Extension of the SOHO Mission

EXECUTIVE SUMMARY

SOHO, together with *Cluster*, forms the Solar Terrestrial Science Programme (STSP), the first cornerstone in ESA's Horizons 2000 programme. Since its launch on 2 December 1995, *SOHO* has provided an unparalleled breadth and depth of information about the Sun, from its interior, through the hot and dynamic atmosphere, to the solar wind and its interaction with the interstellar medium. Research using *SOHO* observations has revolutionized our understanding of the Sun, and science teams from around the world have made great strides towards a better understanding of "the big three" areas of research that *SOHO* set out to tackle: the structure and dynamics of the solar interior, the heating of the solar corona, and the acceleration of the solar wind – but much remains to be done. The findings have been documented in an impressive body of scientific literature and popular articles whose number continues to grow. At the same time, *SOHO*'s easily accessible, spectacular data and basic science results have captured the imagination of the space science community and the general public alike.

Here we propose a mission extension of four years, covering the period from April 2003 through March 2007, allowing *SOHO* to observe an entire 11-year solar cycle.

SOHO, together with *Cluster*, provides an unprecedented opportunity to understand the changing behaviour of the Sun over an entire solar cycle, as well as its influence on the Earth, one of the four major scientific quests of ESA's long-term space science strategy. A mission extension will give us new and deeper insights into subjects as diverse as variations in the solar tachocline and zonal flows, the physics of coronal mass ejections, the acceleration of the solar wind in a variety of coronal conditions, the evolution of the solar and heliospheric magnetic field, and comets. The spacecraft and payload are in good health and there are no technical limitations which should prevent *SOHO* from observing for an entire solar cycle.

SOHO was the highest rated project among extended missions in the 2001 NASA Senior Review of the Sun-Earth Connection Mission Operations and Data Analysis Programs, and funding was approved for the four-year review period FY 2002 through FY 2005. NASA also indicated the intention to continue supporting *SOHO* through the initial operations of the Solar Dynamics Observatory, currently scheduled for launch in 2007. *SOHO* is operated from the SOHO Experiment Operations Facility at NASA Goddard Space Flight Center, and NASA covers the major part of the operating costs. The additional cost to ESA at this stage in the mission represents excellent value-for-money in return for a significant enhancement of the scientific harvest from the *SOHO* spacecraft.

1. SOHO and ESA's Strategic Goals

The first major theme of the scientific quest put forward in ESA's Science Programme Space Strategy[1] is "the influence of our Sun on the Earth and the behavior of our star". This is precisely what *SOHO* has been addressing for the last six years, and what we here propose to continue for another four. NASA's Senior Review Board called *SOHO* "the flagship mission for solar investigations". It has invigorated all areas of solar research and an extended mission will continue to stimulate and give impetus to the community for many years to come. The following sections discuss the scientific merits of the extension proposal in more depth.

Another important, yet recent element in ESA's space science strategy is communication, education and public outreach, "to exploit the excitement of space science as a unifying theme to make scientific education more attractive to the youth and science in general attractive to the less young"[2]. Here, too, we believe that *SOHO* has made - and will continue to make - outstanding contributions. We have shared the excitement of space science discoveries with the public through immensely popular, continuously updated web pages, numerous press releases, interactive CDs, travelling museum exhibits, a large number of public talks, and the ubiquitous adoption of time-lapse movies of *SOHO* images by TV and internet media. Movies from *SOHO,* used in the awesome vision of the SOLARMAX film, showcase images of astounding aesthetic value and visualise the origins and effects of space weather in a way no other medium could, reaching large audiences worldwide. These activities will be continued as an integral part of an extended mission.

2. Some Scientific Highlights from 6 Years of SOHO

SOHO enjoys a remarkable "market share" in the worldwide solar physics community: over 1100 papers in refereed journals and over 1500 papers in conference proceedings and other publications, representing the work of over 1500 scientists. A searchable *SOHO* publications database[3] is available under the *SOHO* home page. It is not too much of an exaggeration to say that virtually every living solar physicist has had access to *SOHO* data.

