DETECTION AND SIMULATION OF DEBRIS CLOUD IMPACTS

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ABSTRACT

The observations of clustered impacts on the geostationary orbit impact detector GORID are supposed to be caused by space debris cloud particles. In order to confirm this assumption, extensive investigations of the respective particle sources including the development and application of the DIADEM software were initiated. A brief description of the modelling approach is given. The results of DIADEM simulations of both GORID cluster detections on GEO and SPADUS cloud detections on LEO are discussed. It is shown that such impact clusters can be assigned to debris clouds created by SRM (solid rocket motor) firings. However, in case of GORID, many more clusters were measured. Consequently, additional sources for debris clouds must exist at least in the GEO region.

1. INTRODUCTION

A large number of clustered impact events were recorded on the geostationary impact detector GORID (Drolshagen, 2001), but also the LEO orbiting SPADUS instrument experienced several impact streams (Tuzzolino, 2001). Fig. 1 shows the number of so called "class 3" events (which are supposed to be real impacts) per 12 hours measured by GORID. The large data gap in October/November is related to the spacecraft movement to another position in GEO.

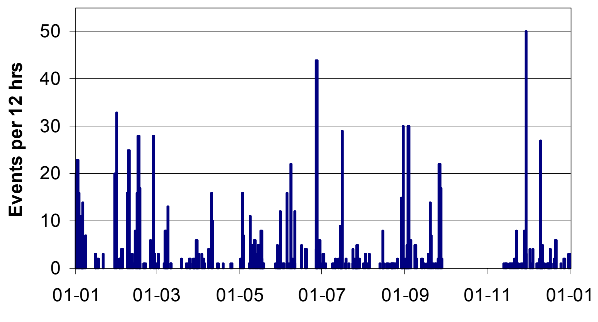

Figure 1. GORID class 3 events in year 2000 (Drolshagen, 2001)

Amongst the impact events approximately 74 % can be assigned to so called event clusters (Green, 2004). An impact event is supposed to belong to a cluster of events, if the time span between two subsequent events is less than 0.05 days (corresponding to 1.2 hours).
In order to find explanations for this class of particle impacts, a simulation tool called DIADEM was developed (Bunte, 2000, 2001, 2003), which incorporates models of the debris and meteoroid background environment and of so called debris clouds generated by spacecraft fragmentations or solid rocket motor (SRM) firings. The DIADEM debris population is based on MASTER 2001 (Bendisch, 2002), while the meteoroid background flux is calculated by an implementation of the Divine-Staubach model (Staubach, 1996).

2. DEBRIS CLOUD IMPACT SIMULATION

2.1. Cloud Detectability

A debris cloud is considered to be detectable if the cloud flux contribution at a certain point in space exceeds the debris and meteoroid background flux. This implies that the spatial density of the cloud has to be larger than that of the background populations, which in turn requires a very large number of cloud particles. In section 3 it is shown, that this is the main condition for the detectability of a debris cloud.
In addition, major conditions for the detection of debris clouds are the orbit and the viewing characteristics of the detector in relation to the particle orbits of the dense cloud. Investigations have shown, that slight changes in the target orbit and in the detector orientation may cause completely different flux signatures, or even inhibit the detection of the cloud particles.
It is obvious that the detectability of debris clouds is decreasing – often rapidly – with time, since the dispersion of the cloud due to different orbital elements and the respective orbit perturbations leads to a decrease of the cloud's spatial density. Moreover, in most cases the very small cloud particles – which are most important for the detectability due to their large number – are reentering the Earth's atmosphere shortly after the cloud generation event.

