COMPUTATION OF DESTRUCTIVE SATELLITE RE-ENTRIES

B. Fritsche, G. Koppenwallner

HTG Hyperschall-Technologie Göttingen, Max-Planck-Str. 19, 37191 Katlenburg-Lindau, Germany
HTG-mail@t-online.de

ABSTRACT

The software system SCARAB ('Spacecraft Atmospheric Re-entry and Aerothermal Break-up') is designed to calculate the destruction of spacecraft during their re-entry flight through the Earth atmosphere. This software has a modular structure, combining flight dynamics, aerothermodynamics, thermal analysis, and structural analysis. The software has been applied to several test cases. Some results could be verified with in-flight measurements, other results were compared with other existing re-entry prediction tools. Now we are working on re-entry survivability studies for satellites at their end of mission. Currently there are several satellites of interest in orbit which will make an uncontrolled re-entry during the next few years. For satellites without controlability the SCARAB S/W computes the satellite destruction history and the ground impact risk. For 'controlled re-entries' (uncontrolled re-entry after a de-orbit boost) the computations can give recommendations for the choice of suitable entry conditions. The present paper presents results of current studies.

1. INTRODUCTION

Earth-orbiting space objects which were not designed to survive a re-entry into the atmosphere, usually burn up during re-entry, but very heavy or compact ones or parts thereof may survive and reach ground. If it is known that parts of a spacecraft will survive the re-entry, then the object should be de-orbited with a controlled maneuvre, if this is possible. A recent example is the Compton Gamma Ray Observatory (CGRO), with a mass of about 17 tons, which was de-orbited over the Northern Pacific Ocean. A very acute case is the Russian space station Mir, with a mass of more then 130 tons. Another class of spacecraft comprises objects which are going to re-enter in an uncontrolled manner during the next several years. Figure 1 shows the orbital height of some of these satellites during the last two years. The shown cases are: Abrixas, a X-ray satellite, moving uncontrolled since its malfunctioning shortly after launch in April 1999; Sax, another X-ray satellite; Rosat, also a X-ray satellite, moving uncontrolled since its end of mission in February 1999; Tubsat-N, a small 'nano'satellite with communication functions; and Champ, which explores the gravitational and magnetic field of the Earth. All these satellites will re-enter the Earth atmosphere uncontrolled. The Tubsat satellite will burn-up completely. This is also probable for Abrixas and Champ, with their masses about 500 kg, but a more refined analysis is certainly required for Sax and Rosat, with masses of more than 1 ton.

2. THE SCARAB SOFTWARE SYSTEM

The SCARAB S/W system [1–4] consists of several modules:

- a system manager with a menu-driven user interface,
- a geometry module for the construction of a spacecraft from elements and for the generation of surface panels,
- a model definition module for the specification of model-dependent parameters (e.g. mass properties, reference quantities),
- a material data module containing material data tables,
- four re-entry analysis modules (see below),
- a visualisation tool for animated view of the re-entry history.

2.1. Flight dynamic analysis

The flight dynamics module of the SCARAB system analyses the motion of a spacecraft during its entry into the Earth's atmosphere. The analysis starts with user-defined initial conditions (state vector, atmospheric environment, etc.), and computes the position and the attitude of the spacecraft as function of time. The current flight dynamic state is forwarded to the other SCARAB analysis modules. During entry, the thermal or the structural analysis module are able to detect a spacecraft disintegration event, causing the original S/C to break-up into smaller parts. In this case the flight dynamic analysis has to be terminated and, after generation of new models for the S/C parts, to be restarted for each of the fragments separately. The flight dynamic computation will stop again, if the traced fragment itself disintegrates, or if it is destroyed by heating, or if the fragment hits ground.

The final motion of the fragments is computed on a probabilistic basis with 3 degrees of freedom. The trajectories are computed starting with the last point computed with the full simulation. The geometry is projected onto its principal axis of inertia. From these projected areas an effective body shape is determined to get the aerodynamic coefficients as function of Mach number and angle of attack. The ground dispersion is examined by computing trajectories for the most probable and the most unfavourable set of coefficients. As result of the calculations one gets a number of trajectories and corresponding impact points, with the dispersion ellipse forming their envelope. Using this information the on-ground casualty risk can be computed.

