L1 Lissajous (2006 - 2020)

Figure 8. The ACE 14-year Lissajous Orbit (Sunward View from Earth)

Side View of ACE L1 Lissajous Orbit

Solar Ecliptic Rotating Frame XZ Plane Projection

Figure 9. The ACE 14-year Lissajous Orbit Trace (Side View)

The basic philosophy for ACE Lissajous station-keeping was from the beginning similar to that of SOHO, in that the Project desire was to coast as long as could be tolerated, the better to minimize operational impact to science. Although there was no hard specification on the upper size limit for station-keeping burns, it was decided based on SOHO experience that 0.75 m/sec formed a reasonable guideline.   For ACE, however, there were two complicating factors that SOHO did not have to contend with.

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The first of these complications was the need to do frequent spin-axis reorientation maneuvers to keep the science instruments pointed in the general direction of the Sun and the HGA trained on the Earth. These reorientation maneuvers perturb the orbit with residual delta-Vs typically on the order of 1 cm/sec. For libration point orbits, perturbations of that magnitude can be quite significant, and they can affect the frequency of station-keeping burns. This factor is not at all times a negative for orbit maintenance, however. There are periods when a series of such perturbations in the same direction extend the coast time as well as other periods when they shorten the coast time. As these attitude maneuvers have a prediction horizon of just three weeks into the future, but are only planned one at a time (the day before planned execution), there is no way to predict these perturbations on a long timescale. Hence predicting just when the next station-keeping should occur is difficult; often, a date is not selected for a station-keeping maneuver until just a few weeks before the event.

The second complexity facing the ACE mission was the need to do Lissajous Z-axis control maneuvers beginning about two years into the mission. Lissajous control means doing maneuvers that force the Lissajous to repeat the same phase over and over again, to keep it from closing down to the point where it crosses some defined Solar Exclusion Zone, which for ACE was originally 5.0 degrees around the Sun direction, but later changed to 4.75. The maneuvers necessary for this are often referred to in the literature as "Z-axis control" maneuvers. This name arises from the fact that the thrust is directed perpendicular to the ecliptic plane, toward either the NEP or the South Ecliptic Pole (SEP) depending on the goal and location in the Lissajous. There are two locations in the Lissajous where these maneuvers can be performed: where the z-component of velocity (RLP frame) passes through zero, which occurs at the northern and southern RLP Z-axis extremum points. Z-axis control is basically independent of station-keeping; station-keeping is necessary whether or not Z-axis control is performed. But the station-keeping schedule and the magnitudes of station-keeping maneuvers may be affected by Z-control, because the Z-control maneuvers may change the energy of the orbit. Theory shows that the magnitude of the Z-axis control maneuvers is proportional to the out-of-plane amplitude (Az) of the Lissajous; the larger the amplitude, the greater the delta-V cost.[7] During pre-launch mission design it was shown that Lissajous control for ACE's 6-degree orbit would cost about 24 m/sec per year (which means about 7.3 kg of fuel per year for ACE). There are two options for Z-axis control: 1) a maneuver can be performed every time a Z-extremum is reached (occurring every three months), or 2) a maneuver can be executed at just one of the Z-extremum locations, occurring every six months. The advantage of the first option is that the maneuvers are half the size of the second option, although the disadvantage is that burns are performed twice as often. For ACE, the once-every-sixth month option was selected, to minimize the number of operational impacts to the science.[7]

