STRAYLIGHT IN ISOPHOT ?

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ABSTRACT

Design measures and preflight tests were the first steps taken to reduce and check for instrumental straylight. Requirements for ISO derived from the natural sky brightness were the basis for relevant preflight studies involving ISO and ISOPHOT. Inspections of the cryostat identified several IR photon leaks. Their elimination was verified by a "Dark background test". In flight, the extended profiles of bright point-like sources were measured to study potential near-field straylight. During solar eclipses the straylight of the Sun and the Moon was searched for. Finally we checked for a potential unwanted signal of the Earth when it fully illuminated the inner sunshade. Surprisingly, the 170 μm Serendipity Survey contributed to our knowledge of instrumental straylight. To summarise, straylight was a negligible contribution to most measurements, but it can be a small correction factor under rare observing conditions near the detection limit.

Key words: Instrumentation: detectors – Instrumentation: photometers – Space vehicles: instruments – Infrared: general

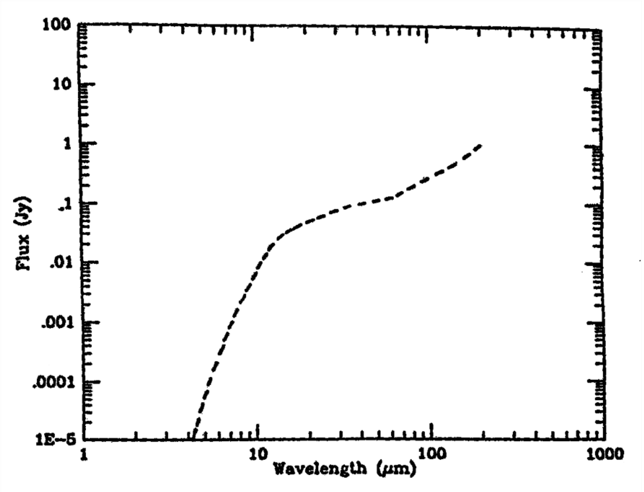

Figure 1. Diffuse astronomical background expressed as flux in a diffraction limited aperture versus wavelength. The MIR is dominated by the emission of interplanetary dust, the FIR by that of the interstellar dust. Straylight specifications for ISO require a flux below 10 % of the natural sky brightness.

1. REQUIREMENTS

Planned as a sensitive telescope for the entire infrared wavelength regime, ISO (Kessler et al. 1996) had to fulfill stringent straylight requirements. The ISO Science Team defined that straylight had to be below 10 % of the natural sky brightness for $2.5 < \lambda < 240\,\mu$m, see Figure 1. Potential celestial straylight sources are the Sun, the Earth, the Moon and the bright planets. But straylight might also arise internally by self-emission of baffles, the sunshade, or structural elements inside the cryostat. This implicitly assumes that the telescope itself and the instruments are very cold (T < 4 K) to keep their emission negligible.

The straylight suppression of ISO followed classical routes. The satellite was equipped with a passively cooled sunshade, a He gas cooled long main baffle around the telescope and cold Cassegrain baffles. The surfaces of these were coated accordingly: all baffles with IR black paint, the sunshade was gold-coated to keep its emission low. Optics and baffles were aligned carefully and kept extremely clean. The celestial sources (Sun, Earth, ...) were required to be always beyond a defined avoidance angle in order not to illuminate critical parts of the baffle/telescope system. Details are given in Figure 2. The focal plane chamber was planned to be a cooled blackened light-tight enclosure around the 4 instruments, protecting them against the emission from the innermost radiation shield (T $\sim$ 27 K) of the ISO cryostat.

2. VERIFICATION

All the important requirements and specifications had to be verified preflight and in-flight. On ground, the telescope could not be checked experimentally because no optical tests were planned for cost reasons. However, a thorough straylight analysis (GUERAP) by AEROSPATIALE gave theoretical confidence in the performance of the baffle system. The ISOPHOT instrument (Lemke et al. 1996), analysed by ZEISS, could be additionally checked in the laboratory. By illuminating all critical beam paths with a red laser we found increased straylight resulting from the edges of the (slightly oversized) field mirror. Contrary to planning and analysis the mirror was manufactured with a small chamfer, and this reflected some light into unwanted directions. Two baffle rings were mounted additionally to avoid this.