2.2. Aerothermodynamic analysis

The aerothermodynamic analysis module of the SCARAB system computes the aerodynamic forces and moments acting on a spacecraft during re-entry. It also computes the heat transfer due to convective heating by the ambient atmosphere. The forces and moments are used by the flight dynamics analysis to determine trajectory and attitude history, and by the structural analysis to compute the mechanical loads on the spacecraft structure. The convective heat transfer is used by the thermal analysis to determine the thermal loads and the thermal response of the spacecraft.

2.3. Thermal analysis

The thermal analysis module of the SCARAB system analyses the thermal response of a spacecraft to external heat input. It computes the internal heat flow from the current temperature distribution, and it computes the temperature changes resulting from the balance of all external and internal heat flux terms. Considered are heat transfer by aerodynamic heating, thermal conduction and radiative heat exchange (including back radiation to the free stream). The thermal analysis also treats the phase change of the spacecraft material by melting, and it detects local failures of the spacecraft assembly and issues a destruction event message to the system, if such failure occurs.

2.4. Structural analysis

The structural analysis module of the SCARAB system analyses the structural response of a spacecraft to mechanical loads. These loads are due to aerodynamic and inertial forces and moments. The structural analysis computes the deformation of the spacecraft structure under these loads. It detects local destruction of the spacecraft walls and global destruction by breaking into parts. Since the strength of the spacecraft material depends on its temperature, there exists a strong coupling between structural and thermal analysis.

3. RESULTS OF CURRENT STUDIES

3.1. Space Station Mir

The Russian space station Mir has been in orbit now for 15 years. It's now just the time that the station will be de-orbited[1]. With our SCARAB system it is possible to perform a re-entry calculation of Mir. Unfortunately we could not get enough detailed data on the geometry and other properties of the station, like mass, moments of inertia, materials, etc. Therefore we could only do a very simplified re-entry analysis of something that looks similar to the Mir station. Figure 2 shows our geometric model of the Mir. It takes into account all major parts of the station: the modules Mir, Kvant, Kvant-2, Spektr, Piroda, Kristall, and the Progress spacecraft; also the solar panels, and some antennas. So far we are near reality. Now, for a flight dynamic analysis we need the mass distribution in the station. But we have only the total mass (approximately). To have something more, it was assumed that the mass distribution is uniform, i.e. the walls are of constant thickness for all parts. The value for this thickness was adjusted to get the right total mass for the material selected (aluminum). To start a calculation, the initial state vector is required. Relying on NASA information distributed via Internet (March 16) the following initial orbit data were used:
Epoch: 03/22/01 05:48:31 GMT, apogee x perigee = 209.7 x 82.6 km, inclination: 51.66 deg, arg. of perigee: 239.7 deg. These data set corresponds to the conditions after the final of three de-orbit burns, the first starting at an altitude of approx. 218 km, about 5 hours before.

The first calculation carried out with the above mentioned parameters did not yield meaningful results. The assumption that the total mass is distributed in equally-thick walls yields too high heat capacities of the walls, thus preventing them from reaching the melting temperature at a reasonable flight altitude. Therefore the model was re-defined, shifting the mass from the solar arrays (containing about half of the total mass when all walls have the same thickness) to the remaining parts, arriving at a thickness ratio of about 1:9 instead of 1:1. Figure 3 shows the computed geometry at an altitude of 60 km. All solar arrays with the reduced thickness are molten away. Figure 4 shows the flight altitude vs. time for this case. It can be seen that the station is 'captured' by the atmosphere before reaching the perigee of its initial elliptical orbit. The flight path after the end of the 6D calculation was computed with the 3D ground dispersion analysis. The variation in the ground impact location is due to the probabilistic variation of the attitude in the 3D analysis, where the attitude is not known deterministically. It has to be noted that this variation corresponds to the ground dispersion ellipse of ONE fragment. If the fragmentation of the space station would be considered, each fragment had its own ellipse.

Figure 5 shows the angular velocity of the station dur-

[1] The de-orbit maneuvre is currently scheduled for March 22, 2001, just two days after the presentation of this paper.

ing entry. The shown time interval corresponds to flight altitudes between 60 and 85 km. The station is mainly rotating slowly, reaching 45 deg/s (8 seconds per rev.) at 60 km altitude. Since this result strongly depends on the real moments of inertia, the true motion can be different. After the de-orbiting of the Mir is done, we will carry out a more detailed post-flight analysis of the re-entry, including fragmentation of the modules.