We can assert this with confidence because all of the *SOHO* experiments make all their data available, online, on the Web, through the *SOHO* archives and PI sites. The *SOHO* master archive has been developed at GSFC by the ESA *SOHO* Project Scientist team with significant contributions from European partners. Three copies of this archive have been established in Europe (IAS, France; RAL, UK; Univ. Torino, Italy).

In addition to professional access, amateurs routinely download LASCO images to search for new comets. As a result, over 360 of the 1300 comets for which orbital elements have

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[1] ESA/SPC(2000)32, rev.2, Section 2
[2] ESA/SPC(2000)32, rev.2, Section 4.6
[3] http://soho.estec.esa.nl/publications/

been determined since 1761 were discovered by *SOHO*, and *more than 60% of those by amateurs accessing LASCO data via the Web*. Similarly, over 400,000 people across the world routinely download LASCO, EIT, and MDI images several times daily as their *SOHO* screensavers update themselves.

It is not possible in this report to cover all the findings that have come out of the *SOHO* mission during the 6 years since launch. The following is a brief summary of some of the achievements:

Solar Interior

- Global helioseismology using data from *SOHO* have given a number of new and improved results, like:

- GOLF, VIRGO and MDI giving the most precise measurements to date of the sound speed profile and the (differential) rotation profile within the Sun.
- MDI data revealing “zonal bands” in the northern and southern hemispheres where currents flow at different speeds (~ 5 m/s) relative to each other. The zonal bands were found to migrate towards the equator with time, and they were shown to penetrate to a depth of at least 56 Mm.
- Data from MDI and the GONG network of ground based observatories showing quasiperiodic changes in the rotational contrast near the “tachocline” – the interface between differentially and uniformly rotating layers of the Sun. This is at the base of the convection zone, and the presumed location of the solar dynamo. The observed periods (15-16 months in equatorial regions) are in stark contrast to the 11-year period of the sunspot cycle, thought to be driven by dynamo processes in the same region.

- A new technique called “time-distance helioseismology” or “solar tomography”, applied almost exclusively to the high-quality, high-resolution MDI data, has proved to be one of the most exciting and promising techniques for probing 3D structures and flows below the solar surface. With this technique, MDI data has:

- Provided the first ever image of the convection zone of a star, showing the first maps of vertical and horizontal flows as well as sound speed variations just below the visible surface.
- Shown that the entire outer layer of the Sun, to a depth of at least 25,000 km, is slowly but steadily flowing from the equator to the poles. The polar flow rate is fast enough to transport an object from the equator to the pole in a bit more than a year.
- Offered the possibility of studying the birth and evolution of active regions below the Sun's surface, revealing the complicated structure of emerging regions in the solar interior that travelled very rapidly through the upper 18 Mm of the convection zone.
- Revealed sunspot "fingers" - long, narrow structures at a depth of about 4 Mm connecting the sunspot with surrounding pores of the same polarity. Pores with the opposite polarity on the other hand are not connected to the spot.

- Detected strong inward flows towards sunspots, solving the long-standing riddle of why sunspots last so long. Such inward flows are required in theoretical models of sunspots to stabilize the structure, even though surface material is often observed flowing out of the spots.
- Revealed that sunspots are very shallow, changing from cooler to hotter than the surroundings only 5000 km below the surface – i.e. the cool part of a sunspot is more similar to a stack of two Euro coins than a tree trunk.

- High precision MDI measurements of the Sun's shape and brightness obtained during two special 360 degree roll manoeuvres of the *SOHO* spacecraft, producing the most precise determinations of solar oblateness ever. There is *no excess oblateness*, unambiguously ruling out the possibility of a rapidly rotating core.

- Using "helioseismic holography", a technique that has been known in theory for over a decade, researchers using high quality MDI observations of the near side of the Sun were for the first time able to *image an active region on the far side*. In this process, the Sun acts like an acoustic lens, revealing the active region on the far side through a slight decrease (about 12 seconds) in the total roundtrip sound travel time of about 6 hours. Since spring 2001, this technique is being applied routinely to MDI data, and space weather forecasters now have almost real-time access to far side images of the Sun.