Potential self-emission of the ISO's cryostat interior could be checked by visual inspection of the open cryostat. An annular gap between the main baffle and the primary mirror inten-

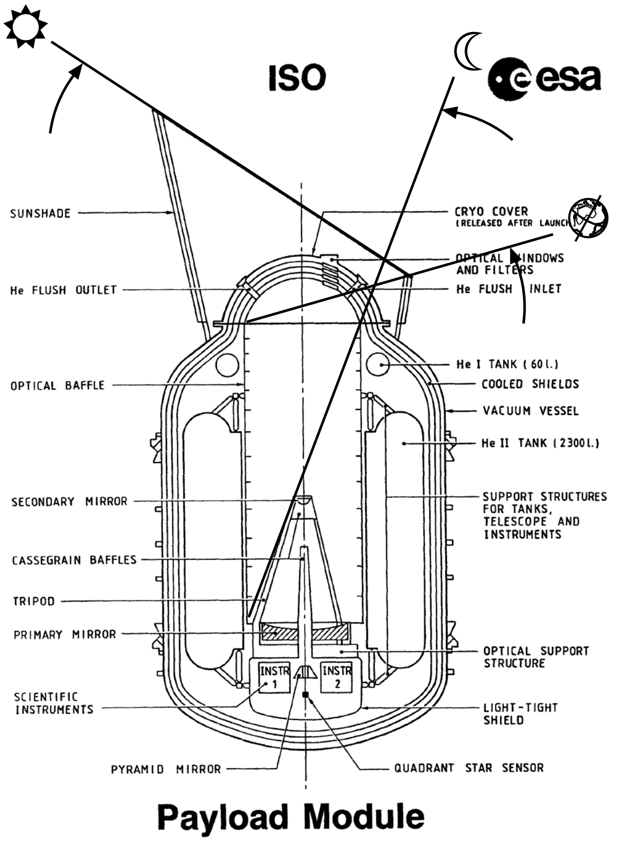

Figure 2. Simplified scheme of the ISO satellite with an illustration of the avoidance angles for the Sun (> 60°), the Moon (> 24°) and the Earth limb (> 73°); Jupiter (> 5°) is not indicated.

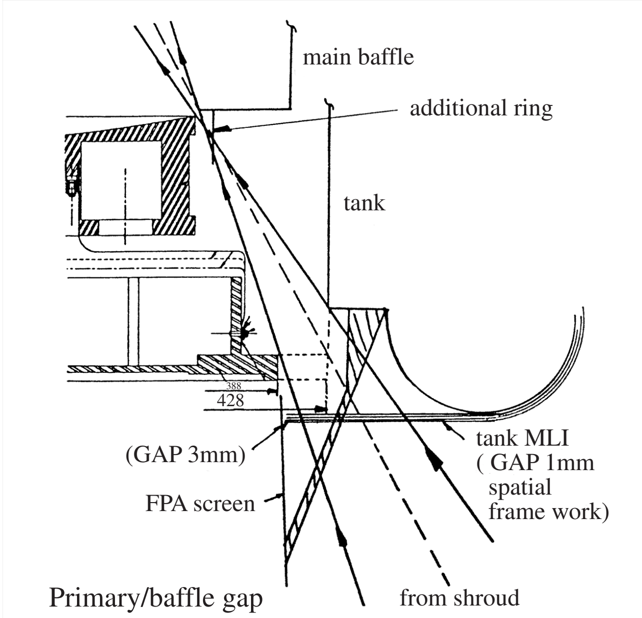

Figure 3. Straylight caused by self-emission from the cold interior of the cryostat (T ∼ 27 K) could pass between the primary mirror edge and the main baffle. The AEROSPATIALE study recommended additional baffle rings.

tionally foreseen (launch vibrations!) had already been identified in the straylight study (Figure 3). However, it was not closed in the hardware state as recommended and in addition many more leaks via gaps, IR transparent materials etc. were discovered. Independent calculations by ESA and the ISOPHOT team resulted in a prediction that the internal straylight would be 10^8 – 10^6 times out of specifications. Obviously the "as built" status differed from the "as designed" drawings in a few details which were negligible to mechanical, cryogenic, and electrical engineers but were important to achieve infrared low background conditions. Following this, ESA called in an expert Straylight Working Group.