3.2. Automated Transfer Vehicle

The Automated Transfer Vehicle (ATV) is a satellite to supply the International Space Station (ISS) with fuel, water and other consumables. It also has the task to lift the ISS to a higher orbital altitude in order to compensate the altitude loss of the station due to atmospheric drag. After delivery of its goods it shall be filled with waste from the ISS and re-enter into the Earth atmosphere in a destructive way. Its first flight is scheduled for the year 2004.

For ATV we are currently working under contract for ESA/ESTEC. As a consequence, we have very detailed information about every part of this spacecraft. This situation is completely different to the Mir case, where we have very little information. Figure 6 shows the geometric model created for ATV. It consists of about 300 geometric primitives, with almost 100000 surface panels. This huge amount of panels is partly due to the modeling of many details inside the spacecraft, like tanks and cargo carriers, not visible in Figure 6.

The initial conditions at beginning of re-entry are again conditions after a controlled de-boost manoeuvre. In fact, the desired impact area on ground is very similar to the Mir case, i.e. in the Southern Pacific. The final orbit shall be more elliptic than in the Mir case, but a more important difference is an initial spin of 10 deg/s about the pitch axis. This is done to be sure that the spacecraft is not 'bounced back' by the atmosphere due to lifting forces.

To detect break-off of the big solar arrays, the mechanical stresses in the joints between solar panels and main body are monitored. Figure 7 shows the actual and breaking stress in one of these joints. The actual stress oscillates according to the rotating motion of the spacecraft about its pitch axis. The breaking stress varies with the temperature of the joint. At 567 s after beginning of the calculation (altitude 200 km) the joint breaks. This corresponds to an altitude of 93.5 km. Actually all four joints are breaking at almost the same time. Figure 8 shows the geometry of the spacecraft body after breaking of the joints. The break-off results in the generation of 5 fragments: the body and four solar arrays. For each fragment the re-entry calculation can be continued. Figure 9 shows as example the velocity of all fragments after breaking. It can be seen that the velocity of the main body remains almost unchanged, while the solar panels are strongly decelerated. Regarding their ballistic coefficient the solar panels are moving much faster directly after separation than they would do if they re-entered as single parts from the beginning. Accordingly, they are heated very strongly. Figure 10 shows the mass history of the solar arrays after separation. They are melting within approx. 20 seconds, demising at an altitude of about 90 km.

The main body continues the re-entry, also loosing mass by melting. Due to its high mass, the relative mass loss is much smaller than for the solar panels. Therefore it seems reasonable to look for the most probable impact point of the body, assuming that either the body remains essentially intact despite the melting process, or that the fragments generated later on will follow essentially the same trajectory. Figure 11 shows the flight altitude vs. time for the original geometry, and the for main fragment after breaking of the solar arrays. The first 100 s of the latter trajectory are computed with the full 6D analysis, the last part is computed with the 3D analysis. Figure 12 shows the corresponding ground tracks.

Referring to Figure 8, the outer shell(s) of the spacecraft melt away, thus exposing the interior parts to the flow and hence to the heating. This is shown in Figure 13, where most parts of the outer shells are molten away, revealing some details of the construction parts inside the spacecraft, like tanks and cargo racks. In addition, the docking system, originally located at the top of the spacecraft has been removed by thermal fragmentation.

The complete results of the ATV re-entry analysis will be reported at the final presentation of the contract in April.

4. CONCLUSIONS

The software system SCARAB is designed to calculate the destruction of spacecraft during their re-entry flight through the Earth atmosphere. With the modeling system of SCARAB very complex spacecraft geometries can be constructed. For complex models a lot of information is required about the shape and material properties of all construction parts. The present paper has demonstated, that the SCARAB S/W is able to analyse the uncontrolled re-entry of complex spacecraft. The cases discussed are the space station Mir, the ATV spacecraft, and the Rosat satellite.

