CENTIMETRE-SIZED ORBITAL DEBRIS OBSERVED WITH IRAS

R.M. van Hees, A.R.W. de Jonge, P.R. Wesselius

Space Research Organisation of the Netherlands, SRON/Groningen,
P.O. Box 800, NL-9700 AV Groningen, The Netherlands

ABSTRACT

In this paper we show that the IRAS orbital debris database contains at least several thousand observations of centimetre-sized space debris at altitudes between 1,000 and 6,000 km. The observations are still relevant, although obtained in 1983, because the observed orbital debris objects are still in orbit due to the high altitudes. Thus the observations can put a lower limit on the actual debris population. The completeness of this subset as function of size, inclination and altitude is studied and the results are briefly discussed.

1. INTRODUCTION

There is a growing awareness of the orbital debris problem. A lot of effort is put in the development of reliable models of the orbital debris population. Nowadays most models accurately show the distribution down to 10 cm sized objects as a function of altitude and inclination, but there is still a lot of uncertainty about the smaller sized population (see for example Ref. 1). Particles in the range from 1 mm to 10 cm are able to damage a satellite (see Ref. 2) and are therefore important for risk analysis. The most important sources of information about this population at low altitudes are Solar Max (Refs. 3, 4, 5), LDEF (Refs. 4, 5) and recently the Haystack radar (Refs. 6, 7).

In this article we will show that IRAS (InfraRed Astronomical Satellite, see Ref. 8) was capable to detect centimetre-sized objects at altitudes between 1,000 and 6,000 km.

2. DETECTING ORBITAL DEBRIS WITH IRAS

IRAS performed astronomical observations in 1983. Serendipitously orbital debris was seen as well. In most "official" data products these data have been eliminated, except in the first set of infrared images "Sky Flux" (Ref. 9). A systematical re-analysis of the IRAS data in 1990-1992 has led to the production of a complete set of IRAS data only pertaining to orbital debris. The IRAS orbital debris database contains all potential observations of orbital debris; it is so complete that it is unreliable (of order 95% of the entries are false). However, the accompanying analysis software can easily create reliable subset-databases, and derive information on temperature, orbit, and sizes of the observed objects (Ref. 10).

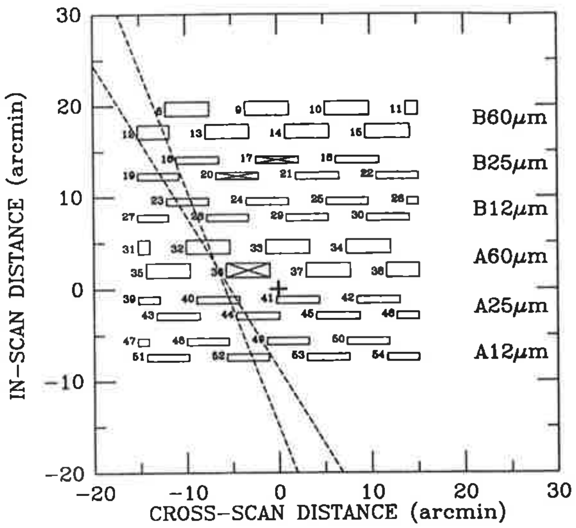

Figure 1: *IRAS focal plane. Of the 62 infrared detectors the three filled-in were inoperative; the cross-hatched detectors showed a higher noise level. The orbital motion and scan direction of IRAS were along the y-axis. Only (closeby) ODO's can exhibit skew scan patterns; an example is shown.*

2.1. IRAS orbital debris observations

Figure 1 shows the IRAS focal plane layout. The parameters derived from an observation of an orbital debris object (ODO), in IRAS focal plane coordinates, are in-scan velocity (velocity in the in-scan direction), angle with respect to the in-scan direction, time of crossing in-scan position zero and a cross-scan position at that time.

We do not get any information about the distance between IRAS and an observed ODO or its radial velocity. The analysis software of the IRAS orbital database can derive orbital elements for an observed ODO, but due to the lack of information only for circular orbits, with a rather poor accuracy (Ref. 10). The latter is caused by the large uncertainties in the observable parameters.