3. PREFLIGHT TESTS AND ANALYSES

Numerous recommendations from this group to close all identified photon gaps and to modify electrical and mechanical feedthroughs were implemented in the process of cryostat and instrument integration by industry. Optical tests with photomultipliers verified the success of these measures. As a final verification the "Dark background test" was performed, where the entrance opening at the upper end of the baffle underneath the cryostat's ejectable cover was closed by a cold metallic plate (Figure 4). Although "dark signals" below the straylight specifications were expected at all wavelengths, ISOPHOT measured an excess flux in the far infrared assignable to a black body with T ∼ 24 K (Figure 5). The subsequent analysis was able to trace this as the emission of the struts suspending the LHe tank and being partially inside the straylight shielding. This emission was predicted to disappear eventually in-flight with the outer case of the cryostat being much colder (-50°C) than in the laboratory (+20°C).

In the final Integrated System Tests the ISOPHOT FIR channels were almost blinded, because the radiation passing through and being emitted by the cryostat's two alignment windows (Figure 6) exceeded the dark background specs by a factor $\sim 10^5$. Sensitive tests of the instrument became impossible, only a cold shutter closing the entrance windows could have helped, but this was not available.

In parallel to the preflight measurements of the cryostat's internal straylight sources a new study of the external straylight suppression by the baffle system was performed by BRO, Tucson and was monitored by ESA and the Straylight Working Group. This analysis applied the APART programme which deals with both scattering and diffraction. It modelled the optical system by many more knots than the earlier GUERAP analysis and considered the meanwhile slightly modified "as built" status of ISO. It became very meaningful, because this analysis also included the two photometric instruments ISOCAM and ISOPHOT.

The main results of the BRO analysis were: (i) the as built configuration was basically sound, (ii) straylight predictions were quantified and therefore testable in flight and (iii) critical

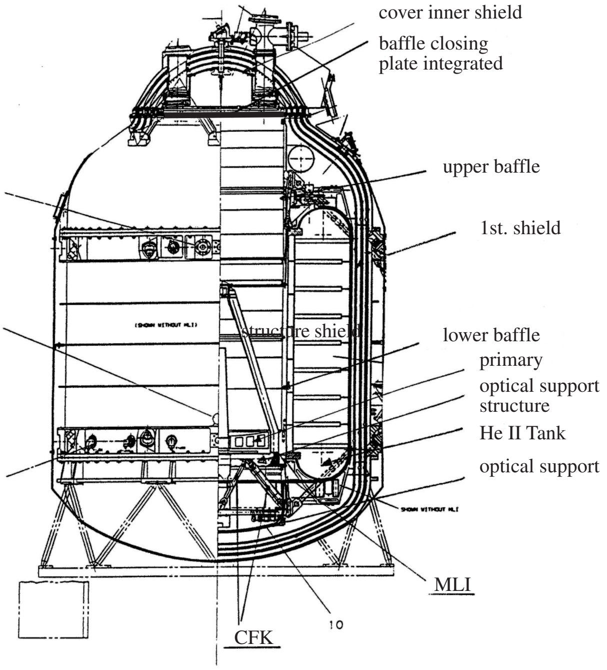

Figure 4. ISO's cryostat equipped with a cold plate at the upper end of the main baffle. In this configuration the "Dark background test" was performed.

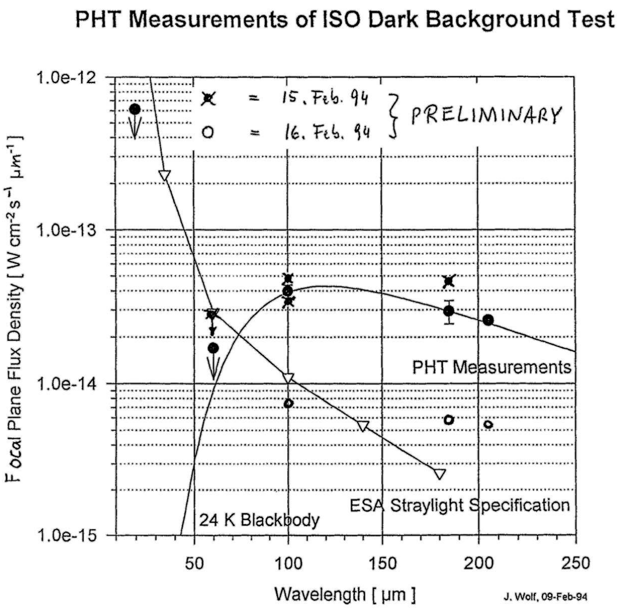

Figure 5. ISOPHOT indicated an excess radiation in the Dark background test, ascribable to a T$\sim$24 K black body radiation eventually identified as "warm" CFK-struts suspending the LHe tank (see Figure 4).

items (oversized secondary baffle, etc.) were identified (Peterson 1993, Pfisterer et al. 1993).