It has to be noted that SCARAB is a numerical tool. The accuracy of the analysis depends, apart from the input data and the modeling details, on the algorithms used. This is especially true for the engineering methods used for the aerothermodynamics, which were originally developed for the re-entry of simple-shaped bodies. But also additional effects not yet treated have to be taken into account, for example bursting of tanks with residual fuel, which can change the re-entry history considerably. The authors of this paper are aware of this facts, and the software is going to be upgraded continuosly.

REFERENCES

1. Fritsche B., Roberts T., Romay M., Ivanov M., Grinberg B. and Klinkrad H., *Spacecraft Disintegration During Uncontrolled Atmospheric Re-Entry;* Proc. of the Second European Conference on Space Debris, Darmstadt, Germany, ESA SP-393, pp. 581–586, 1997.

2. Fritsche B., Klinkrad H., Kashkovsky A. and Grinberg E., *Spacecraft Disintegration During Uncontrolled Atmospheric Entry;* Paper IAA-99-IAA.6.7.02, presented at the 50th IAF congress, Amsterdam, The Netherlands, 1999.

3. Fritsche B., Klinkrad H., Kashkovsky A., Grinberg E., *Aplication of SCARAB to Destructive Satellite Re-Entries;* Paper IAA-99-IAA.6.5.08, presented at the 51th IAF congress, Rio de Janeiro, Brazil, 2000.

4. Fritsche B., Koppenwallner G., Ivanov M., Kashkovsky A., Grinberg O. and Boriskin O., *Advanced Model for Spacecraft Disintegration During Atmospheric Re-Entry;* Executive Summary, ESOC Contract No. 12804/98/D/IM, Katlenburg-Lindau, Germany, 2000.

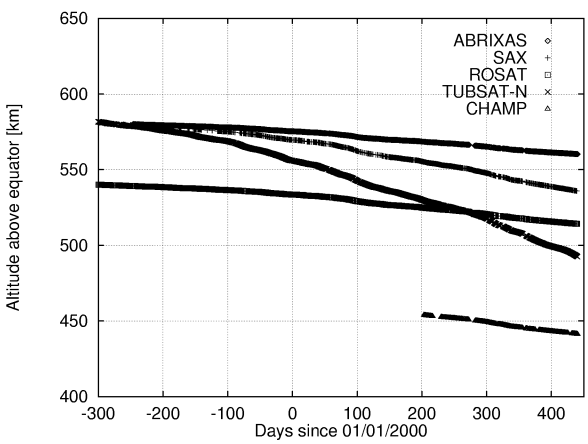

Figure 1. Orbital altitudes of some satellites entering the Earth atmosphere during the next decade (derived from NASA TLEs)

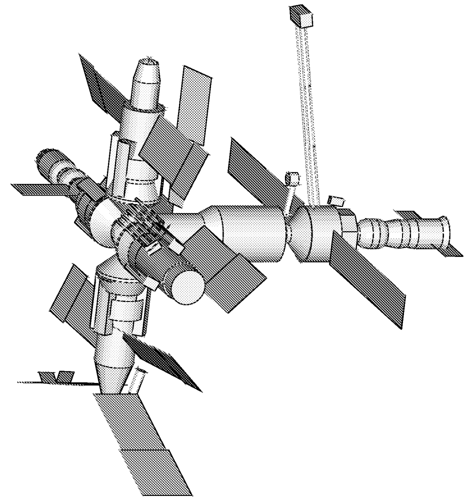

Figure 2. SCARAB model of the Mir space station

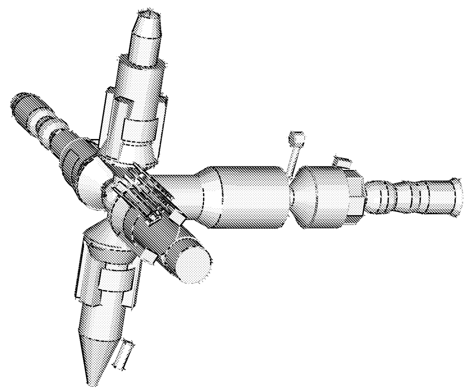

Figure 3. Mir space station during re-entry after loosing its solar arrays by melting