The original plan was to maintain Z-axis phase control through the remainder of the mission. Figure 10 shows the Lissajous controlled out to 2009, when all fuel would have been depleted. That plan would have required 20 Z-axis control maneuvers, performed once every six months. However, only five such maneuvers were performed, during the period from late 1999 to mid-2001. After the fifth burn, the Z-axis control campaign was abandoned following a decision by the ACE Science Working Team to stop, so as to save fuel for an extended mission. Table 2 summarizes the Z-axis maneuvers that were performed.
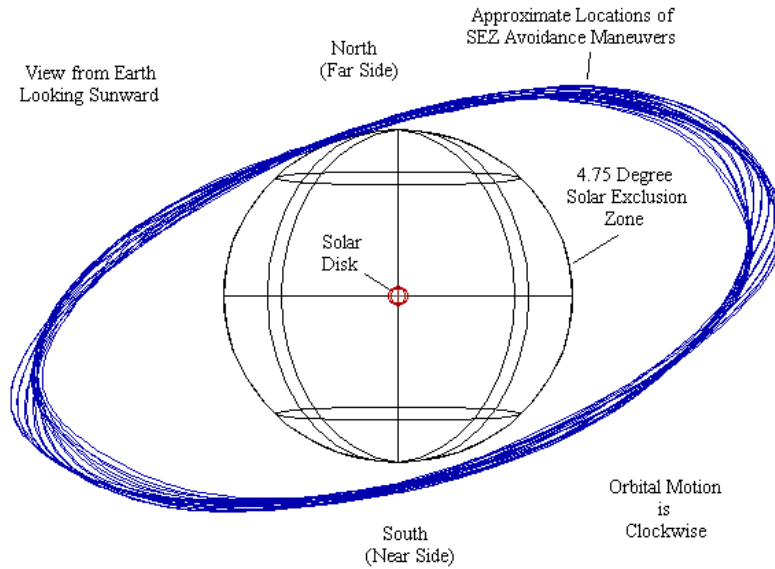
**Figure 10. ACE Z-axis Control Demonstrated for Period 2000 to 2009
(Sunward View YZ-plane Projection)**

Table 2. ACE Lissajous Z-axis Control Maneuvers.

Burn Number	Date (m/d/y)	Delta-V (m/sec)
1	11/18/1999	3.7
2	2/18/2000	7.25
3	8/12/2000	8.75
4	2/3/2001	11.75
5	7/30/2001	9.93

Note: All delta-Vs directed toward SEP using radial thrusters

   Since cessation of Z-axis control and removal of the SEZ constraint in mid-2001, the ACE Lissajous has been allowed to evolve naturally.   Figure 11 shows the oscillatory behavior of the Sun-Earth-Vehicle (SEV) angle when the orbit is left in its natural state.

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ACE Lissajous Orbit Sun-Earth-Vehicle (SEV) Angle Plot
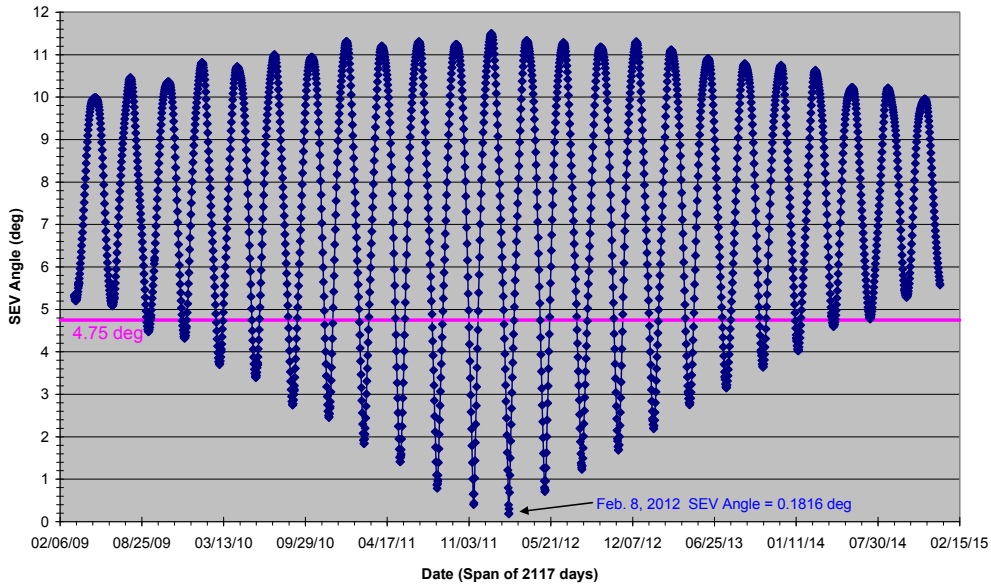**(March 2009 - Dec 2014)**

Figure 11. The ACE Sun-Earth-Vehicle (SEV) Angle Plot (March 2009 to December 2014).