Solar Atmosphere

- EIT, SUMER and CDS observations clearly demonstrate that the solar transition region and corona is extremely dynamic and time-variable in nature. In sum, *SOHO* instruments have highlighted the many shortcomings of current static models of the solar atmosphere, as they are simply not able to reproduce the observed flows and variability.

- Coordinated measurements by SUMER and CDS have provided new observational data concerning the temperature structure in coronal holes, commonly believed to be the origin of the high-speed wind streams. The temperature measured starts at about 1 MK at the base, a higher value than anticipated and of the same order as for closed field regions. However, the temperature drops much more rapidly with height than had been expected, to only 0.3 MK at 1.3 solar radii. This clearly rules out a thermally driven fast solar wind.

- The two spectrometers SUMER and CDS observe extensive evidence of explosive events in transition-region lines. These could be the signature of magnetic reconnection events associated with localized small magnetic dipoles that appear in magnetogrammes obtained by MDI near the base of many of the explosive events studied.

- A new class of solar variability dubbed "blinkers" has been identified by CDS in quiet Sun regions. They appear as EUV intensity enhancements of about 10-40% with a typical duration of about 15 minutes.

- The UVCS coronagraph has revealed dramatic differences in the line widths of the strong hydrogen Lyman-alpha line, and even more so in the resonance lines of O VI, in coronal streamers at heliocentric heights from 1.25 out to 3.5 solar radii. While the protons are only mildly anisotropic above 2-3 solar radii and never exceed 3 MK, the O VI ions are strongly anisotropic at these heights, with perpendicular kinetic temperatures approaching 200 MK. An ion-cyclotron resonance with Alfven waves affords one possible explanation for generating the higher observed velocities in the O VI ions.

- A far-ultraviolet and extreme-ultraviolet (FUV, EUV) spectral atlas of the Sun between 670 Å and 1609 Å, derived from observations obtained with the SUMER spectrograph, identifies over 1100 distinct emission lines, of which more than 150 had not been recorded or identified before. The atlas contains spectra of the average quiet Sun, a coronal hole and a sunspot on the disk, providing a rich source of new diagnostic tools to study the physical parameters in the chromosphere, the transition region and the corona. In particular, the wavelength range below 1100 Å as observed by SUMER represents a vast improvement over the spectra produced in the past.

- LASCO has discovered infalling matter at coronal heights. These inflows show a strong correlation with nonpolar coronal holes and the Sun's nonaxisymmetric open flux, but only a broad long-term correlation with conventional indicators of solar activity.

- The VIRGO instrument measures both total solar irradiance (TSI) and spectral irradiance, the latter in three bands (centered at 4020, 5000 and 8620 Å). VIRGO extends the record of TSI measurements into cycle 23.

- EUV irradiance measurements are being made on a regular basis by the CELIAS/SEM and CDS instruments. Due to its influence on the terrestrial atmosphere, the solar variability may constitute significant sources of climate changes. Tracking the long term variations of the solar spectral irradiance is therefore of critical importance.

Solar Wind

- SUMER observations of coronal hole outflow velocities show a clear relationship between coronal hole outflow velocity and the chromospheric network structure, with the largest outflow velocities occurring along network boundaries and at the intersection of network boundaries. This can be considered the first direct spectroscopic determination of the source regions of the fast solar wind in coronal holes.

- UVCS has discovered that the high-speed solar wind in coronal holes achieves its high velocity - up to 800 km/s - by “surfing” magnetic waves in the Sun's outer atmosphere.

- UVCS observations show that solar-maximum equatorial coronal holes exhibit 3-5 times lower outflow speeds than solar-minimum polar coronal holes. Since wind speeds observed at 1AU are similar in the two cases, the bulk of the acceleration must occur outside the region observed by UVCS, i.e. above 3 solar radii.