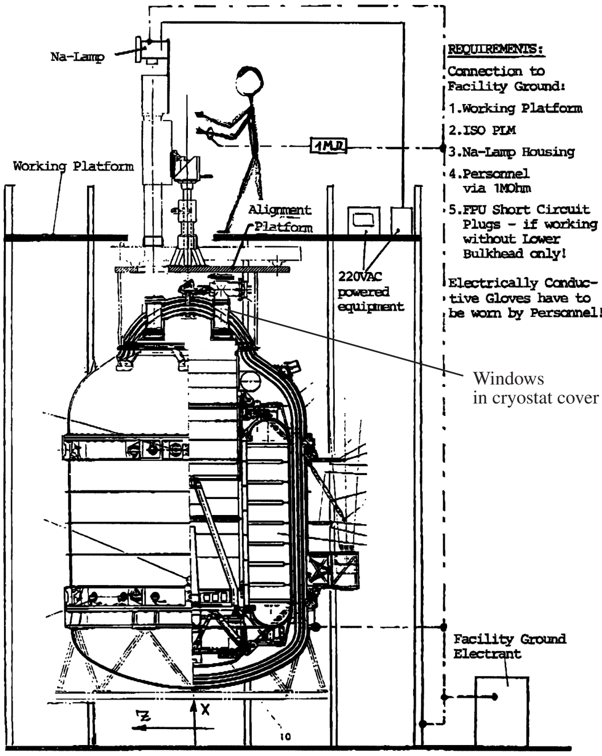

Figure 6. The alignment windows in the cryostat cover caused a large background in the FIR channels by transmission and self-emission. No cold shutter to close the windows was in place.

4. IN-FLIGHT MEASUREMENTS

The first step was the determination of the "near-field straylight", that is the off-axis angular dependence of the signal close to a bright point-like celestial target. For the far infrared cameras (170 μm) Saturn was chosen, but because of its enormous brightness (32000 Jy) it was approached only to $\gtrsim$ 5 arcmin distance in order to avoid signal saturation and detector transients. A road map of the scans around Saturn is presented in Figure 7. The result of these scans around Saturn is the extended beam profile shown in Figure 8. There is excellent agreement with the theoretical predictions of the BRO analysis. In a similar way, measurements were made at other wavelengths with other detectors. In the MIR (P2 detector, λ $\sim$ 25 μm, bright source was Mira) the extended wings of the beam profile could not be detected because the zodiacal light is too bright ($\sim$ 40 MJy/sr) at this wavelength.

In September and October 1997, during its extended lifetime, ISO experienced several total solar eclipses of up to 140 min duration inside the science window. Our proposal to ESA to use them for straylight verification measurements was accepted, because regular observations inside the Earth's shadow were very much restricted (e.g. no change in pointing was allowed) due to the lack of electrical power. For the assessment of Sun straylight, before entering the shadow ISOPHOT was first carefully calibrated on celestial standards and against the inter-

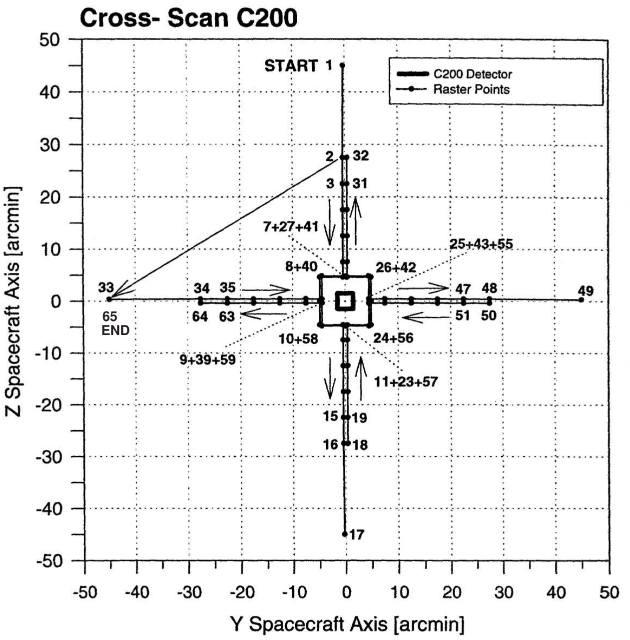

Figure 7. Road map of scans around Saturn (at the centre) by which the near-field straylight was checked. Numbers indicate measurement positions. The scans were extended to large distances in order to determine the sky background and were performed in two directions in order to assess possible memory effects. The size of the C200 array used for these scans is indicated at the (0,0)-position.