Figure 1 shows as an example an observation of an ODO, which was detected by the 12 μm wavelength detectors: 52 and 23, the 25 μm wavelength detectors: 44, 40, 23 and 19, and the 60 μm wavelength detectors: 32 and 12. The path across the IRAS focal plane is indicated with two dotted lines crossing these detectors with the smallest and the largest possible angle. Although this object

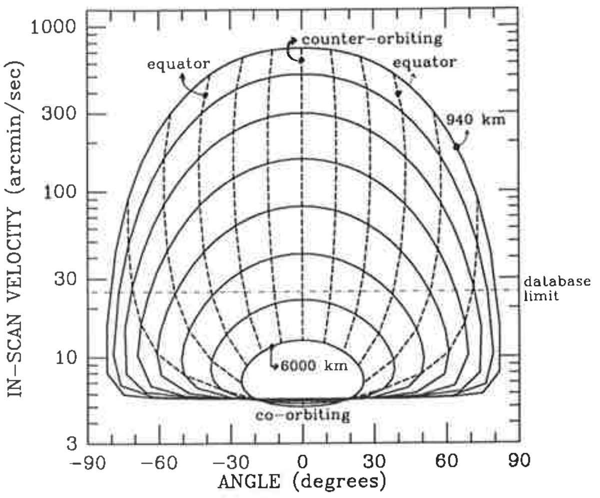

Figure 2: *Relation between OD orbit and IRAS observations, where IRAS is assumed to look in the direction of the zenith and the ODO's are moving in circular orbits. The closed contours show for a constant altitude the relation between in-scan velocity and angle across the IRAS focal plane. The plotted altitudes are at 940, 980, 1,060, 1,220, 1,540, 2,175, 3,450 and 6,000 km. The inclination varies between co-orbiting and counter-orbiting, and is shown in steps of* 30° *with a dashed line. Observations with in-scan velocities above 25 arcmin/sec are not stored in the IRAS OD database.*

was observed by 8 detectors, the uncertainty in the angle of the path across the IRAS focal plane is 5 degrees. The uncertainty in the in-scan velocity is inversely proportional to the in-scan velocity and less than 5%.

Figure 2 shows the relation between orbital debris orbit and IRAS observations (IRAS looking in the direction of the zenith). The observed object is assumed to move in a circular orbit with altitudes between 940 and 6,000 km and inclinations between co-orbiting and counter-orbiting with respect to the IRAS orbit.

The inner closed contour in Figure 2 shows how in-scan velocity and angle across the IRAS focal plane vary, for an object in a 6,000 km altitude orbit, as function of inclination w.r.t. the IRAS orbital plane. The in-scan velocity varies between 4 arcmin/sec (co-orbiting w.r.t. IRAS) and 12.5 arcmin/sec (counter-orbiting w.r.t. IRAS), while the angle varies between -25.5 and 25.5 degrees (those values are reached when the difference between IRAS and OD orbital plane equals 39°).
The closed contours intersect at low in-scan velocities, which implies that we will derive more than one set of orbital elements at these points for one combination of in-scan velocity and angle across the IRAS focal plane. It also means that close to these intersections the derived set of orbital elements is very sensitive to errors in the observed parameters.

We have studied the relation between the observed parameters and orbital debris orbit, in case IRAS was not looking at the zenith. Not looking at the zenith has a noticeable effect on the in-scan velocity, especially for nearby co-orbiting OD: the in-scan velocity found is reduced w.r.t. the values shown in Figure 2 (up to 40%). The smallest in-scan velocity found is larger than 3.4 arcmin/sec for a co-orbiting object just above IRAS, and IRAS is looking 40° away from the zenith.

2.2. Completeness as function of in-scan velocity

The IRAS OD database is limited to observations with in-scan velocities between 3.1 and 25 arcmin/sec. Figure 2 shows that the OD database is complete for altitudes down to 3,100 km. The completeness of the IRAS OD-database, for objects in circular orbits, is not affected by the database lower-limit on the in-scan velocity of 3.1 arcmin/sec, but the database upper-limit on the in-scan velocity does discriminate against observations of objects below 3,100 km altitude as shown in Table 1.