2.2. DIADEM

The flux contributions of the particle clouds and of the background debris and meteoroid populations is calculated with the DIADEM tool, which has been described in earlier publications (Bunte, 2000, 2001, 2003). The basic mathematical approach (Divine, 1993 and Kessler, 1996) has been extended to account for the highly asymmetric spatial distribution of the cloud particles. The temporal changes of the cloud particle spatial distribution is already considered by the cloud generation process, and are consequently considered in the flux

Proceedings of the Fourth European Conference on Space Debris, Darmstadt, Germany, 18-20 April 2005
(ESA SP-587, August 2005)

analysis when using the DIADEM time loop. Since the cloud particle propagation within POEM considers the rotation of the nodal line and of the apsidal line, this must be also considered in the target orbit temporal evolution in DIADEM. Simple analytical expressions have been implemented to calculate the changes in the target orbit's right ascension of the ascending node and in the target orbit's argument of perigee.

For each point along the target orbit, the flux on a spherical target is derived from (Bunte, 2000):

$$F = \frac{1}{4} \sum_{dir=1}^{4} \left[N \cdot \left(v_{imp} \right)_{dir} \right] \qquad (1)$$

where N is the spatial density at the target position, and the impact velocity v_{imp} is the difference of the particle velocity and the target velocity:

$$v_{imp} = \left| \vec{v}_{part} - \vec{v}_{tar} \right| \qquad (2)$$

The summation over four impact velocities in equation (1) and the corresponding division by four accounts for the fact that four impact directions are equally probable under the assumption of a debris population which is symmetric with respect to the Earth's equatorial plane and with respect to the Earth's rotation axis. From the four possible velocity vectors at a distinct position in space, the corresponding right ascension of ascending node, argument of perigee and true anomaly of the particle's orbit can be determined. Since the distributions of these orbital elements of the particle cloud are known, they can be used to calculate flux weighting factors to account for the asymmetries caused by these distributions of the orbital elements. In the calculation of the asymmetry factors it has to be ensured, that the distributions are probability density distributions, e.g. for the true anomaly distribution D_f:

$$\int_{0}^{2\pi} D_f \, \mathrm{d}f = 1 \, , \qquad (3)$$

and a uniform distribution of the corresponding orbital element, i.e. $D_f = const.$, which means that each true anomaly f is equally probable, yields the asymmetry factor $c_{asym} = 1$. If the latter is fulfilled for the right ascension of ascending node distribution, the argument of perigee distribution, and the true anomaly distribution, this corresponds to a symmetric debris population.

The validation of the software was performed by means of appropriate test cases, and is briefly described in (Bunte, 2003).

3. COMPARISON OF MEASUREMENTS AND SIMLATION RESULTS

3.1. GORID Debris Cloud Detections

A correlation of the GORID cluster events in the year 2000 with different types of SRM firings which generate clouds able to reach GEO are shown in Fig. 2. Included are all GORID class 3 events which are supposed to be members of an event cluster. The impacts are given in terms of the local solar time (LST) vs. the event date and time in UTC. (Note: the LST of the SRM firings given in Fig. 2 is not their true LST.)

The data gap in October/November 2000 is again clearly visible.

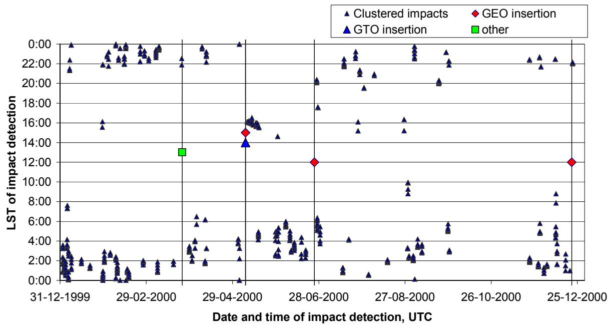

Figure 2. GORID event clusters and SRM firings in year 2000

It is remarkable that the majority of the clustered events are centred around local midnight (20:00 to 06:00), an effect which is not yet fully understood (Green, 2004). Fig. 2 shows that the GEO insertion burns in May and in June (marked by red diamonds) are followed by clustered particle impacts immediately after the respective firings, while a clear correlation of the other types of firings with cluster events can not be observed. It should be noted, that the same conclusion cannot be made for the entire GORID operational period. In some cases a detection of the GEO insertion burn cloud takes place after a gap of several days (Bunte, 2003), and in other cases no event clusters are visible. In particular, GTO insertion burns (marked by blue triangles) are not detectable in GEO, since only a small number of SRM slag particles is able to reach GEO. A correlation of event clusters with other SRM firings, which are in all cases related to high eccentric orbit insertions, could not be confirmed yet.