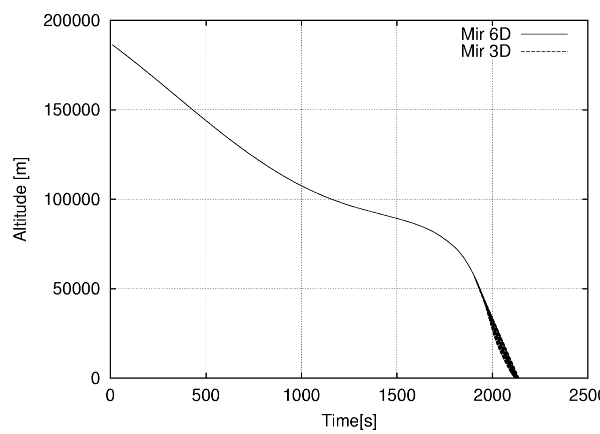

Figure 4. Flight altitude vs. time during Mir re-entry

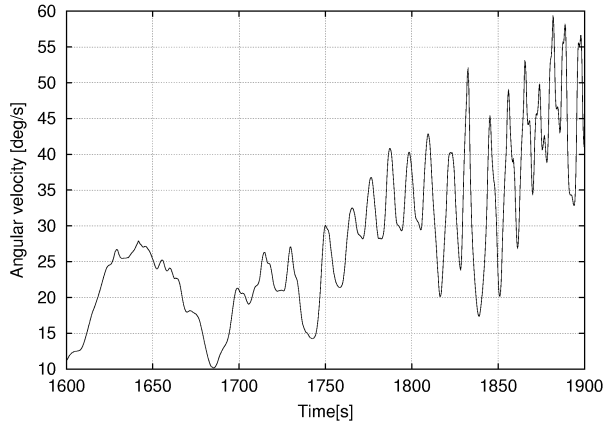

Figure 5. Angular velocity during Mir re-entry

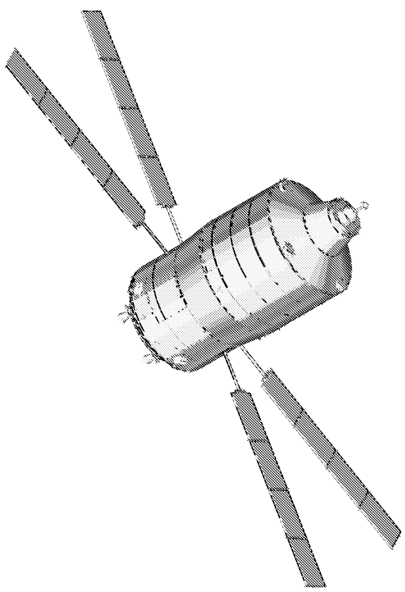

Figure 6. SCARAB model of the complete ATV

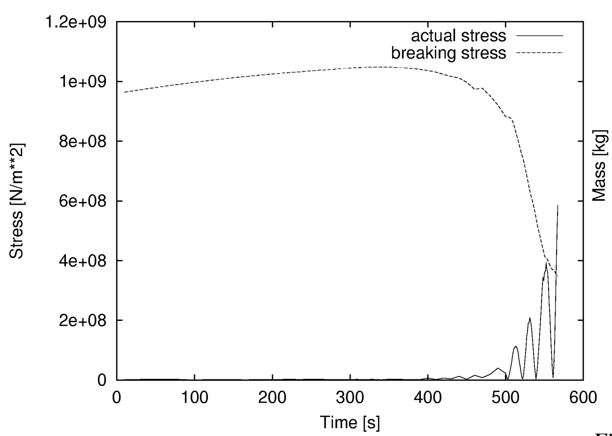

Figure 7. Actual and maximum stress in one of the joints connecting the solar panels with the satellite body