2.3. Completeness as function of altitude

The completeness of the OD database is also a function of altitude, because IRAS observed the sky from 900 km altitude. Thus the observed volume decreases relatively as we get closer to IRAS. On average a celestial source was seen 6 times during the IRAS mission of 10 months. If we correct the observed volume with the total volume at a given altitude, and we assume that the distribution of the debris population over altitude and inclination does not affect the number of observations on average, we get Figure 3. Note that this is a simplified model; the actual distribution of the debris population may affect this picture.

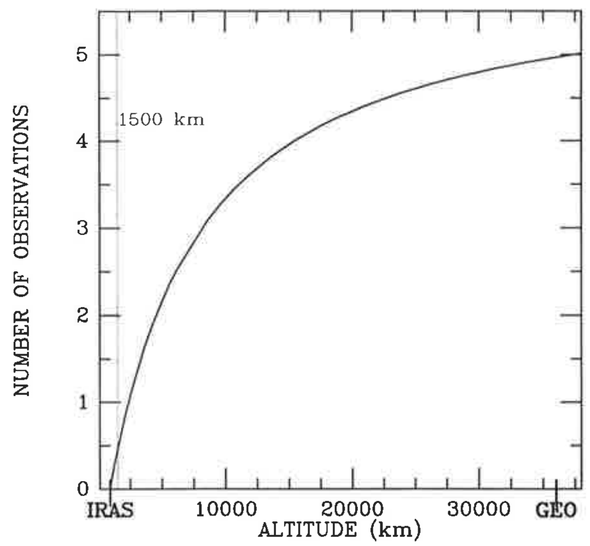

Figure 3: *The average number of observations of OD as function of altitude, during the IRAS mission.*