If Z-axis control had been maintained, the SEV angle would never have dropped below the 4.75 degree line (the radius of the old SEZ). As it is currently, the trajectory will cross the old SEZ no fewer than 20 times between mid-2009 and early 2014. In fact, as seen from Earth, ACE will actually cross the solar disk on February 8th, 2012. (This will not be the first time; a prior traversal of the solar disk occurred in June 2004 without any loss of data.) A snapshot of the Lissajous during the period from February 2010 to January 2013 is shown in Figure 12. This period includes the transition from a collapsing pattern with counter-clockwise motion to an opening pattern with clock-wise motion that occurs in February 2012.
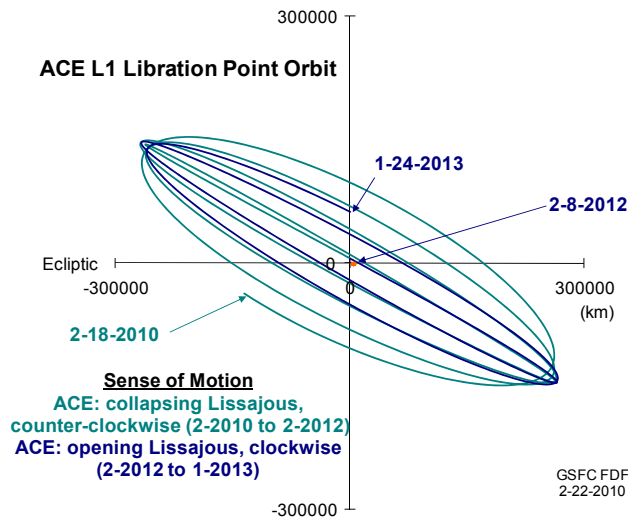

Figure 12. The ACE Lissajous Transition from Collapsing to Opening

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There have been 58 ACE station-keeping maneuvers from 15 January 1998 to 30 June 2011, as shown in Figure 13. The first three burns were much larger than expected due to problematic orbit determination results that were due to a DSN range ambiguity problem. This problem was resolved[3], and station-keeping magnitudes returned to a more reasonable range. However, during the Z-axis control era (late 1999 through late 2001), the stationkeeping costs were elevated at times, particularly for two cases where fairly large energy corrections were needed following the Z-axis burns. Since the Z-control era ended in 2001, the situation settled down very well, with delta-Vs averaging 0.33 m/sec with average intervals between burns of 103 days. Average annual delta-V costs over the past eight years have been approximately one meter per second per year.
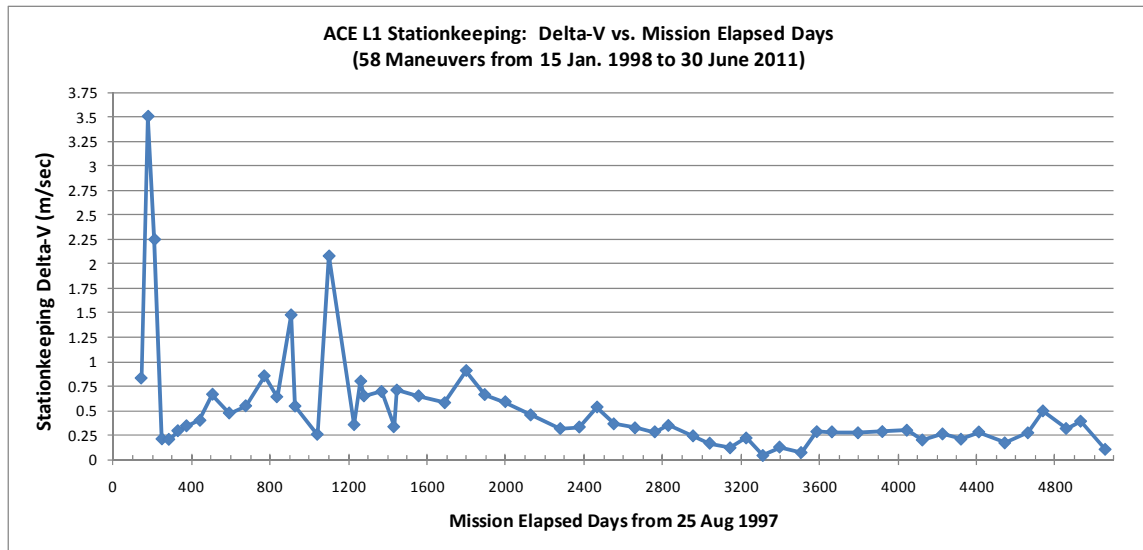

Figure 13. ACE L1 Lissajous Orbit Station-keeping Maneuvers

THE INTERNATIONAL PHYSICS LABORATORY (WIND) MISSION

The International Physics Laboratory has been known universally by its nick-name WIND even before launch (not an acronym, the name WIND simply refers to its primary mission, which is study of the solar wind). Launched on November 1, 1994, WIND was actually the first of these three missions into space. However, it was not made a dedicated libration point orbiter until its arrival at L1 in mid-2004, although it had visited the L1 region at times prior to that. Like ACE and SOHO, part of its mission is to study the upstream solar wind, although in its far-ranging travels it has also studied the interactions of the solar wind with the Earth's magnetosphere, including upstream bow-shock phenomena as well as geomagnetic tail phenomena.

