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Summary of Cleanliness Discussion: Where was the SOHO Cleanliness Programme Really Effective?

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The working group on cleanliness has been formed to recapitulate for each instrument the measures taken during the SOHO cleanliness programme and their effects. U. Schühle, together with B. Kent and R. Thomas, has collected the individual instruments' input to a catalogue of questions reviewing their efforts and experience. Thus, an open and straightforward discussion of the cleanliness issues for the individual instruments is presented. The actions during design and assembly as well as experience in-flight are summarized and commented with hindsight. Special emphasis has been given to the phase of extreme conditions during SOHO's loss-of-attitude.

20.1 Introduction

The somewhat provocative question in the title of this report did generate discussion and promoted input from the experimenters of all SOHO instruments represented at the Workshops.

The cleanliness programme within the SOHO project was a common effort of ESA and the SOHO experimenters. The goal was to ensure stable radiometric performance of the spacecraft and, in particular, of all instruments during the SOHO mission. Thus, cleanliness requirements had to be defined for instruments and spacecraft (the latter mostly based on the requirements set by the instruments), and, since each experiment on SOHO was sensitive to contamination in a different way, it was necessary to define cleanliness requirements for the individual instruments. This resulted in a "Cleanliness Control Plan" that governed all activities related to cleanliness and contamination.

The performance of the instruments during scientific operation proves that the cleanliness effort was effective, and, by tracking changes in responsivity over the mission duration, it can now be shown quantitatively how effective it was.

During its discussions, the Cleanliness Working Group (whose composition was identical with the authors of this report) tried to collect the experimenters' experience in reducing — and, as it turned out, nearly eliminating — degradation of the radiometric performance by cleanliness control. The experiment and spacecraft representatives were invited to "tell their story" about the specific measures for contamination control that later were successful in reducing radiometric degradation. The period of SOHO's loss-of-attitude has, however, affected some of the experiments, and the inferred degradation mechanisms were included in our discussions.

For the benefit of future space missions, and as a means to gather as much information as possible from all parties involved, the PIs of the relevant experiments have been asked to state

- where their instrument cleanliness programme was most effective,
- which design features they had used to improve cleanliness,
- how they had derived and implemented their cleanliness requirements, and
- how they had monitored and verified cleanliness.

20.2 Cleanliness Measures, as Viewed by Experimenters

The following is a compilation of the various responses received. We are reproducing them here without modification in order to provide proof of all the information available.

20.2.1 CDS

A) Where was the cleanliness programme really effective?

Instrument design features

Instrument design is central to contamination control.

- The optics bench was configured as a complete metal enclosure containing only metal support structures and optical components – with two well-considered exceptions.
- The entrance apertures to the telescope and thence the rest of the optics were controlled by doors, to prevent ingress of contaminants during ground assembly and in-flight thruster firings.
- The only mechanism that required lubrication inside the optical bench was the slit-scan mechanism lead screw which used a burnished dry lead film.
- The scan-mirror drive could be operated outside the optical bench and was driven through a labyrinth seal. Flexibility was provided by unlubricated flexural pivots.
- All electronics were outside the optical bench. The grazing-incidence spectrometer detector pre-amplifiers and high-voltage units accessed the detectors via sealed feedthroughs.
- Purge systems used during assembly and spacecraft integration used clean, dry gas delivered to the cleanest volumes first.
- Quartz crystal microbalances (QCM) at ambient temperature were installed to monitor deposition on optics.
- Vent ports were fitted with labyrinth seals.
- A sacrificial dust-cover, fabricated from Kapton, was used during spacecraft integration, and was removed during red tag item removal.

Were cleanliness requirements defined for the instrument sub-assemblies, optics, detectors?

- Each element of the optical chain had a contamination budget which defined allowed levels of molecular and particulate contamination at designated phases of the programme (integration, post-delivery and end-of-life).
- In addition, each type of system (for example electronic, structure, mechanism, cable) and each material (for example Al alloy, elastomer, electronics board) had a designated cleaning procedure which included a vacuum bake with a required final partial-pressure limit for organics.

What were the bases for these definitions?

- Optical modelling was used to estimate the contamination that resulted in a 10 % loss in performance. This was used as the end-of-life budget for molecular contamination. However, these programmes had to be used with caution as they were based on the rather unrealistic case of modelling with smooth, uniform layers of contaminant for which the refractive index was known. For hydrocarbons the refractive index values (n and k) for carbon and polythene were used.
- Molecular transport calculations using ESABASE software were carried out to supplement optical modelling, and to indicate potential problem areas.

- The allowable reduction in performance due to particulates was determined on scientific grounds, such as loss of throughput due to absorption, loss of contrast due to scattering. This resulted in a budget for surface obscuration by particles for each optical element. The time required to meet such surface cleanliness levels in a cleanroom of a given class was given by a series of curves calculated by U. Schühle (see report of the SUMER group) and these curves were used to define procedure times and cleanroom conditions.

What measures were taken to satisfy these requirements?

- All materials used in any part of the CDS instrument were subjected to a screening process which included an outgassing measurement.
- All components were precision cleaned by use of a procedure developed in-house which had been verified using X-ray photo-electron spectroscopy (XPS).
- Component cleaning included a vacuum bake at pressures of $\approx 100\ \mu$Pa for at least eight hours at a temperature appropriate for that component (e.g., 60 °C for electronics and 100 °C for structural components made out of Al alloy).
- Following the vacuum bake, parts were transferred to heat-sealed clean bags and then opened only in a clean assembly area.
- CDS was assembled in a Class 100 cleanroom, which had been independently verified by the CDS science team.
- The number of staff members in the cleanrooms was controlled based on experience gathered during build of the engineering model (EM). Cleanroom clothing, especially gloves, were verified to be adequate.
- The CDS team was given frequent briefings on the importance of cleanliness.