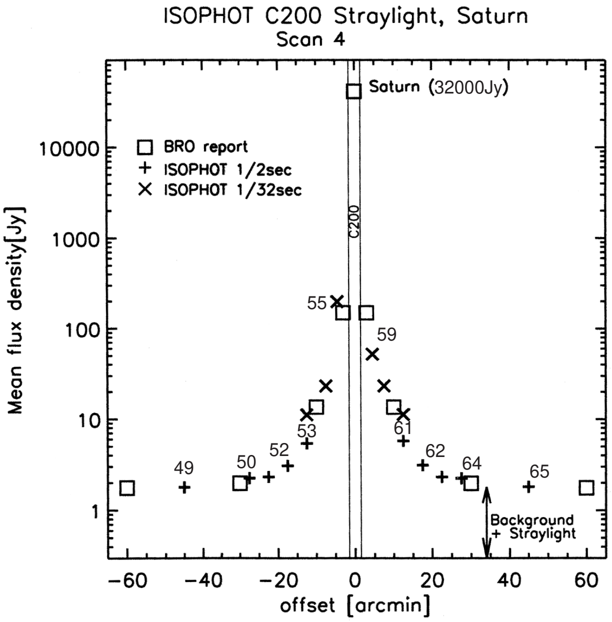

Figure 8. Beam profile and near-field straylight as measured on Saturn at 170 μm. The numbers refer to the road map shown in Figure 7. Crosses represent the ISOPHOT measurements (there is a small discontinuity at an offset angle of ∼ 12 arcmin due to the increase in reset interval time for the fainter signals at larger offset angles). Squares are predictions of the BRO analysis; they are in excellent agreement with the measured values.

nal calibrators, then the pointing was locked to a dark sky position and the signal monitored during the passage of the shadow region. It resulted in no measurable signal decrease/increase when entering/leaving the umbra (Figure 9). By this sensitive differential measurement an upper limit of $\leq 0.010\,\mathrm{MJy\,sr^{-1}}$ could be derived for the solar straylight at $170\,\mu$m and $\leq 0.016\,\mathrm{MJy\,sr^{-1}}$ for $25\,\mu$m (Kranz 1998).

The Moon straylight was similarly determined. However, the satellite could not be commanded to change its pointing with respect to the Moon's position during the eclipses. Therefore we observed the dark sky field during 3 subsequent days, while the Moon moved from an offset angle of $\sim 62°$ close to its avoidance angle of $\sim 24°$. Again, no straylight was detected, see Figure 10.

Earth straylight was the potentially largest component, because the Earth could occasionally illuminate most of the sunshade's gold coated inside. The measurement sequence tested this condition at the beginning of the orbit. Later the Earth's light disappeared gradually from the inside of the sunshade, see Figure 11. No straylight was identified within the error limits. As the configuration of a sunlit sunshade was quite rare, there is no need to correct data. For very sensitive measurements it is however recommended to check whether they were taken under this configuration.

To summarise, even ISO's most sensitive channels, the FIR ones, were verified as not suffering from straylight caused by the three most relevant infrared emitting bodies illuminating

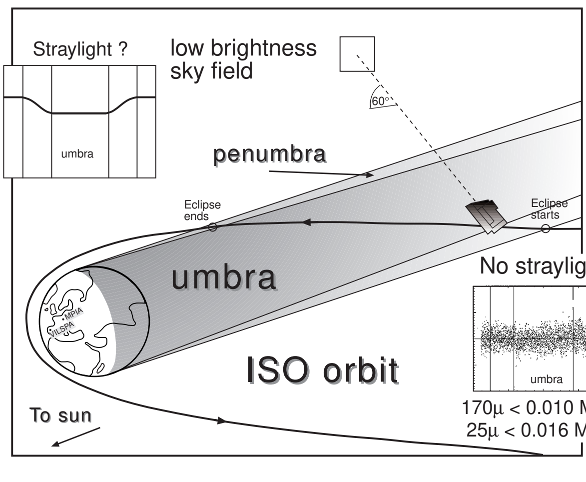

Figure 9. Illustration of the straylight measurements on the Sun during the total solar eclipses inside the science window in September 1997.