Weighing 1254 kg at launch, the WIND spacecraft has a cylindrical body of diameter 2.44 m and height of 1.78 m. Assorted booms and wires extending both radially and axially belong to a number of the eight science instruments aboard (see Figure 14). It is a spinning spacecraft with a nominal spin rate of 20 rpm, and its positive spin axis (also the body $+Z_B$-axis) pointing toward the South Ecliptic Pole (SEP) within a constraint circle of one degree. The primary attitude sensors are a pair of Sun sensors and a star tracker. WIND is also equipped with a single-axis accelerometer. Attitude determination and control is performed on the ground.
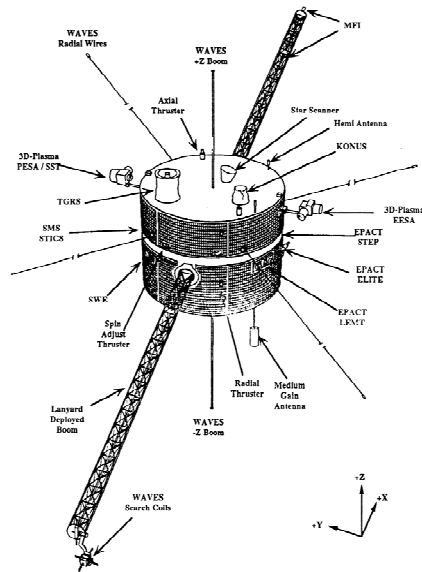
Fig. 1. WIND laboratory configuration.

Figure 14. The WIND Spacecraft

The WIND monopropellant blowdown propulsion system consists of six hydrazine fuel tanks and a total of eight 22 N thrusters for delta-V and spin axis precession maneuvers, and four 2.2 N thrusters for spin-rate change maneuvers. The six fuel tanks can be latched as two half-systems for drawing from one half-system at a time. Four of the 22 N thrusters are radials arranged in pairs on diametrically opposite faces. The remaining four 22 N thrusters are mounted as a pair of axials on both the top and bottom decks. The radials provide delta-V parallel to the Ecliptic plane, while the axials impart delta-V normal to the Ecliptic. At launch, WIND carried 368 kg of fuel, providing a delta-V capability of an estimated 604 m/sec. Current fuel reserves total 57.8 kg. WIND communicates with the ground via a medium gain antenna (MGA) mounted off-set from the spin axis on the body $-Z_B$-axis deck.

WIND was the relative latecomer to L1 orbit, but nonetheless, up to that time, enjoyed some of the most amazing travels in the history of spaceflight. For example, the mission initially employed multiple double lunar swingby sequences to keep its line of apsides aligned in an approximate solar direction so that it could sample repeatedly the solar wind at apogee distances. Later, during WIND's extended mission, WIND's line of apsides was twice re-oriented using the "lunar backflip" transfer technique .[11] In later years, WIND also flew in a series of Distant Prograde Orbits that carried it as far as 323 Earth radii (Re) ahead of the Earth and then behind the Earth (i.e., along Earth's orbital track (cf. Figure 15).[*] Throughout its mission, WIND has completed 38 successful targeted lunar flybys. Time and again these lunar flybys were used to make large changes to orbital energy and radically re-shape the trajectory and/or to make dramatic transitions to new orbital regimes. The remarkable story of this complex and highly dynamic flight is beyond the scope and size of this paper. The reader is referred to several interesting papers by Franz, who was the trajectory designer for the 7-year extended mission culminating in the final arrival at L1 in mid-2004 (References 10 through 13). Figure 15 illustrates the final 2.5 year flight prior to L1 insertion in 2004.