How were these measures verified?

- The cleanrooms were monitored for particulates by facility staff and independently by CDS contamination control staff.
- Particulate fall out (PFO) plates were used to monitor the cleanroom environment and the surfaces of the instrument. PFO plates were monitored weekly and monthly.
- Vacuum chambers were monitored with high-sensitivity (10 pPa) residual gas analysers and gold-on-glass witness mirrors which were inspected by XPS measurements.
- The cleanroom environment was monitored with aluminium-on-glass witness mirrors which were inspected by infrared reflectance spectrometry.
- All facilities for vibration, thermal vacuum and calibration were subject to a cleanliness audit immediately prior to and during CDS tests.
- The complete instrument was thoroughly inspected using an ultraviolet lamp (black light) and a bright, white-light source.

B) Would you make any changes with respect to cleanliness control for a future similar instrument?

In general the control procedures taken on CDS worked well. The engineering model was a useful test of these and some things were changed as a result of that experience. So a potential change is that the very large overhead associated with contamination control early in the programme needs to be recognized.

C) Would you look for changes at spacecraft level for a SOHO II? If so, which?

This also worked well; the formation of the Contamination Control Board, in particular, provided a spacecraft-wide view of contamination. It is our impression that the spacecraft contractor was not aware of the importance of contamination control as early as the experiments; once they were aware, this was reasonably well-controlled.

D) How was the stability of calibration affected by contamination?

CDS responsivity remained constant until the loss-of-attitude after almost three years of operation. This indicates that none of the optical surfaces was compromised by contamination effects. The on-board QCM's in the NI and GI spectrometers indicated an integrated contaminant load of up to 10 ng cm^{-2} and 50 ng cm^{-2}, respectively, until this time.

E) Evidence for performance changes in flight with explanation:

Until the accidental loss-of-attitude at the end of 1998 there was no change in CDS operating parameters. However, following the recovery from attitude loss, during which CDS was exposed to temperatures in excess of 100 °C for up to three months, some changes have been observed.

The QCM in the normal-incidence spectrometer (NIS) saw a post-recovery contaminant load of ≈ 120 ng cm^{-2} and the QCM in the grazing-incidence spectrometer (GIS) recorded ≈ 440 ng cm^{-2} after recovery. The responsivity of the normal-incidence spectrometer channel 1 (NIS-1) (short wavelength) had decreased by a factor of 1.45 (to be confirmed). The wavelength range of NIS-1 had shifted to longer wavelengths by about 0.05 nm. The responsivity of NIS-2 in first order remained unchanged. The responsivity of NIS-2 in second order, however, had decreased by 15 % (to be confirmed). The NIS-1 spectral-line shapes, which, prior to the accidental loss-of-attitude, were essentially Gaussian profiles now have large, extended wings.

These changes are consistent with a layer of contamination deposited on the NIS gratings as recorded by the QCM. The wavelength shift in NIS-1 is believed to be due to a small mechanical shift in the grating.

20.2.2 EIT/LASCO

A) Where was the cleanliness programme really effective?

Instrument design features

The main design features which addressed the cleanliness issues were:

- The selection of proper materials (all-metal structure, mechanisms and coatings).
- The isolation of the camera electronics in a separate enclosure, outside the optical section, which, itself, was designed as a vacuum tank for the protection of filters during SOHO launch.
- The inclusion of venting ports. However, due to the requirements of an airtight enclosure, there was limited venting at the back of the instrument, in particular in the camera section.
- A front door, which was airtight (EIT was put under internal vacuum during the integration and launch phases).

Were cleanliness requirements defined for the instrument sub-assemblies, optics, detectors?

For the EIT experiment, the molecular contamination was the prime concern. Indeed, the cooled CCD sensor is acting as a very efficient trap for contaminants. Any ice or organic deposit on the detector absorbs EUV radiation very efficiently, leading to a long-term degradation of the instrument efficiency and thus making any in-flight radiometric calibration difficult to achieve.

What were the bases for these definitions?

The cleanliness requirements used for EIT are given hereafter:

Particle fall-out

The total allowed particle fall out for the EIT instrument was equal to an obscuration (surface coverage) factor of 8×10^{-4}. This total amount was distributed as follows:

- environmental tests (on-ground): 2×10^{-4},
- assembly and integration: 1×10^{-4},
- optics manufacturing and mounting: 1×10^{-4},
- tests at spacecraft level: 1×10^{-4},
- launch phase: 3×10^{-4},

Airborne contamination

When the door was open and the instrument exposed to air contamination, the instrument was held in cleanroom Class 300 (FED-STD-209D).

Molecular contamination

EIT's components, CCD Camera and computer were built and handled to the same cleanliness specifications as LASCO. The maximum allowed molecular contamination before launch was a thickness of 2.5 nm of any type of contaminant on filters, mirrors and detector. This corresponds to a maximum level of 250 ng cm $^{-2}$ of any type of contaminant. Detailed specifications are given in Table 20.1.

What measures were taken to satisfy these requirements?