In order to confirm the correlation between GORID's cluster event detections and GEO insertion SRM firings, DIADEM simulations were performed (Bunte, 2003). An example of such simulation is given in the following section.

3.2. Detection of the GEO Insertion Burn of DSP F20

The DSP F20 early warning satellite was launched on a Titan 4B rocket from Cape Canaveral on 8 May 2000. It

was placed into its geostationary orbit with a Boeing Inertial Upper Stage, serial IUS-22, catalogue number 26359 (McDowell, 2000).
As Fig. 3 shows, GORID detected the SRM firing cloud on the first day after its creation.

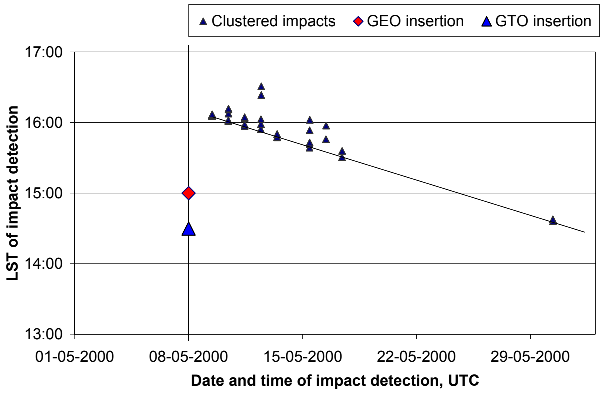

Figure 3. GORID cluster events detected after the DSP F20 GEO insertion SRM firing

An eleven days gap in the GORID operation or data collection and transmission in the second half of May inhibited the cloud impact detection during this period.
34 clustered impacts at around 16:00 LST were detected from 9 May to 17 May; 2 further impacts on 30 May at around 14:30 LST. The shift of the local detection time range of about –4.28 minutes per day is depicted in Fig. 3. It corresponds to the expected daily drift of –3.94 minutes per day on GEO plus the nodal line drift of the cloud particle orbits which is between –0.6 min/day and +0.6 min/day, since the majority of the high eccentric dust particle orbits (similar to GTO) have inclinations between 65 deg and 115 deg. The maximum in the inclination distribution at 75 deg leads to a daily drift of the nodal line of approximately –0.33 min/day.

The SRM firing cloud simulation was carried out using the MASTER 2001 POEM software and its SRM firing module for the generation and propagation of the cloud. The very large propellant mass of the IUS of 2722 kg results in a very large, long living cloud, as can be seen from Fig. 4. The cloud simulation was performed over a period of 1 year.

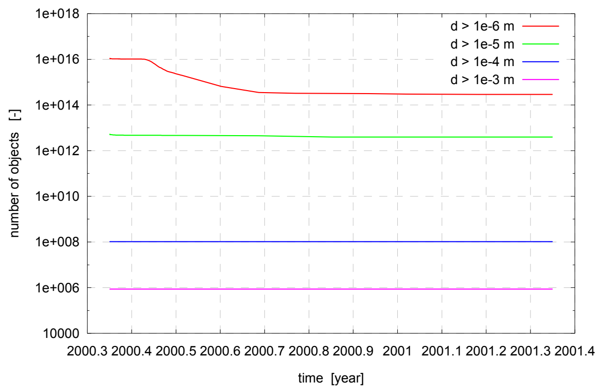

Figure 4. 26359 SRM firing, number of objects vs. time for different diameter thresholds

It can be seen that even very small particles with diameters of a few µm stay in orbit for more than one year. Due to the characteristics of SRM firings the majority of the small Al_2O_3 dust particles have high eccentric orbits while the larger slag particles which are exhausted in the final phase of the burn have orbits similar to the final orbit of the parent spacecraft, i.e. close to GEO.
Fig. 5 shows a typical impact geometry for a dust particle on a high inclined high eccentric orbit. Since GORID is tilted against the equatorial plane by 65 deg towards North, normally only particles traveling from North to South can be seen by the detector. Consequently only those GEO insertion burns generate clouds visible for GORID, which are performed at the descending node of the transfer orbit (Bunte, 2003).