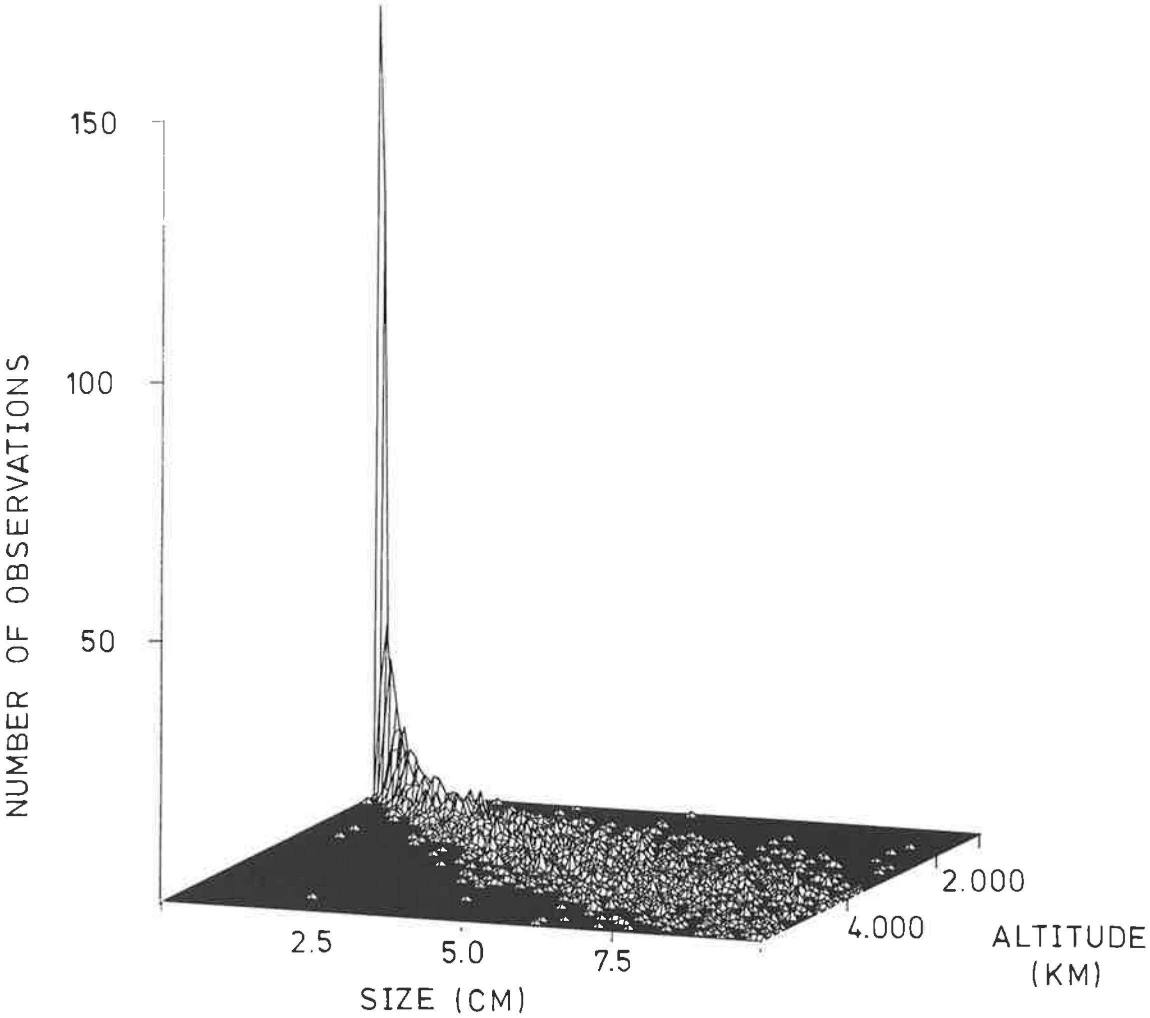

Figure 4: *Altitude-size distribution of the small sized orbital debris population as seen by IRAS, represented in a two-dimensional histogram . The altitude is shown between 900 and 6,000 km with a bin size of 50 km. The size is shown between 0.0 and 10 cm with a bin size of 1 mm. The number of entries found in a bin is corrected for the expected number of false detections.*

3. OBSERVATIONS OF SMALL OBJECTS

3.1. Selecting small sized debris

We want to select observations of small (< 10 cm sized) orbital debris. ODO's are expected to radiate as a black sphere at a temperature of 300 K. On the basis of the limiting sensitivity IRAS should be able to detect 10 cm sized orbital debris at 6,000 km altitude.
The following selection criteria were applied on the IRAS OD database:

1. to discriminate entries containing mostly noise peaks, the path had to be confirmed by at least 4 detectors (instead of 3),
2. observations done against a noisy background were rejected,
3. the temperature of an ODO in thermal equilibrium with the solar radiation is around 300 K. IRAS measured colour temperatures which may differ from the actual temperature due to the used paint and material. Selected were observations with colour temperatures between 200 and 400 K,
4. all the 12 and 25 μm detectors crossed by the path across the IRAS focal plane had to detect the object (the flux at 60 μm is significantly weaker than the fluxes at 12 and 25 μm, if the temperature is around 300 K),
5. the algorithm used to derive orbital elements often returns a solution with a semi-major axis below 7,300 km (less than 20 km above IRAS), due to roundoff errors in the computation. Rejected are entries with all solutions having a semi-major axis below 7,300 km,
6. if the observed object is moving in a circular orbit, and the in-scan velocity is larger than 10 armin/sec, or the angle across the IRAS focal plane is less than

altitude	inclination	
(km)	(degrees)	percentage
910	92 - 106	3.9
920	89 - 109	5.6
940	85 - 113	7.8
980	79 - 119	11.1
1,060	67 - 131	17.8
1,220	58 - 140	22.8
1,540	38 - 160	33.9
2,175	5 - 193	52.2

Table 1: *the range of inclinations of OD orbits for several altitudes, which can be found in the OD database not discriminated by the database limit of 25 arcmin/sec. The last column shows the range of detectable inclinations as percentage of the total range of inclinations w.r.t. the IRAS orbit*

$-25°$ or larger than $+25°$, then the altitude of the orbit has to be below 6,000 km, see Figure 2.

After applying these selection criteria we were left with 2,735 observations of objects with sizes smaller than 10 cm. Due to the cutoff at 920 km altitude the limit on the size of the observed objects is around 0.5 mm.