- CELIAS has doubled the number of elements and isotopes previously recorded in the solar wind.

- During a Venus disk passage, CELIAS observed, for the first time from such a large distance, pick-up ions from Venus' ionosphere, finding a much smaller diffusion cone than anticipated.

Comets

- SWAN has measured the total amount of water ice present in comet C/1999 S4 (LINEAR) on 25 May 2000 and subsequent times, until all of its water ice had been vaporised as the comet fragmented. The amount of water vapour released throughout the observing period was estimated at 3.3 million tonnes. Combined with an HST estimate of the total volume of the fragments on 5 August, a remarkably low value for the density - about 15 kg per cubic meter - was found.

- UVCS made the first high resolution UV spectroscopic measurements of several comets. Measurements of comet C/1996Y1 obtained at 6.8 $R_{\odot}$ confirmed predictions of models of the cometary bow shock driven by mass-loading, as cometary molecules are ionized and swept up in the solar wind. From line widths and Doppler shifts, the solar wind speed at 6.8 $R_{\odot}$ could be determined (640 km/s). The outgassing rate of the comet was estimated at 20 kg/s, implying a net active area of the nucleus of only about 6.7 m in diameter and a mass of about 120,000 kg.

Other discoveries and milestones include:

- Discovery of a magnetic surface “carpet”, subducted and replaced on timescales of 1.5-3 days, that may be the source for the energy required to heat the corona.

- The first detection of a flare-induced “sun-quake”.

- First measurement of the acceleration profile of the slow solar wind from 3 to 30 solar radii.

- First measurement of the acceleration profile of the fast solar wind from 1.5 through 3.5 solar radii.

- Detection of 11-25 minute polar plume oscillations indicative of compressive waves.

- The discovery of "EIT waves" and their relation to CMEs, dramatically improving space weather forecasting reliability.

- Invaluable statistics on, and spectacular images and movies of, coronal mass ejections and other energetic events, elevating space weather studies to a new level.

- First direct observations of a post-CME current sheet.

- Measurement of ion freeze-in temperatures and its variation with element and over time.

- First detection of active regions on the backside of the Sun through their "lighthouse" effect.

- Discovery of a comet's shadow.

We would like to point out that almost all the discoveries made by *SOHO* is due not only to the comprehensive complement of instruments, but also due to the unique vantage point of the spacecraft, providing a highly stable platform with an uninterrupted and undisturbed view of the Sun. Another key element in SOHO science is the large number of collaborations with numerous ground-based observatories as well as other spacecraft, such as *Ulysses, TRACE*, *NEAR*, *Galileo*, and *Yohkoh.*

3. Scientific Rationale for the Proposed Mission Extension

A mission extension of four years from April 2003 through March 2007 is proposed in order to cover an entire 11-year solar cycle, fulfilling the scientific promise of *SOHO* to answer fundamental questions about the Sun and heliosphere. Launched on 2 December 1995, *SOHO*'s nominal science operations phase started on 2 May 1996, close to the last solar minimum. The next solar minimum is expected to occur around 2007.

The following sections list some of the open questions in solar and heliospheric physics, forming the scientific rationale of the mission extension. Many of them will be answered with the help of future *SOHO* observations.

Solar Interior

We have evidence of large scale, organized subsurface flows toward active regions in MDI data taken during special "continuous contact" runs of 2 – 3 months each year from 1997 – 2001. Each of those samples represents only two solar rotations, so we do not yet know how these flows evolve and relate to the growth/decay phases of activity. Do such flows drive the emergence and decay processes for solar active regions? It is important to obtain additional samples in the declining phase of the solar cycle — without a SOHO extension the next opportunity will not come until after 2012.

That sound wave speed is enhanced beneath magnetic fields is now well established for sunspots, plage, and even pores. Similarly, it has been shown that there is an ordered flow beneath large sunspots. In the future we hope to be able to use such diagnostics to derive space weather predictive information.