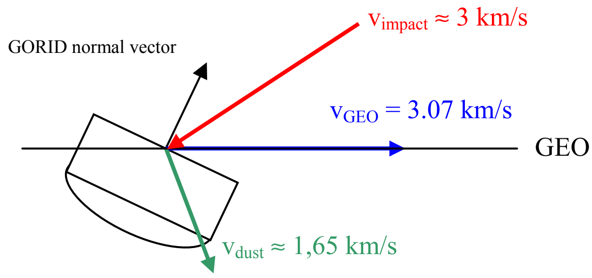

Figure 5. Impact geometry of GEO insertion burn dust particles on GORID. View from the outward radial direction.

The detector is hit with an impact velocity of about 3 km/s, and an impact azimuth angle measured from the velocity vector (clockwise positive in this graphical representation) of about –40 deg. The impact angle measured from the GORID normal vector is about 30 deg.

The results of the DIADEM simulation are shown in Fig. 6 by means of the 3-dimensional flux vs. analysis epoch and impact right ascension diagram.

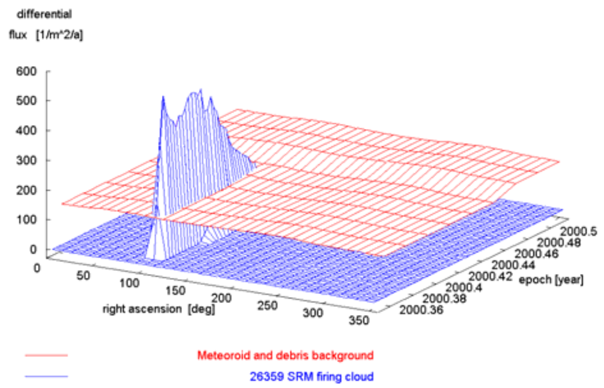

Figure 6. DIADEM simulation of the 26359 SRM firing cloud flux and of the background flux; width of right ascension bins: 10 deg

The cloud flux is well above the background flux for the first month after the firing. During this period the cloud should be detectable. This result of the simulation corresponds to the GORID measurements. In this case there is nearly no delay between the firing and the occurrence of the event clusters, which is confirmed by the simulation.

The cloud flux right ascension of about 105 deg corresponds perfectly to the LST of the cluster impacts (see Fig. 3). The impact velocity and impact angle distributions also match the expected values. The number of clustered impacts detected by GORID (2 ... 8 impacts per day, average: 3.8 impacts per day) also matches the DIADEM simulation result of an average of 3.6 impacts per day on GORID.

The excellent correspondence of the simulation results and the GORID measurements underlines the validity of the DIADEM cloud model.

3.3. Additional Debris Cloud Sources in GEO

Although the simulations confirm that clustered impacting particles can be members of the SRM Al_2O_3 dust clouds of GEO insertion SRM firings, a large number of clustered impacts were detected which cannot be assigned to specific SRM firings. Consequently, other sources of GEO or near-GEO particle clouds must exist.

There is evidence for the existence of clouds of uncatalogued objects in the size range of 0.1 m and larger on near-geostationary orbits but also on GTOs and unexpected elliptical orbits (Schildknecht, 2001 and 2004). It must be assumed that also clouds of smaller particles exist in the GEO region. It is anticipated that the cloud generation process applies only relatively small additional velocities. Consequently, dense clouds are created which stay together for a very long time. A different explanation was given by (Graps, 2004): charge-induced break-ups of SRM slag particles would also result in clouds of small objects with similar characteristics, e.g. area-to-mass ratios.