Coatings and materials have been chosen in accordance with the above requirements. All tests and calibrations were carried out in Class 100 cleanroom environment. The contamination was monitored during the entire period of integration of the experiment by use of a witness mirror which was fixed on the internal side of the front door of the telescope.

Table 20.1: EIT/LASCO contamination control specifications per MIL-STD-1246B (in nm)

Component	Assembly	Integration	Pre-launch	On-orbit	End of Life
CCD	2.5	2.5	2.5	5.0	5.0
Internal Surfaces	5.0	5.0	5.0	10.0	10.0
External Surfaces	20.0	20.0	20.0	20.0	20.0

Once on the spacecraft, EIT was kept permanently under vacuum to protect its internal filters during the launch. This prevented any additional contamination until SOHO was in space. Information about the calibration and test setups can be found in *Delaboudini ère et al.* [1995], *Song* [1995], and *Defise* [1999].

How were these measures verified?

Besides the analysis of the witness mirror, the EIT approach was based on the stringent control of material selection and of cleanliness procedures.

B) Would you make any changes with respect to cleanliness control for a future similar instrument?

- Based on the experience with EIT (see below), carefully considered requirements should be introduced to ensure that instruments are kept sealed long enough after launch so that proper outgassing of the spacecraft is achieved.
- Regarding the instrument design itself, it is highly probable that contaminants would have been driven off much more rapidly without the confinement in the camera section. Adequate escape paths should be included in future designs, either between the different instrument sections or towards the outside.

C) Would you look for changes at spacecraft level for a SOHO II? If so, which?

No.

D) How was the stability of calibration affected by contamination?

A steady decrease of the overall instrument responsivity started as soon as the instrument door was opened in space, with the CCD sensor operated at its nominal temperature (-68 °C), in January 1996. Subsequent CCD bakeouts restored the responsivity only in part. Starting in the summer of 1996, a non-uniform degradation of the sensor was detected. The degradation pattern formed a negative image of the average Sun, suggesting that it was due to the accumulated dose of EUV radiation at the focal plane. Those effects affected strongly the in-flight calibration and flat-field determination.

E) Evidence for performance changes in flight with explanation:

The current understanding of the processes affecting the EIT response is as follows:

- Two components contribute to the degradation: internal charge-collection efficiency losses (CCE) in the CCD sensor and absorption of EUV radiation by deposited contaminants. The first effect is independent of contamination issues.

- Both above mechanisms had similar importance before the spring of 1998, but the CCE effect seems to account for all further degradation afterwards.

- EUV flat-field images obtained in March to April 1996, before the first CCD bakeout, show the distinctive patterns of ice crystals. This provides additional support to the general hypothesis that a thick ice layer, well above the 5-nm specification, was deposited on the CCD chip right after launch. This might be associated with the premature opening of the EIT launch lock.

- Although the bulk of the contamination can be identified as water ice, part of the degradation might be due to organic contaminants which polymerized on the detector under the action of EUV radiation. This deposit cannot be driven off efficiently by subsequent bakeouts.

- In the first part of the mission, even short one-hour bakeouts produced a strong recovery which was followed by a quick decay of the responsivity. After mid-98, bakeouts have a much more limited effect. A slow and steady decay is then observed.

- The above behaviour suggests that contaminants were trapped inside the camera section, because this volume was largely closed, with few paths for particles to escape through the optical section of the telescope (Al filter on front of the CCD, two small vents, optically obstructed, to avoid stray light). Therefore, during bakeouts, contaminants were driven off but remained in the immediate vicinity of the CCD, and they then quickly re-deposited on the cold CCD sensor surface.

- We surmise that trapped contaminants have been entirely released out in 1998 due to enhanced internal heating of the telescope. The cause is still unclear: sudden increase of the pinhole area in the front Al filters, allowing more visible light to enter the telescope tube, or the abnormal heating associated with SOHO's loss-of-attitude.

20.2.3 SUMER

A) Where was the cleanliness programme really effective?

Instrument design features

Most effective was a design for cleanliness. Many features of the instrument design have been implemented for cleanliness reasons. Below is a list of these design features and the reasons for their implementation (in parentheses):

- Clean metal optical housing (i.e., no organic composite material in optical compartments).

- Aperture door to close/open the optical compartment (to reduce ingress from outside).

- A window, which blocked UV, as part of the aperture door (to keep the primary mirror at highest temperature by insolation).

- Solar wind deflector plates (with high voltage applied to deflect solar wind away from the telescope mirror).
- Use of ultra-high vacuum components/materials inside optical housing (high-T materials).
- Avoid organic material inside optical compartments (to minimize potential outgassing).
- Keep primary mirror at highest temperature by solar illumination (to reduce deposition on sensitive surfaces).
- Dry lubrication on $\mathrm{MoS_2}$ basis for all mechanisms (inorganic lubrication, no outgassing).
- Use flexural metal pivots instead of bearings where possible (no lubrication needed).
- Keep electronic components outside optical compartments to keep organic materials away from optics. For example, detectors were sealed around their front faces to keep their rear-sides isolated from the optics.
- Large venting ports for all subsections of the optical compartments (for efficient venting).
- Plasma and straylight barriers at venting ports (to avoid ions getting inside spectrometer).
- Purging of optical compartments at all times (to overpressurise and clean away offgasing species).
- Spring-loaded aperture door (as venting port, but loaded to keep overpressure).

Were cleanliness requirements defined for the instrument, sub-assemblies, optics, detectors?