In subsequent analysis of this subset we will assume that, in spite of our strict selection criteria, 10% of the entries are not due to observations of orbital debris. These entries may be caused by noise peaks and cosmic ray hits, which happen to line up with the right timing to be consistent with a constant in-scan velocity. The number of these false detections is very sensitive to the background noise and the required timing accuracy. In the statistics we will correct for the number of false detections N_f. The expected number of false detections can be calculated:

$$N_f = K \times \Delta d \times \Delta t^{n-2} \times N_p^n / v$$

N_p is the average number of peaks per detector per second at the time of the observation. Δd is the distance (in arcmin) between the outermost detectors that have "seen" the ODO. A margin Δt is allowed to confirm to the timing corresponding to a linear motion. The ODO has been detected by n detectors with an in-scan velocity v. The scaling factor K is used to achieve the assumed 10% false entries. The number of observations is the number of entries in the subset minus the expected number of false detections.

3.2. Properties of small sized debris

The properties of the small sized orbital debris population as seen by IRAS are bound by the selection criteria applied, and the used instrument. We have to take this into account if we want to study the distribution of the subset as function of altitude and size. Figure 4 shows the number of observations of small sized orbital debris, found in the IRAS OD database, as function of altitude and size. The number of entries found in a bin is corrected for the expected number of false detections. Eventually this distribution can be converted to number per km^3 per year. From the distribution of the observed orbital debris objects as shown in Figure 4 follows:

1. there must be a enormous amount of small objects ($<$ 1 cm). Although IRAS saw just a small part ($<$ 10%) of the volume at low altitude, and just those objects within a small inclination band ($<$ 15%), there are far more small objects observed that larger objects,
2. the number of observations per unit volume would drop much steeper as function of altitude than the shown distribution.

Taking this into account would make the observed distribution look like the distribution of orbital debris described in for example Ref. 2, 3, 4:

- almost no debris at altitude above 3,000 km,
- a cumulative cross-sectional area flux which increases by a factor 1,000 if the area decreases by a factor 10 (for sizes less than a centimetre).

In this paper we have assumed that the observed objects are moving in circular orbits. This is not the case: a substantial part of the space debris population smaller than a centimetre are meteoroids (Refs. 1, 2, 3). And recent studies with the Haystack radar have shown that probably a substantial part of the small objects are moving in elliptical orbits (Ref. 7).

4. REFERENCES

1. Sdunnus, H., Klinkrad, H., *An introduction to the ESA Reference Model for Space Debris and Meteoroids*, paper presented at the First European Conference on Space Debris, Darmstadt, Germany, April 5-7, 1993.

2. Report on Orbital Debris, *Interagency group (space)*, Washington, D.C., U.S.A., 1989.

3. Space Debris, the report of the ESA Space Debris Working group, *ESA Space Debris Working group, ESA SP-1109*, Paris, France, 1988.

4. Positional Paper on Orbital Debris, *Ad hoc Expert Group of the International Academy of Astronautics, Committee on Safety, Rescue, and Quality*, 1992.

5. Zook, H.A., McKay, D.S., Bernhard, R.P., *Results from Returned Spacecraft Surfaces*, paper no 90-1349, AIAA/NASA/DoD Orbital Debris Conference, April 16-19, 1990.

6. Tracy, T.E., Stansbery, E.G., Stanley, J.F., Sherrill, G.P., *Orbital Debris environment characteristics obtained by means of the Haystack radar*, paper presented at the First European Conference on Space Debris, Darmstadt, Germany, April 5-7, 1993.

7. Reynolds, R.C., Kessler, D.J., *Orbital Debris environment for Space Station*, paper presented at the First European Conference on Space Debris, Darmstadt, Germany, April 5-7, 1993.

8. Infrared Astronomical Satellite (IRAS), Catalogs and Atlases, Volume 1, Explanatory Supplement, *NASA Scientific and Technical Information Division NASA RP-1190*, Washington, D.C., U.S.A., 1988.

9. Dow, K.L., *Earth orbiting objects observed by the Infrared Astronomical Satellite*, Master thesis submitted to the Department of Astronomy of the University of Arizona, U.S.A., 1992.

10. Wesselius, P.R., Hees, R.M. van, Jonge, A.R.W. de, Roelfsema, P.R., Viersen, B., Advances in Space Research, Edt. by Flury, W., Pergamon Press, Oxford, UK, 1993.