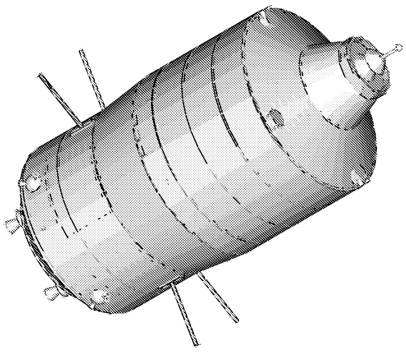

Figure 8. ATV geometry after breaking of the solar panels

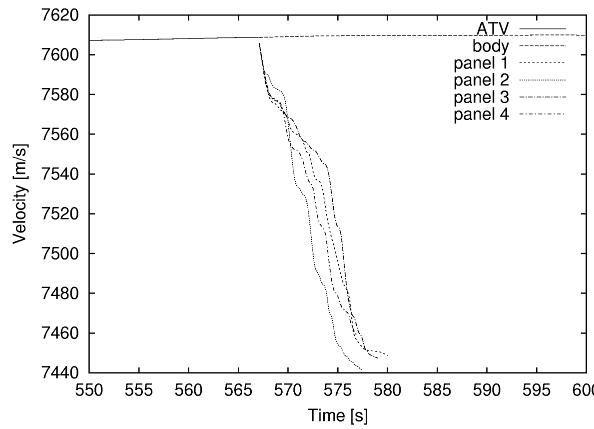

Figure 9. Velocity history of the fragments after break-off of the solar panels

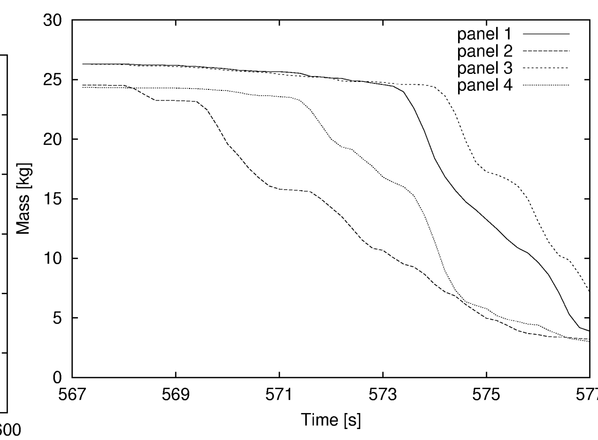

Figure 10. Mass history of the solar panels after separation from the satellite body

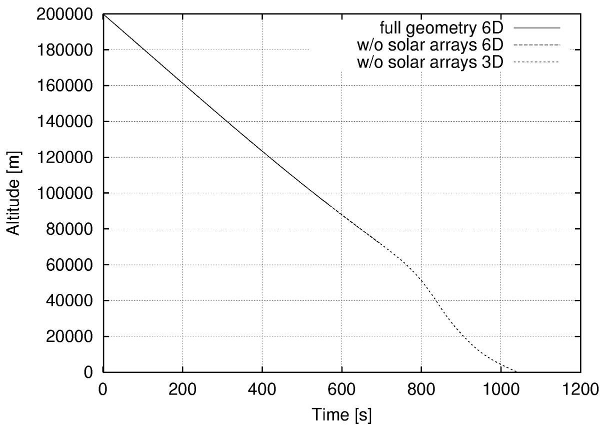

Figure 11. Flight altitude vs. time before and after breaking of the solar arrays

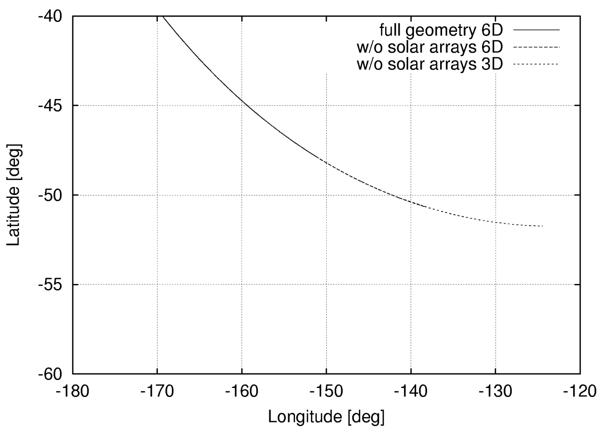

Figure 12. Ground track before and after breaking of the solar panels

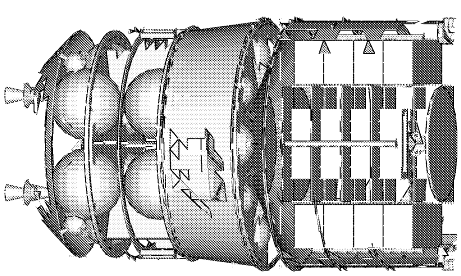

Figure 13. ATV geometry after melting of large parts of the outer shell structure