Cleanliness requirements were defined and were applicable for all flight hardware. Contamination modelling calculations resulted in different requirements for optics, detectors, and other sub-assemblies. All cleanliness requirements have been calculated by modelling the degradation due to all possible types of contamination and degradation effects that could be expected during exposure to solar EUV irradiance and solar-wind particles, self-contamination by dust particles and outgassing organic condensables, as well as effects of a combination of these.

What were the bases for these definitions?

The basis for the determination of a cleanliness requirement was the acceptable performance degradation throughout the entire mission that was caused by all possible contamination sources. A loss of 15 % of the reflectivity of each mirror was set as a limit of acceptable performance loss. This would result in about 50 % overall loss of responsivity, and determined the level of molecular contamination inside the optical compartment. The obscuration effect by particles on each mirror was not considered to be of driving importance, because the effect of scattering was more stringent: the scientific objectives of SUMER required that the scattered intensity from the telescope mirror must be below 1×10^{-5} at an angle of $2'$.

With respect to calibration stability, molecular contamination was regarded as the major concern. Normal-incidence mirrors are more affected than grazing-incidence mirrors. A normal-incidence grating is also affected the most by a contaminating layer, because not only is the reflectivity degrading but so too is the diffraction efficiency. Mirrors were identified as the most sensitive surfaces of the SUMER instrument. To derive the amount of contamination that could be tolerated, it was assumed that any organic material of sufficient thickness on a mirror would lead to an attenuation of the reflected beam. Also taken into account was the fact that the effect of organic contaminants may be dramatically enhanced when the surface is exposed to solar ultraviolet radiation when photo-chemical reactions lead to polymerization of deposited material. Some time ago this was identified as the prime degradation process of optical instruments in space which are exposed to solar UV radiation.

To confirm quantitatively theoretical model predictions, experimental studies have been performed by contaminating mirror samples in vacuum while monitoring the amount of contamination and intermittent measurements of the reflectivity. As a result, a tolerable contamination layer of 60 ng cm^{-2} (of material with a uniform density of 1 g cm^{-3}) was specified to stay within the budget set by the requirements mentioned above.

In addition, irradiation by solar wind particles (protons and α particles) may contribute to the polymerization process, although at a much smaller rate, since their flux is much smaller than the UV flux. However, the radiation damage due to this particle bombardment, which was investigated in an experimental simulation, led to a visible alteration of the surface, presumably associated with a roughening of the surface profile with degrading effects on the scattering properties of the mirror. Thus it was concluded that for SUMER a solar-wind deflector was needed.

With regard to particulate contamination, a theoretical calculation was made to study the amount of obscuration and scatter caused by accumulated dust particles on the telescope mirror. The level of cleanliness of a surface is characterized by a particle size distribution according to MIL-STD-1246B. Our calculation, therefore, modelled the effect of opaque, spherical particles with a size-distribution given by MIL-STD-1246B and giving rise to an angular scattering distribution derived by Fraunhofer diffraction theory. The number of particles larger than a given size can be plotted as a function of this cleanliness level. This is shown in Figure 20.1.

The angular distribution of radiation scattered by Fraunhofer diffraction was calculated with the given particle size distribution. At very small angles, any particle size contributes to the scattering and, as a result, the scattering level is approximately given by the obscuration factor. Thus, from Figure 20.2, the cleanliness level which must be achieved for a given straylight specification can be derived.

In order to comply with the requirements given above, the surface cleanliness level of the optical compartment of the instrument was specified. All surfaces inside the SUMER instrument had to be compliant with a cleanliness Level 200 (according to MIL-STD-1246B). Under the assumption of a dust settlement function in cleanrooms (a result of empirical studies in cleanrooms found by *Buch and Barsch* [1987]), the exposure time of mirrors in cleanrooms could be calculated for different air-cleanliness classes. The result is shown in Figure 20.3 for cleanroom classes between Class 10 and Class 100 000. It can be used to help decide which class of cleanroom is needed for the project.

What measures were taken to satisfy these requirements?

To stay within the contamination budget, which was extremely tight for those surfaces

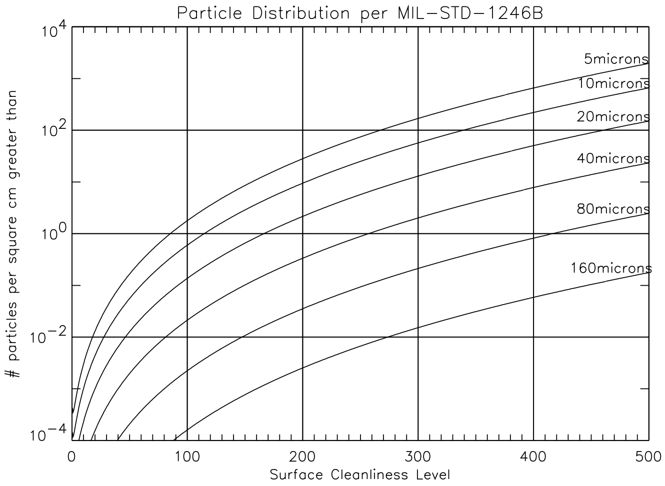

Figure 20.1: Number of particles equal to or larger than a given size versus Surface Cleanliness Levels of MIL-STD-1246B.

of the instrument that are inside the optical compartment, strict rules for the flight hardware had to be implemented. Measures implemented to maintain cleanliness were:

- Material and component selection: materials that are high-vacuum compatible, or stable at high temperatures, were preferred; no plasticizers were allowed.
- Outgassing tests of all components that contained organic parts: components had been subjected to detailed outgassing tests at increasing temperatures, including chemical identification of outgassing species. If the component was found to be acceptable, the conditioning procedure (bake-out temperature and time) was derived from this test.
- Precision cleaning of all flight hardware: cleaning procedures have been written for different types of hardware according to their compatibility with cleaning solvents.
- Vacuum baking and purging cleaning of all parts and components after cleaning: after they had been cleaned, all components were placed in a vacuum oven with an oil-free roughing pump (membrane pump) and purged with dry, clean gaseous nitrogen during the baking process. This turned out to be more effective than high-vacuum baking.
- Cleanroom facility (Class 100): the time of exposure of optical parts in the cleanroom during integration and alignment tests made the use of a Class 100 cleanroom a requirement. Such a cleanroom was used for the integration of all flight hardware components.
- Charcoal-filtered cleanroom air: the air circulation system of the cleanroom was equipped with charcoal filters to avoid organic contaminants in the cleanroom air.
- Oil-free pumping systems for test and calibration systems: all vacuum systems had oil-free pumps.

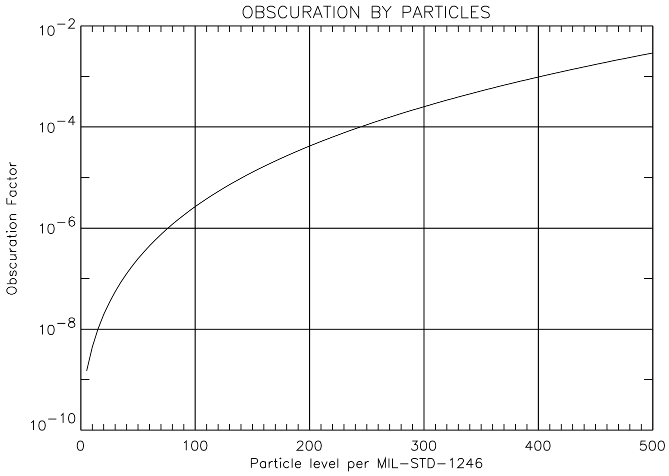

Figure 20.2: The obscuration factor versus Surface Cleanliness Level. The area is obscured by the particle distribution of MIL-STD-1246B.

- Packaging in clean bags: hardware was always packed in cleanroom bags for storage.
- Purging of the instrument whenever possible with dry N_2 (Grade 5.0, corresponding to a relative purity of 99.999 %).

How were these measures verified?

A variety of control and verification methods had to be used:

- Particle counters in all cleanroom areas.
- Inspection with bright UV lamp and white-light spot beam. The UV black light lamp was very useful for detecting fluorescing dust. Flakes or chips of metal, which do not fluoresce under UV light, were detected by use of a bright white-light spot under grazing incidence.
- Microscopic inspection of incoming or cleaned hardware. A UV black light was used for visual inspection and detection of dust particles on surfaces.
- PFO monitor plates used as witness plates in cleanrooms/benches. The surface coverage of the monitor plates can be evaluated by a PFO-meter.
- Use of witness mirrors and verification by IR analysis.
- QCM monitors were used in vacuum test chambers.
- Verification of surface cleanliness level by particle counts using tape-lift-sampling (according to ASTM E 1216). The number of particles larger than a given size was counted under a microscope and compared to the chart in Figure 20.1.

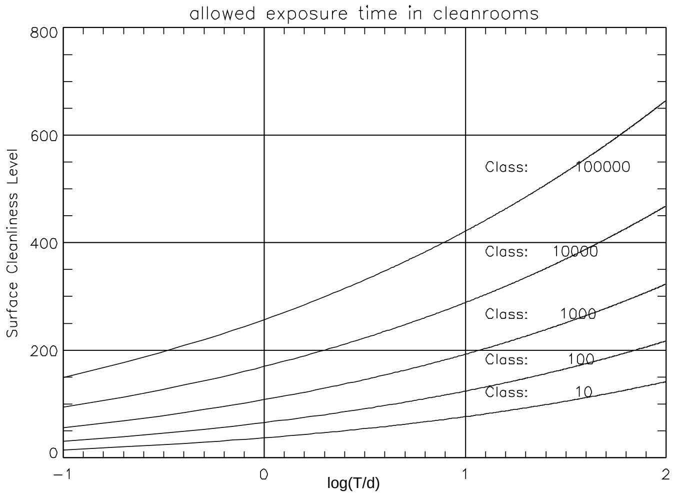

Figure 20.3: Surface Cleanliness Level (of MIL-STD-1246B) versus time of exposure in laminar flow cleanrooms of Classes 10 to 100 000 (FED-STD-209D).

B) Would you make any changes with respect to cleanliness control for a future similar instrument?

- Given the loss of responsivity experienced during the loss-of-attitude of SOHO (see point “E” below), there is no reason to relax the cleanliness requirements or descope any of the efforts.
- Intensify control and verification of material selection process.

C) Would you look for changes at spacecraft level for a SOHO II? If so, which?

For a PI-payload type of mission, intensify common material selection and screening. Make rough vacuum baking with dry pumps and purging mandatory for cleaning hardware.

D) How was stability of calibration affected by contamination?

The calibration turned out to be remarkably stable during the nominal mission time. There was no effect of contamination until a redistribution of contaminants occurred due to temperature excursions during SOHO’s accidental loss-of-attitude.