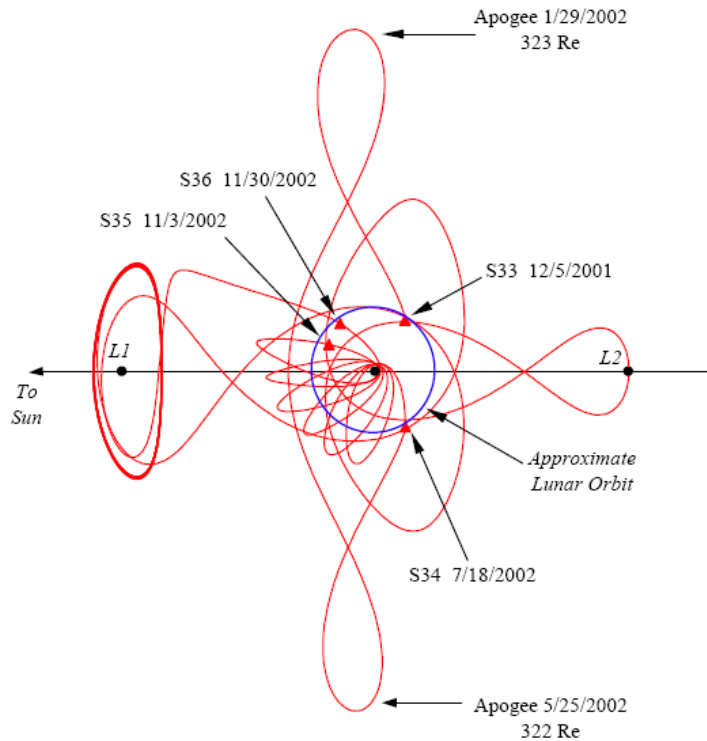[*] For scale, lunar orbit distance is approximately 60 Re.

Figure 15. The WIND Final DPO, L1 => L2 => L1 Transfer, and Final L1 Lissajous (Franz[13])

The final DPO flown by WIND began with lunar flyby S33 on 5 December 2001. Following 323 Re apogees both ahead of and behind Earth, the exit from the DPO came with lunar flyby S34 on 18 July 2002. That flyby commenced a series of six large phasing loops. Lunar flyby S35, occurring on the final phasing loop on 3 November 2002, adjusted the timing for achieving the final flyby S36 on 30 November 2002. S36 sent WIND on a single loop around L1, with a return to a very large loop around the Earth-Moon system on the way to L2. Following a single loop around L2, WIND returned Earthward for yet another large loop around the Earth-Moon system on its way to L1 for the final time. The trajectory led to a free insertion, i.e. no deterministic delta-V, into a large-amplitude Lissajous orbit with dimensions similar to those of SOHO's halo orbit. This entire phase of WIND's extended mission required only five deterministic maneuvers—but none for the L1 to L2 and back to L1 transfer—totaling just 44.3 m/sec. Of that total, a single out-of-plane maneuver after S36 of 22.5 m/sec established the desired Z-amplitude for the first L1 loop. This was necessary to achieve the desired out-of-plane dimension desired for the final Lissajous. The dimensions of the achieved Lissajous were approximately 6 degrees out-of-plane and 23 degrees in-plane. This Lissajous evolves very slowly, and will not complete its collapse downward to the 3-degree Solar Exclusion Zone required for WIND until June 2018.

No Z-axis control is needed for the WIND Lissajous orbit, which means that only station-keeping maneuvers—30 to date—have been performed for WIND since mid-2004 (see Figure 16). To accommodate DSN scheduling requirements, WIND station-keeping maneuver frequency has been kept close to a 90-day cadence, much as SOHO is. Also similar to SOHO, WIND station-keeping delta-Vs are directed either parallel or anti-parallel to the WIND-to-Sun line.
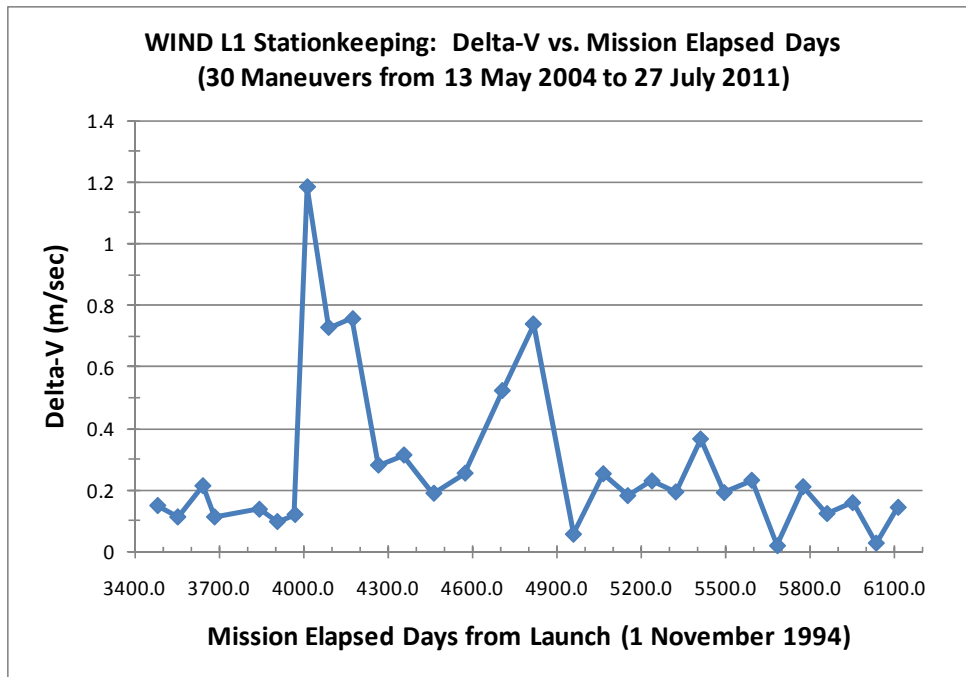
Figure 16. WIND L1 Lissajous Orbit Station-keeping Maneuvers