How does the rotational shear at the tachocline vary? This shear layer at the base of the convection zone shows variations near the equator with a period of about 1.3 years. This variation, as well as its implications, is not yet understood. It has withstood a number of tests of reality and the result remains intact. We anticipate the opportunity of seeing what happens in the declining phase of the solar cycle.

How does the poleward flow vary with depth, latitude, and phase of the solar cycle? The existence of a poleward flow of 10-20 m/s at the surface has been known for two cycles but only with MDI observations has it been well characterized and observed to extend into at least the first 10% of the convection zone. There is at best a suggestion in the noisy, groundbased data that the poleward flow extends only to lower latitudes in the years nearer to maximum. This possible variation with the cycle is a topic of current investigation with *SOHO*.

The extended solar cycle

There are several solar parameters that vary with a cycle time longer than 11 years. There are at least three aspects to the extended cycle that can be examined with continued MDI observations into the declining and minimum phases of the cycle.

- There is evidence that the toroidal component of the field can be detected in MDI magnetograms. We can watch the emergence of high latitude new cycle fields, measure their toroidal component, and detect the interactions of the next cycle's fields with those of the current cycle.

- MDI magnetograms, obtained every 96 minutes, can be used to study the emergence of ephemeral regions at high latitude. We can thus study, in greater detail than possible from the ground, the evolution of the new cycle emerging regions in order to compare them to ephemeral regions of the present cycle: are there significant differences? This study will also lead to better understanding of the connections between the current and the next cycle.

- We can continue to study the zonal flows in the convection zone. Historical data predicts that we will shortly be able to detect the shear zone which will later be associated with the centerline of next-cycle activity. By watching this process unfold within the convection zone we should gain insight into the operation of the cycle dynamo, or at least further constrain models.

Acceleration of the solar wind

Polar coronal holes are enlarged by episodic surges of alternating-polarity magnetic flux bundles moving poleward from mid-latitudes. A solar-cycle-long *SOHO* mission would give us the opportunity to understand the full life cycle of polar coronal holes, the source of much of the solar wind flow for a significant part of the solar cycle.

UVCS measurements of density and ion kinetic temperature perpendicular to the magnetic field show an apparent anticorrelation. Is this because higher density regions are collision-dominated, or is there a density dependence of ion cyclotron wave generation and dissipation? Spectroscopic observations at the solar cycle phase when polar holes and the dipole streamer belt are growing rapidly will provide new insights.

The declining phase of a solar cycle is also the period most likely to feature low-latitude coronal holes. In the high-speed streams from those holes, we can use *in situ* instruments on *SOHO* and ACE to characterize coronal electron temperatures, non-Maxwellian distribution, and ion differential speeds, and *SOHO* spectrographs (SUMER, CDS, and UVCS) to measure plasma properties for some of the ions available to the *in situ* instruments. Models consistent with both *in situ* and remote sensing measurements should constrain, for example, flow speeds for different ions of the same species in the corona. That, in turn, should allow us to determine how heating and acceleration processes depend on ion charge, without having to consider ion mass dependencies.

The heliospheric magnetic field and its origin, the solar magnetic field, will be "relaxing" over the next few years to their simpler, solar minimum configurations. Do coronal streamer properties change smoothly or abruptly during this period? Do the same physical processes heat streamers and accelerate the slow solar wind? If not, can we distinguish which processes are responsible for each?

Coronal Mass Ejections and Space Weather

Data from the last six solar cycles show that the distribution of events disturbing the geomagnetic field is broader, and peaks later, than traditional measures of solar activity (*e.g.* sunspot "number"). The time lag from "solar maximum" is typically 2 – 3 years. Why is this so? Is it because new-cycle magnetic flux, migrating from high solar latitudes, leads to solar events with different properties than earlier in the cycle? Is it because CMEs have a less complex solar magnetic field from which to escape, because the number of active regions is low? Or is it because, as a result of these solar changes, the interplanetary field is more amenable to the propagation of fast shocks? Or is the well-known persistence of large flares and fast CME's throughout the decline from solar maximum a reflection of interactions with the low-latitude coronal holes?