E) Evidence for performance changes in flight with explanation:

During the operation of the instrument in space, no degradation due to contamination could be detected, thus proving the effectiveness of the cleanliness efforts. After SOHO’s loss-of-attitude, however, a loss of responsivity was found. We assume that the loss in spectral responsivity was as indicated in Table 20.2

These relative responsivity changes are thought to be due to residual contamination present inside the instrument; contamination apparently had been collected on cooler sur-

Table 20.2: Relative responsivity loss after SOHO's loss-of-attitude, measured at several wavelengths:

He I 58.4 nm	26 %
Mg X 60.9/62.4 nm	28 %
N V 123.8 nm	39 %
Ne VIII 77.0 nm	34 %
H I Ly continuum 88.0 nm	29 %

faces of the instrument structure during the preceding years. Following the loss of SOHO's attitude, the telescope mirror was the coldest surface, since it was not illuminated, while its radiator faced cold space. As a result, during this time, contaminants might have been driven off any surface that was heated while the Sun was hitting the spacecraft sideways, and these were probably collected on the cold mirror.

20.2.4 SEM

A) Where was the cleanliness programme really effective?

Instrument design features

The instrument was designed so that all electronics were completely separated from the spectrometer. Specifically, the electronics was located immediately under the optical bench in an enclosed box which could slowly vent to space but not toward the optical bench. Further, a shutter was kept in front of the solar-viewing aperture for several days so that the instrument could outgas without sunlight polymerizing any hydrocarbons that might have condensed on the thin-film filters in the optical train prior to spacecraft commissioning in flight.

Were cleanliness requirements defined for the instrument sub-assemblies, optics, detectors?

Cleanliness requirements were limited to storage of the instrument optical components in a dry-nitrogen atmosphere when they were not in use.

What were the bases for these definitions? What measures were taken to satisfy these requirements?

During calibration, all vacuum systems were oil free and during fabrication only clean benches and filtered, air-conditioned laboratories were utilized. The basis for the modest requirements was our previous experience in sounding-rocket missions where a comparison of pre-flight and post-flight calibration consistently showed insignificant changes in instrument responsitivity when the above procedures were followed. (With hindsight, the evidence gained from rocket flights may not have been entirely valid for the circumstances of a long-term spacecraft mission.)

How were these measures verified?

The programme manager verified that the above procedures were followed. No further checks were implemented until underflight calibration rockets were flown following the launch and commissioning of SOHO.

B) Would you make any changes with respect to cleanliness control for a future similar instrument?

No.

C) Would you look for changes at spacecraft level for a SOHO II? If so, which?

We do not believe we could practically improve our contamination control without the installation of a Class 100 clean room at the University of Southern California. The result would probably be of marginal value.

D) How was the stability of calibration affected by contamination?

It seems most likely that spacecraft outgassing has been the source of our observed (minor) degradation of instrument responsivity.

E) Evidence for performance changes in flight with explanation:

The changes in responsivity of the SOHO SEM instrument are consistent with the deposition of a contamination layer equivalent to the absorption of a total of 15.0 nm of carbon on our optical elements (aluminium thin-film filters) since the time our instrument was delivered for integration on the spacecraft until now (1 October 2001). This is rather little integral contamination since 1995, but its effect must be accounted for and the responsivity must be corrected accordingly, so that we can measure the absolute solar irradiance with an accuracy of 10 %. The sounding-rocket underflights have been necessary to continue to ensure this accuracy. The contaminant deposition rate has now slowed significantly, as has the change in instrument responsivity. Lower outgassing of the spacecraft and/or our instrument would evidently be helpful in reducing, or perhaps eliminating, noticeable contamination-induced responsivity changes. This assumes that the spacecraft test-chambers were not the source of apparent contaminant-driven responsivity changes.

20.2.5 UVCS

A) Where was the cleanliness programme really effective?

Instrument design features

The cleanliness programme was laid out in appropriate process-control documents that specified a total allowable quantity of chemical and particulate surface contamination, procedures for the cleaning of parts, allowable solvents and materials. The cleanliness requirements on UVCS were as follows:

- For the interior of the UVCS housing and all items internal to housing, non-volatile residue was to be < 100 ng cm^{-2} and particle count was to be $< 8 \times 10^4$ m^{-2} for sizes > 5 μm.
- For the exterior of UVCS housing and all items external to the housing, non-volatile residue was to be < 250 ng cm^{-2} and particle count was to be $< 9 \times 10^5$m^{-2} for sizes > 5 μm.

What were the bases for these definitions?

For our optics, the requirements were based on the allowable and expected UV absorption through, and UV induced polymerization of, the adsorbed layers. In addition, the particulate levels were controlled to a low level to minimize scatter of direct sunlight impinging on optical surfaces (e.g., the sunlight trap) within the instrument. For other surfaces it was based on models of outgassing, migration of material to the optical surfaces and subsequent photo-polymerization.

Certain components, such as detectors and the structure itself, required special attention. The UVCS structure was made of Graphite Fiber Reinforced Epoxy (GFRE), which had a non-negligible coefficient of moisture expansion. Thus it had to be kept very dry through a rigorous purging programme. A specification for total allowable moisture absorption and appropriate test and measurement procedures were developed. The detectors' photocathodes, which also are sensitive to moisture, were open to the ambient environment. Attempts at a continuous dry-nitrogen purge for them were made.