ISO's orbit. The detailed upper limits are given in the lower right corner of Figures 9, 10 and 11 respectively. Figure 12 shows the comparison of these results with the prediction of the two independent preflight analyses and demonstrates that the requirements were met.

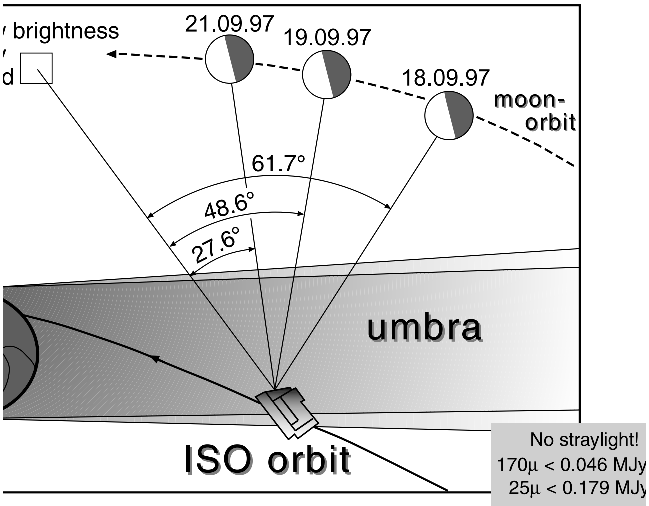

Figure 10. *Illustration of the straylight measurements on the Moon. Because ISO could not approach the Moon while inside the Earth's shadow, the Moon had to move while ISO observed the same dark field on the sky on subsequent days.*

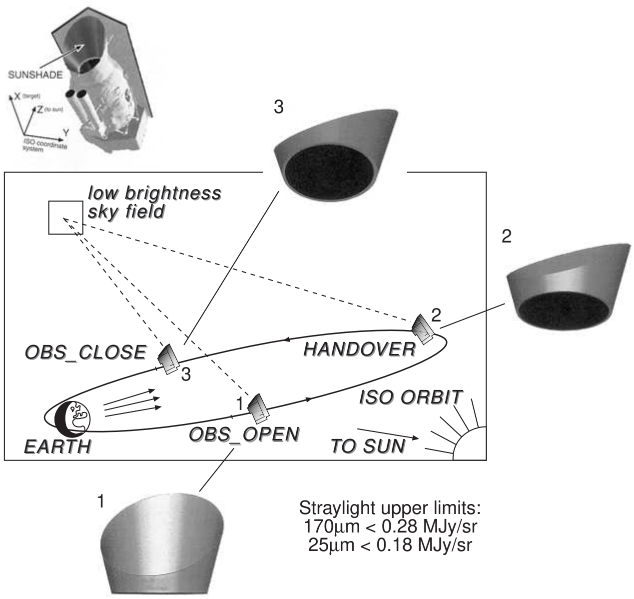

Figure 11. *Illustration of the Earth straylight measurements. At position 1 the Earth is close to its avoidance angle and fully illuminates the inside of the sunshade. At position 3 the Earth's radiation no longer enters the shade.*

5. THE SERENDIPITOUS SURPRISE

From the ISOPHOT Serendipity Survey database an image of Saturn and its environment at 170 μm was composed after the mission (Figure 13). It shows the hexa-pronged image of the planet in the centre, a configuration we assign to diffraction on ISO's tripod. At a distance of 0.7° to 1.0° the planet's image is surrounded by a faint elliptical ring. Although its origin is not clearly understood, we tentatively assign it to straylight caused by grazing reflections from the oversized secondary