The largest CMEs are in general the most geoeffective (when earthward-directed), as well as the fastest. Does size, as determined by LASCO and EIT, correlate with thermal content, as UVCS should be able to determine? What is the temperature structure of CMEs? Will the latitude of origin of CMEs evolve gradually back to the dipole streamer belt, or will it shift abruptly from its current, broad distribution in latitude?

CMEs are only geoeffective when they contain or drive several hours of southward B_z when they arrive at Earth. It has been shown that field extrapolations based on the photospheric magnetic field underlying the areas where CMEs erupt yield good estimates of the B_z. Recent developments the in processing of MDI magnetograms has led to the concept of a "synoptic frame" in which synoptic, whole-Sun Carrington grids of magnetic field are supplemented by rapidly updated magnetic information for the visible disk. Initial analyses of these data are promising and may lead to better estimates of the sign and strength of the B_z component of the field carried by CMEs. Tools to use these data are presently being developed. Combined with future SOHO observations they should significantly improve space weather forecasting capabilities.

Is there a relationship between flare energetics and the post-CME current sheet? Is there a spatial relationship between the volume in which impulsive phase flare particle acceleration takes place, and that in which post-CME heating (presumably due to reconnection) occurs? One of several areas in which *SOHO* can support the upcoming NASA *HESSI* mission is to take advantage of the opportunity to characterize both the primary energy release plasma (with *HESSI*) and the plasma heated, presumably by reconnection, in what has been considered the “gradual” phase of flares but is really the early phase of CMEs.

Why keep SOHO going?

While we have made considerable progress in the understanding of the Sun, we have still not realized the full potential of *SOHO* to explore the diverse parameter space offered by the solar cycle:

We have learned many new things about the solar interior, but still do not know whether there are gravity-driven oscillation modes in the deep interior of our star. The chances of a detection is directly related to the length of the observation time series.

We do not yet understand the time evolution of zonal flows, or whether the convergence zones for active region flows drive the latitudinal distribution of the regions over the cycle.

We have seen the effects of coronal mass ejections on the lowest layers of the corona, studied the Doppler motions and heating characteristics of CME ejecta, and detected inflows in the corona, but we still do not know what causes CMEs to erupt, nor how they are accelerated, nor whether the variation in the rate is the same from cycle to cycle.

We have made great progress in understanding the origin and acceleration of solar wind plasma in polar coronal holes, and in extending that understanding to low-latitude holes, but we still need to understand the origins of the slower, low-latitude wind and how the spatial distribution of the wind varies over the solar cycle.

We are entering the phase of maximum geoeffectiveness in the solar cycle, and as we learned inadvertently during the mission interruption, there is a recognition that *SOHO*’s space weather capabilities are international resources that should continue uninterrupted. Until at least the launch of the *STEREO* mission in 2005/6, no similar capabilities are planned.

The combination of *SOHO*, *Yohkoh*, and *TRACE* is likewise unique in characterizing solar activity, and when joined by *HESSI*, the scientific community will have the once-in-a-lifetime ability to cover *all temporal scales of solar activity from milliseconds to a solar cycle*.

Coupling this grand alliance of sunward-gazing spacecraft with the fine-tuned, Earth-centered observations of *Cluster*, *SOHO* can make large and vital contributions, unrivalled in quality and scope, to a long chain of observations. We may be able to follow solar activity from its subsurface stages through the emergence of surface active regions, whether on the near or far side of the Sun, to the brilliance of flares and violent onset of CMEs, racing outward, passing *SOHO* and other spacecraft before crashing into Earth's protective cocoon of magnetic flux; in short, following solar activity from cradle to grave.

Finally, due to its influence on the terrestrial atmosphere, solar variability may constitute an important driver of climate changes. Variations in the total solar irradiance will directly influence the amount of energy absorbed by land and oceans. Furthermore, the EUV spectrum at wavelengths below 1200 Å is the dominant source of energy for heating and ionization in the terrestrial upper atmosphere at altitudes above 90 km. Changes in the amount of EUV radiation will therefore change the chemistry, dynamics and temperature of the Earth's atmosphere. Good knowledge of the solar spectral irradiance is thus of critical importance for understanding climate variability, and to disentangle natural variations from human made climate changes.