What measures were taken to satisfy these requirements? How were these measures verified?

To control particulate contamination, cleanrooms of Class 10 000 and cleanbenches of Class 100 within cleanrooms were used for all assembly work. The cleanroom air-handling systems typically used prefilters containing activated charcoal to remove hydrocarbons from the circulating air and thereby limit the deposition of volatile hydrocarbons. To minimize water absorption and moisture-induced degradation, humidity was controlled, and purging programmes were instituted as appropriate.

Special attention was paid to materials selection: only those with low or no outgassing characteristics were used whenever possible. In cases where there were no low- or zero-outgassing substitutes available, the quantities were limited and/or the material was enclosed or encapsulated to prevent or limit the outgassing. Attention was paid to design details. For example, no enclosed (and therefore uncleanable) volumes or voids were allowed in the UVCS structural elements. In addition, electronic subassemblies, which typically run “warm” and outgas plasticizers, were vented to the exterior of the UVCS instrument, away from optical surfaces.

Laboratory tests were carried out on the GFRE material. Samples of the material were heated and located in proximity to optical surfaces that were simultaneously illuminated with intense UV radiation. The UV reflectance of those optics was measured in situ as a function of exposure time to determine if the GFRE was emitting UV-absorbing material that was collecting on the (room temperature) optical surface. No change in UV reflectance of the test optics was found for tests of the material used for UVCS. Special care was taken with lubricants: in some assemblies (for example in cavities containing optical components) none was allowed. In other cases, only those had very low vapour-pressures and did not contain silicone were allowed.

To drive off volatiles, cables and other parts were vacuum baked before installation. The instrument structure was vacuum baked several times primarily to drive out absorbed water, but this was effective in removal of other volatiles as well. The instrument was purged with dry nitrogen gas whenever it was not actively being assembled, tested, or aligned. Frequent measurements were carried out of particle and molecular deposition onto witness plates that “traveled” with the instrument.

”Washes” of some subassemblies could be directly carried out. The rinses were then analyzed both to determine quantities of residue, both volatile and non-volatile, and, using infrared absorption techniques, to determine its identity. Temperature-controlled quartz-crystal microbalances (TQCMs) together with analysis of material deposited onto traps cooled by liquid nitrogen were used during vacuum exposures of component parts and the entire instrument to measure outgassing rates. The identity of the material deposited onto the traps was determined using infrared-absorption measurements. Reflectance measurements in the vacuum UV were carried out on the flight components themselves late in the programme.

Based on the findings, it was decided to replace the optical elements just before final assembly. The replacement occurred approximately ten months before launch. Finally, the instrument was allowed to outgas in flight for one month prior to solar-UV exposure. The idea was to allow absorbed moisture and other volatiles to escape to space before UV polymerization was possible.

B) Would you make any changes with respect to cleanliness control for a future similar instrument?

UV detectors would have doors and be actively pumped prior to launch. There would be time scheduled for changeout of optics immediately prior to final delivery.

The cleanliness control programme was generally successful. Consequently no part of it can be easily identified as “excessive” or “unnecessary”.

C) Would you look for changes at spacecraft level for a SOHO II? If so, which?

Final delivery of instruments should be as close to launch as is possible. Optical components or subassemblies could then be changed out as necessary.

D) How was the stability of calibration affected by contamination?

The UVCS end-to-end calibrations were done in June of 1995. Based on component measurements as compared to end-to-end response, there was loss of quantum efficiency of a factor of two for the UVCS O-VI detector and a factor of four for the UVCS Ly-α detector. Purging of the open UV detectors was therefore only marginally successful.

In flight we have carried out observations of a number of stars and compared our intensity measurements, based on the June 1995 calibration, to those of other instruments on other spacecraft. In general, agreement within the estimated uncertainties has consistently been found. Many of these observations have been repeated on a yearly basis from the beginning of the mission. No changes have been observed. In addition we have compared co-temporal and co-spatial observations of the corona to those made by Spartan 201. Again, agreement within the uncertainty has been found.

Using the internal occulter to control the vignetting of the aperture, we have also carried out measurements of the response of UVCS as a function of unvignetted aperture. Again, except for perhaps the first 1 mm of mirror at its edge, no discernible changes in response has been found during the mission, or compared to component-level testing.

E) Evidence for performance changes in flight with explanation:

As mentioned above, repeated observations of the same stars (both before and after the accidental attitude loss), have been carried out. In general we have not seen discernible changes in UVCS response to those stars. Observation of interplanetary hydrogen Ly-α emission as a function of unvignetted aperture indicates no measurable change during the mission even though the mission-integrated light exposure to the mirrors has been very non-uniform (as is required by the coronagraphic occulting system). We therefore believe that the performance of UVCS is stable and essentially unchanged since its end-to-end test in 1995.

20.2.6 VIRGO

A) Where was the cleanliness programme really effective?

The approach of VIRGO was a pragmatic one, no verification but stringent control of measures:

- Very stringent requirements for materials selection.
- Degassing of all manufactured parts before assembly into sub-units or the experiment in vacuum at temperatures between 60 °C and 120 °C (depending on material, parts, etc.).
- Assembly of printed circuits in clean benches (before cleaning and degassing).
- Assembly of all sub-units and the experiment in a Class 50 000 cleanroom with charcoal filters (hydrocarbons rather than dust were the important issue).
- After assembly, purging with grade 6 N_2 (implying a relative purity of 99.9999 %) with lowest available amount of hydrocarbons.
- When leaving the cleanroom, purging was always maintained (during tests with the Sun and transportation to environmental tests, Assembly, Integration and Verification (AIV) etc.).
- Flooding at the end of the vacuum tests was always performed through the purging line.