Even with a handful of outliers, the station-keeping maneuvers have averaged a modest 0.28 m/sec, with an average interval between burns of 91 days, since 2004. The performance since mid-2008 has been especially good, with an average delta-V of just 0.17 m/sec. The main station-keeping challenge for WIND is propulsion system performance variation. That variation has two main components: delta-V granularity residue due to fixed pulse durations for the radial thrusters, and thruster repeatability that is not as consistent as that exhibited by ACE and SOHO. There have been no WIND contingencies thus far, and spin axis attitude reorientation maneuvers or spin corrections are seldom needed, and typically many years apart.

CONCLUDING REMARKS

The NASA GSFC missions SOHO, ACE, and WIND have been successfully maintained in their respective orbits at the Sun-Earth L1 libration point for 15 years, 13.5 years and 7 years respectively. All three currently average four station-keeping maneuvers per year, and the average annual expenditure of delta-V has trended downward to levels around 1.0 m/sec per year (considerably less, even, for SOHO). All three have enough fuel, barring anomalies, to continue station-keeping for decades to come. At this time, however, all three have authorization to continue operations only until 2014. The prospects for their continued operation beyond 2014 are not clear, although all three are in reasonably good health at present.   Sentiment within the respective Projects seems to favor continued operation for as long as spacecraft working order endures. In fact, many on the science teams would much prefer to have their mission cover two full Solar activity cycles, which for a mission like ACE would mean continuation beyond 2020. At any rate, no formal end-of-mission plan is presently finalized for any of the three. Nevertheless, when the time comes, these spacecraft will need to be disposed of in some reasonable fashion.

The easiest and most obvious disposal option is to simply push them off into orbit around the Sun. This disposal option has been explored in a preliminary way by the author, but no formal study has yet been completed for any of the three missions. How to do it is not so much the issue as is the character of the final heliocentric orbit achieved. Objects leaving the Earth-Moon sys-

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tem with just the barest escape energy end up in very Earth-like orbits that eventually make the object return to the Earth-Moon vicinity on some periodic basis. (Sometimes this is deliberate. The International Cometary Explorer (formerly ISEE-3), in a 30.6-year Earth return orbit, is by design returning to the Earth-Moon vicinity in August 2014.)[14] It may be prudent to find a disposal orbit that minimizes the frequency of Earth returns or, if possible, to find a way to prevent a return altogether. These considerations are expected to be addressed in future work.

Other possibilities for disposal or extended missions exist as well. Perhaps foremost are options for bringing a spacecraft back to the Moon for either crash landing, going into orbit around it (this includes Earth-Moon libration point orbits), or using a lunar flyby for a more energetic escape. Bringing any of them back to Earth is a highly unlikely option. Of the three, only WIND is truly suited—by design, history, and health of its systems—for anything like complex deep-space flight. SOHO, while fine doing small burns in a halo orbit, is too crippled from past anomalies for anything more strenuous. And ACE, while healthy, has performance limitations and constraints that significantly reduce its attractiveness for more exotic post-L1 options. Detailed examination of the more exotic end-of-life options will likely depend on future interest and direction from the Projects.

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