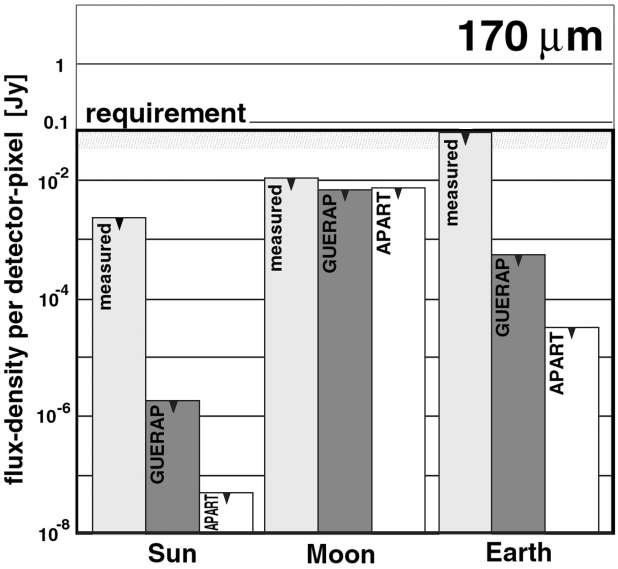

Figure 12. *Comparison of finally measured upper limits for Sun, Moon and Earth straylight at the wavelength of 170 μm with the scientific straylight requirement and the levels predicted by 2 independent studies (APART, GUERAP).*

mirror cover. Its deviation from the design was earlier commented on critically by the Straylight Working Group and also identified in the BRO analysis as a potential source of straylight. Although the brightness of the ring is less than $\sim 1\,\%$ of the central target, observations $\sim 1°$ off very bright targets should be checked for this ghost.

6. LESSONS LEARNT

They can be summarised in 8 points:

1. The straylight precautions for ISO and ISOPHOT were successful.
2. Contaminations from Sun, Moon and Earth were below the detection limit.
3. The near-field straylight (beam profiles) were close to predictions.
4. Detailed straylight analyses deliver reliable predictions.
5. Eclipses were a lucky chance for straylight verifications (Sun off/on).
6. PI teams should be involved in IR straylight design and inspection of payloads of future comparable satellites.
7. Integrated system tests should allow "dark" measurements by a cold shutter behind alignment windows.
8. There is a need for an efficient blackening procedure for the far infrared applicable to the various surfaces of a cold telescope and the scientific instruments.

The only remaining open questions at present are: (i) what is the definite origin of the ghost ellipse seen in the Serendipity Survey, and (ii) how much straylight bypasses the filter wheels due to scattering by surfaces coated with non-ideal black paint inside the ISOPHOT instrument? The latter question has a preliminary answer and although the bypassing straylight is minimal, it has to be considered as a small factor when determining the faintest sources like the Extragalactic Background Light.

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REFERENCES

AEROSPATIALE Straylight Study, 1989, ISO.AN.B130.032

Kessler, M.F., Steinz, J.A., Anderegg, M.E. et al., 1996, A&A 315, L27

Kranz, Th., 1998, Physik-Diplomarbeit, Univ. Heidelberg

Lemke, D., Klaas, U., Abolins J. et al., 1996, A&A 315, L64

Peterson, G.L., 1993, BRO Straylight Report No. 2260

Pfisterer, R.N., Milsom, D. & Peterson, G.L., 1993, BRO Straylight Report No. 2270

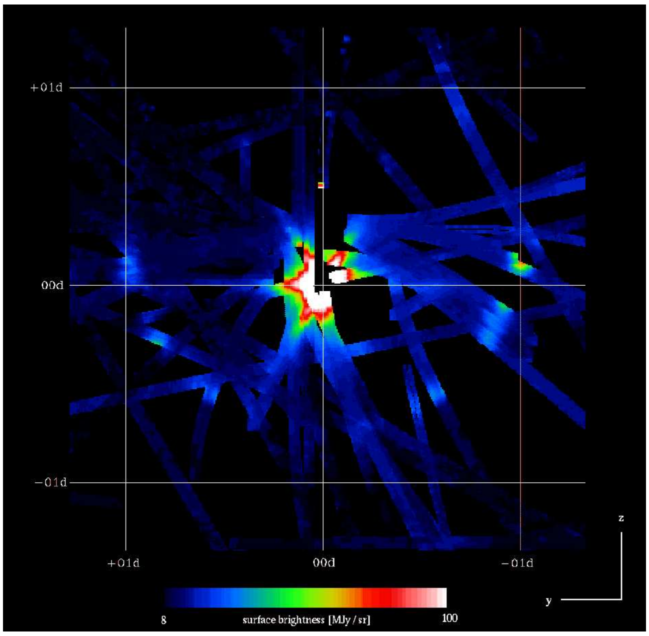

Figure 13. The image of Saturn as composed by random slews of the ISOPHOT Serendipity Survey at 170 μm. Beyond the diffraction figure of the telescope's tripod a faint ghost ellipse is seen with a semi major axis of $\sim 1^{\circ}$.