In order to get an impression of the behaviour of such cloud populations in the GEO regime, first investigations were conducted at ESTEC (van der Sommen, 2004). Arbitrary debris clouds were generated in GEO with zero additional velocity. The size range of 50 µm to 1 cm yields different area-to-mass ratios of the created aluminium spheres. The cloud particle orbits propagation shows that the major perturbing effect is the solar radiation pressure which leads to large eccentricity variations with a period of approximately one year. The amplitude of the variation depends on the object's area-to-mass ratio and can even result in the decay or the escape of the particle. An investigation of the detectability of such particle clouds was performed. The findings of the analysis can be summarised as follows:

- The impact geometry allows detection by GORID, if the particles are travelling from North to South, i.e. at the descending node of their orbit.
- The impact velocities are well below 1 km/s.

Future activities to confirm that GORID was able to detect particle clouds which originate from cloud release in GEO will be

- impact tests on a GORID mock-up with medium sized particles (e.g. 100 µm to 1 mm) and low impact velocities of some hundreds of m/s to verify that the detector is able to generate a signal,
- DIADEM simulations of arbitrary debris clouds to assess the required number of clouds and/or particles to explain the numerous cluster detections of GORID.

3.4. SPADUS Cloud Detection in March/April 2000

In March and April 2000, the SPADUS instrument onboard the Argos spacecraft was hit by an unusually large number of small particles. Two events are supposed to be the origin of the cloud detection: the break-up of a Chinese rocket body or the SRM firing related to the IMAGE satellite orbit insertion (Tuzzolino, 2000), (Neish, 2003).

The characteristics of the cloud detection are given in the following list:

- 45 impacts in the period from 26-03-2000 to 23-04-2000
- impact right ascension: 10 deg ... 30 deg and 190 deg ... 225 deg
- impact declination: ± 60 deg … ± 80 deg
- South/North ratio of the number of impacts: 4.6

There is a 2 weeks gap between the Long March rocket body (satellite number 25942) break-up on 11-03-2000 and the detection of the cloud.

The IMAGE satellite was launched into a highly eccentric polar orbit by an SRM (object 26115) firing on 25 March 2000.

Both the fragmentation of object 25942 and the 26115 SRM firing were simulated using POEM 2001. The upper stage break-up simulation yields about 10^{10} objects in the size range of some microns and larger. However, within hours after the event only about 4×10^8 particles greater than some 10 microns remain in orbit. The SRM firing simulation results in a cloud of about 10^{14} objects and relatively slow decrease of the number of particles in orbit. Nearly all particles smaller than 100 µm are decayed after 5 months.

Fig. 7 represents the results of a DIADEM analysis of the fragmentation cloud flux on SPADUS.

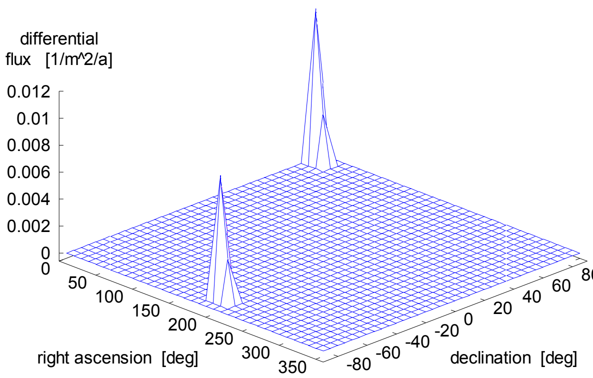

Figure 7. DIADEM simulation of the 25942 break-up cloud flux on SPADUS

The cloud flux occurs exactly at the positions where the SPADUS instrument detected the impacts belonging to "stream #3". However, the background flux is not considered in Fig. 7, since it is by orders of magnitude larger than the fragmentation cloud flux. A different picture is obtained in case of the DIADEM simulation of the SRM firing cloud. Fig. 8 includes both the debris and meteoroid background flux (red) and the cloud flux (blue) on SPADUS.