An extended *SOHO* mission, covering an entire solar cycle, will be a key element in the quest to better understand our variable star and its influence on Earth.

Annex A: Spacecraft Status and Trend Analysis

General

After six years in space, the spacecraft is healthy and performs entirely within specifications. All the equipment is running on the main branch - no recourse to the redundant units has been required. Although all three gyros were lost after the successful recovery of the spacecraft in September 1998, the gyroless software performs flawlessly.

Power Subsystem

The solar array has degraded by 13% in the six years since launch – at about half of the forecasted rate (4% per year). The present power budget allows 30% degradation before any conservation measures need to be devised.

Data Handling Subsystem

All the telecommand and telemetry functions operate nominally. The Solid State Recorder works well, with no degradation, as does the tape Recorder, which undergoes periodic maintenance as the backup telemetry storage. The Onboard Time drift is two orders of magnitude better than specifications. The High Gain Antenna Pointing Mechanism shows no indication of degradation.

AOCS Subsystem

Attitude and orbit control is performing flawlessly, with the reaction wheels taking on the tasks normally performed by gyros when not using the star tracker for roll control. The new “star swap” feature has allowed the spacecraft to remain in normal mode throughout all of the recent severe proton events. There are no signs of degradation.

Propulsion Subsystem

The propulsion subsystem is nominal. The average hydrazine consumption is on the order of 2 kg/year, with a current reserve of 122 kg.

Thermal Subsystem

All spacecraft temperatures are nominal. As predicted, temperatures on the +X panel increase slowly due to aging of the materials, and +X heaters have been trimmed down. Nothing indicates that the thermal subsystem cannot support the mission beyond 2007.

Conclusion

The spacecraft is healthy using no redundant subsystems. Fuel reserves and the solar power budget have comfortable margins given the rate of consumption and degradation. Nothing indicates that the spacecraft cannot support an extension through March 2007.

Annex B: Instrument Status

GOLF

- Operating nominally
- Progressive, expected fall-off in throughput not worrying, and will not prevent GOLF from observing an entire solar cycle
- Continuous observations in red wing of Na D line since *SOHO* recovery
  - Noise in red and blue wings similar
  - Avoid risk of operation to move to blue wing
- Reserve: redundant data channel validated but unused

VIRGO

- All instruments within VIRGO are fully operational and work fine and there is no reason to believe that the instruments would not operate for at least another 5 years.
- The degradation of sensitivity is well within specifications and much less than expected from other missions; the main reason being the high degree of cleanliness of instruments and spacecraft.

MDI

- MDI is working very well, having made about 50 million images on board, delivering about 8 million to the ground after onboard computations.
- There is an expected degradation in total light throughput due to changes in the front window transmission. The reduction in transmission to March 2001 was about 10%, or about 2.3% per year.
- The reduction in transmission causes a slow increase of the front window temperature (~ 2ºC per year), which in turn causes a slow drift of the best focus position.
- The drift in best focus position has moved the nominal focus setting back almost to the design point. Shortly after launch it was at the limit of the adjustment range.
- The drift in central wavelength of the Michelson interferometer has nearly stopped.
- There is no detected change in the CCD flat field except for variations with focus change.
- There is a reduction in shutter exposure time uniformity from one part in 12000 to one part in 4000. This corresponds to jitter of 40 μsec for a 165 ms exposure. The pre-launch specification was 50 μs. So, while still within the pre-launch requirement we will watch for changes. There might be a low-impact change to the observing sequence that could reduce shutter usage by about 30%. This will be evaluated if there are further changes. The change occurred in March 2000.
- In summary, with the possible exception of the recently detected shutter jitter, there is no known limit to MDI's useful life within the *SOHO* solar array life expectancy.