B) Would you make any changes with respect to cleanliness control for a future similar instrument?

No.

C) Would you look for changes at spacecraft level for a SOHO II? If so, which?

No.

D) How was the stability of calibration affected by contamination?

Very much so. Compared to the EURECA (EUropean REtrievable CArrier) mission the Solar Photometer (SPM) degraded much less (the observed loss of responsivity after five years is still much less than on EURECA after nine months in space).

E) Evidence for performance changes in flight with explanation:

The loss of attitude influenced the radiometers in a way which is still not completely understood. However it is not an issue of cleanliness.

20.3 Comments on the Measures Taken for the Individual Instruments

20.3.1 CDS

Here the critically clean hardware was mounted inside the instrument's optical bench, with actuators mounted outside, and coupled to an internal movable mirror or slit by flexible couplings. The optical bench was purged with dry gas until launch to minimize ingress of contaminants. The shutter function was provided by a pair of doors mounted on the front face of the instrument exterior.

20.3.2 EIT

The evacuated telescope was a good choice for this experiment. External contamination thus was no threat to performance after assembly (apart from periods when the door had to be opened for functional testing). The low pressure was also imposed by the need to minimize stresses on the thin-film filters during launch.

The moderate vacuum was, however, a nuisance at spacecraft level, particularly once the spacecraft was integrated with the launcher. Also, the vacuum was not quite good enough to remove all effects of moisture on the detector performance.

A bad feature for cleanliness was the necessity for two actuators to drive filter wheels inside the telescope volume, because the windings and lubricants of the actuators are a likely source of molecular contamination. The CCD detector was moreover the coldest item within the telescope and the history of operations shows that periodic warming to +30 °C was necessary to restore performance. A higher bake-out temperature might have been beneficial.

20.3.3 LASCO

This instrument was less sensitive to molecular contamination since it was designed for visible light. This allowed the three telescopes to contain mechanisms with low risk of polymerising deposited outgassing beyond the first optical element since that blocked UV. The front surface of that element obviously was exposed to the full solar spectrum but was itself protected by the shutter door while outgassing materials on the Sun-facing side were limited in number and could be carefully selected. Continuous purging was applied.

20.3.4 MDI

As in LASCO, the first window of MDI limited transmission of short wavelengths (in fact to a 5-nm bandpass in red light) and, like CDS, MDI had an internal optical bench although this was mainly for thermal control. These measures limited the sensitivity to molecular contamination almost entirely to the front face of the entrance window and to the cold CCD.

20.3.5 SEM

SEM did suffer some performance loss as if acquiring a carbon deposit. This instrument was a late addition to SOHO's payload and was fitted in a non-ideal location looking along the surface of a thermal blanket with a poor view of space and so was warmer than is usual.

20.3.6 SUMER

SUMER elected to have two optical compartments. The first accommodates a primary mirror in full sunlight which as a consequence is quite hot (at 80 °C). The second contains a grating and two detectors, but these have low levels of illumination since there is a slit between the two compartments. The entrance door of the instrument has a window that transmits sufficient visible and infrared light to ensure that the primary mirror is at the highest temperature found in the instrument.

20.4 Concluding Remarks

In trying to eliminate the degradation of the radiometric responsivity of the SOHO instruments, a suitable design was paramount. The main measures taken by the larger (EUV) instruments were:

- Ensuring that optics were well separated from potential contamination sources,
- a careful selection of materials,

and before proceeding with the assembly:

- Vacuum baking of relevant items with monitoring of the outgassed products.

Instrument designers also attempted to budget for contamination effects though this is difficult to do with much confidence for the VUV, given the limited knowledge of the character of the deposited materials. This was a particularly delicate problem when the detector had an open (exposed) photocathode whose photo-electron emission could be modified by the deposition of extraneous materials.

More detrimental to the stability of calibration is the effect of scrubbing of the channel plates in the open detectors of SUMER and CDS. This makes continuous compensation for gain degradation necessary. Only with regular calibration comparison measurements (JOP Intercal_01) was this possible. For the SUMER detectors, the gain degradation led to untimely blindness because not enough high voltage was available from the electrical power supply unit to compensate for all the decrease in gain. In future missions, such inherent instability of the channel plate detectors can only be avoided if channel plate detector heads are scrubbed under vacuum and kept sealed under vacuum by a cover which can be opened for calibration and mission deployment. Such a cover mechanism was originally planned for one of the SUMER detectors but fell victim to schedule constraints.

Venting of a detector compartment to a less critical one carries the risk that venting flows might reverse under some circumstances. This is avoided most easily by providing a positive purge gas flow from the optical compartment. An overpressure in the optical compartment can be supported, as it was done in SUMER, by sealing the detectors around the rim of their front faces.

CDS and SUMER stress that cleanliness control must be considered early in the programme and must be adequately funded. Materials selection can consume much test time before selection can be confirmed. A common test programme might be valuable even before instrument phase B commences. This is supported by the answers to the question about spacecraft improvements.

With the exception of the consequences of the period when attitude control was lost and large temperature excursions occurred in most experiments, the radiometric responsivity of the SOHO instruments was essentially stable in flight. The measures taken to maintain a clean spacecraft and clean instruments have been very successful.

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