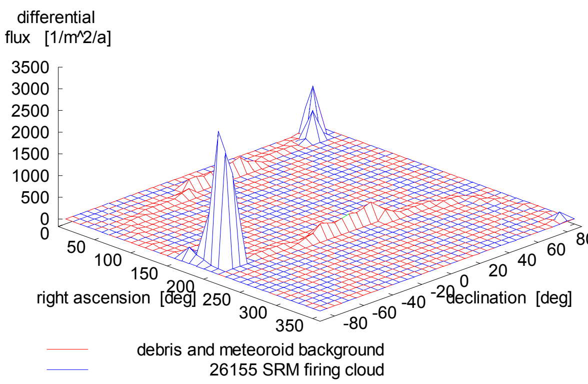

Figure 8. DIADEM simulation of the 26155 SRM firing cloud flux and the background flux on SPADUS

Again the positions of the cloud flux exactly match the measurements. In case of the SRM firing cloud the South/North ratio is greater than 1 as observed by SPADUS, while it is less than 1 in case of the fragmentation cloud simulation. In addition, the fact that the SRM firing cloud flux is much larger than the background flux, indicates that the firing cloud was detected by the SPADUS instrument.

Fig. 9 compares the flux contributions of both clouds as a function of time.

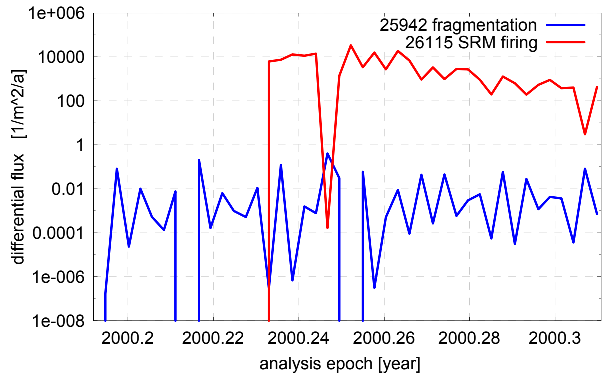

Figure 9. Cloud flux vs. analysis epoch, particle diameter > 3 µm

All particles greater than 3 µm in diameter are considered here. The simulation covers the period from 10 March 2000 to 25 April 2000. It is clearly visible that the average fragmentation cloud flux is below the average firing cloud flux by approximately 7 orders of magnitude. In addition, there is no explanation for the two weeks gap between the break-up and the SPADUS detection, since the fragmentation cloud flux on SPADUS is rather constant over the entire simulation period. Consequently, the conclusion of the DIADEM analysis is that SPADUS has detected the SRM firing cloud which confirms the findings of (Neish, 2003).

A quantitative evaluation of the simulation yields the following results:

- The positions of the impacts in terms of right ascension and declination are reflected by the simulation.
- The South/North ratio determined on the basis of the DIADEM results is 4.5 and thus perfectly renders the measured ratio.
- A number of 26 impacts in the period from 26-03 to 23-04-2000 is derived from the simulation which is only 58 % of the detected impacts. However, this has to be regarded as a very good result, since on one hand the simulation is quite sensitive to small variations of the target orbital elements, and on the other hand it must be anticipated that the POEM cloud simulation does not perfectly match reality.

4. CONCLUSIONS

It is shown, that cloud flux simulations with the DIADEM software, which relies on the MASTER 2001 debris population, could very well explain cloud detection phenomena. DIADEM proved to be a valuable tool also for quantitative evaluations of cloud flux contributions both in GEO and in LEO.

The analysis of the cluster events detected by GORID shows that there is evidence for the existence of currently unknown cloud generation mechanisms in GEO. Additional impact detectors on GEO could improve the knowledge about the GEO particulate environment significantly.

ACKNOWLEDGEMENTS

The work described in this paper was conducted under ESA/ESTEC contract 16272/01/NL/EC "Processing, Analysis and Interpretation of Data from Impact Detectors". All contributions from ESTEC and the study team as well as the support of ESOC are gratefully acknowledged.

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