SUMER

- The detectors are near their calibrated lifetime. In order to preserve detector lifetime and reduce the total counts collected by the detectors as much as possible, SUMER has been and will be operated in a "campaign mode", where the instrument is switched on only during certain selected periods.
- The east-west drive of the telescope mirror - working in high-current mode - caused no difficulties in any of the pointing operations, but cannot be used for raster scans anymore.

CDS

- CDS is nominal and expected to operate at full scientific capability for many more years.
- The detector systems show no signs of degradation above what is expected. The CDS NIS detectors see progressive burn-in. This is a degradation of sensitivity at the locations of the bright emission lines. This is expected and is approaching an asymptotic level for the brighter lines. It gives no cause for concern. The burn-in is carefully monitored and is readily corrected.
- The NIS calibration is well understood for data taken prior to the loss of *SOHO* in 1998. A post-recovery change in sensitivity and its long-term variation is currently being quantified by comparing with the SEM, SERTS and quiet Sun data.
- All voltage levels and currents remain stable and well within tolerances.
- All critical instrument temperatures remain stable. Some temperature monitors close to thermal blankets show increases due to expected deterioration of the blankets; this causes no major concerns.
- All Mechanisms continue to operate satisfactorily.
- The Ground system is fully functional and was recently upgraded.

EIT

- EIT is nominal and expected to operate at full scientific capability for many more years.
- Instrument throughput is decreasing
  - Two components: absorption of EUV by a CCD surface contaminant (no longer a problem since unintentional bakeout during the *SOHO* "vacation"), reduction in charge collection efficiency (CCE) in the CCD due to EUV-induced damage (continues)
  - CCE loss can be tracked accurately with calibration lamp images
  - Degradation now well understood and modelled
  - Present exposure times range from 12 s (195 Å) to 2 min (284 Å): lots of latitude left
  - S/N still very high

UVCS

- UVCS is expected to continue performing at full scientific capability for many more years.
- O VI Detector:
  - No significant decrease in efficiency in O VI portion of this detector.
  - Ly-α portion showed 5 to 10% loss of efficiency on *parts* of detector at a high voltage of 200 EU.
  - Voltage increase from 200 to 205 EU in January 2000 restored full efficiency
  - Max of 250 EU allows nine additional increases of 5 EU.
  - Voltage increase of 5 EU every 1.2 years is expected to keep the efficiency loss at < 5%.
- Ly-α Detector:
  - Has been turned off since November 1998 because it draws about 50% of the maximum current and has regions of elevated background.
  - This behavior is not related to the mission interruption.
  - Still operational and treated as a back-up for Ly-α observations.

LASCO

- The LASCO/C2 and C3 coronagraphs continue to operate with no degradation.
- Photometric sensitivity is unchanged since launch.
- The Fabry Pérot interferometer in the LASCO/C1 coronagraph did not survive the extreme cold the instrument experienced (-80ºC) during the mission interruption.

CELIAS

- MTOF/PM, STOF/HSTOF, SEM nominal
- CTOF impaired since 1996 October (HV power supply hardware failure)

COSTEP

- EPHIN nominal
- LION: front detectors noisy since launch
  - Partially operational for higher flux at high solar activity
  - Separation of electrons and protons possible during solar SEP events

ERNE

- Operating nominally.

- Persistent ESU data request error cause still under investigation, but software patched to reduce data loss to < 4 minutes per anomaly
- Increasing temperatures due to thermal insulation degradation a cause for concern, but recent X-panel heater changes have improved the situation.

SWAN

- Two detectors (+Z, -Z) cover whole sky
- Periscope motors nominal
- +Z sensor degraded by mission interruption in 1998, but –Z sensor unaffected
- UV contamination of +Z sensor has decreased by more than a factor of two since 1998
- H absorption cells (one per sensor head) decreasing in absorptivity (+Z: 15% decrement, -Z: 75%); calibration continues.

In summary, there are no known limitations which should prevent *SOHO* from completing an entire solar cycle with almost all of its complement of instruments operating at full scientific capability.