Detecting, Tracking and Imaging Space Debris

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Among the more than 8700 objects larger than 10 cm in Earth orbits, only about 6% are operational satellites and the remainder is space debris. Europe currently has no operational space surveillance system, but a powerful radar facility for the detection and tracking of space debris and the imaging of space objects is available in the form of the 34 m dish radar at the Research Establishment for Applied Science (FGAN) at Wachtberg near Bonn, in Germany.

In this article, the current space-debris environment surrounding the Earth is briefly presented and the hazard that it and meteoroids represent is discussed. The more than ten years of successful cooperation between FGAN and ESA's European Space Operations Centre (ESOC) in the field of space-debris research is also summarised.

Earth's space-debris environment

Today's man-made space-debris environment has been created by the space activities that have taken place since Sputnik's launch in 1957. There have been more than 4000 rocket launches since then, as well as many other related debris-generating occurrences such as more than 150 in-orbit fragmentation events.

Currently, there are more than 8700 objects larger than 10–30 cm in Low Earth Orbit (LEO) and larger than 1 m in Geostationary Orbit (GEO) registered in the US Space Command Satellite Catalogue. US Space Command tracks these objects with radars and optical telescopes to determine their orbits and other characteristic parameters, including their sizes (Fig. 1). Approximately 6% are operational spacecraft, 21% are old spacecraft, 17% are rocket upper stages, 13% are mission-related debris, and 43% are fragments from (mostly) explosions or collisions. Consequently, about 94% of the catalogued objects no longer serve any useful purpose and are collectively referred to as 'space debris'. In addition, there are a large number of smaller objects that are not routinely tracked, with estimates for the number of objects larger than 1 cm ranging from 100 000 to 200 000.

The sources of this debris are normal launch operations (Fig. 2), certain operations in space, fragmentations as a result of explosions and collisions in space, firings of satellite solid-rocket motors, material ageing effects, and leaking thermal-control systems. Solid-rocket motors use aluminium as a catalyst (about 15% by mass) and when burning they emit aluminium-oxide particles typically 1 to 10 microns in size. In addition, centimetre-sized objects are formed by metallic aluminium melts, called 'slag'. They typically amount to 1% of the propellant mass and leave the motor with low velocities at the end of the burn. There is evidence from ground-based radar measurements that 16 of a total of 31 nuclear reactors used by Russian RORSATs (Radar Ocean Reconnaissance Satellites) have lost their sodium-potassium (NaK) coolant, following their reorbiting and subsequent core ejection in disposal orbits at between 700 and 950 km altitude. The size of the NaK droplets observed ranges from 6 mm to 4.5 cm. The NaK population is assumed to consist of about 60 000 objects, with a total mass of about 50 kg.

It is unclear how severe the space-debris situation will be in future years, because this depends on the scale of future space activities, the degree to which debris generation is controlled, and the effectiveness of any mitigation measures adopted. This problem can be analysed with a space-debris environmental model like ESA's MASTER (see below), which describes the spatial distribution and particulate flux as a function of its size and location in space. These mathematical models have to be validated with measurement data.

Europe still has only very limited capabilities for the detection and tracking of ‘uncooperative’ space objects. As a general rule, radars are primarily used for the characterisation of the space-debris population in LEO, whereas optical telescopes are used for more distant orbital regions such as the geostationary ring (GEO). One high-performance radar facility in Europe able to probe the Earth’s space-debris environment and track and even image space objects is the FGAN Tracking and Imaging Radar (TIRA) system. Because of its unique capabilities, it is used for civil protection (orbit determination and imaging of re-entering risk objects) and to a limited extent for externally funded research-oriented studies, as well as defence-related activities. FGAN therefore cooperates with institutes in Germany and abroad, as well as with national and international organisations such as DLR, ESA, NASA and NASDA.

With beam-park experiments with TIRA alone, or jointly with the Max-Planck-Institute of Radio Astronomy’s 100 m telescope at Effelsberg in Germany (bi-static mode), snapshots typically of 24 hours duration can be taken of the current space-debris population to provide statistical information and rough orbit parameters for objects as small as 1 cm at altitudes up to 1000 km. In several such experiments, uncatalogued centimetre-sized debris could be detected, and in some cases the possible sources identified, such as the droplets generated by RORSAT reactor cores and debris from a Pegasus upper-stage explosion. Ground-based radars are therefore important tools for validating space-debris models.

The hazards posed by space debris and meteoroids

The major concern with debris is that it might hit an operational spacecraft or a larger object such as the International Space Station, with a whole variety of detrimental consequences. The average collision velocity in LEO is greater than in the much higher circular (GEO) orbits and typically ranges between 8 and 12 km/s. In a LEO collision between an operational spacecraft and a catalogued object, it is likely that both would be destroyed and hence many more space-debris fragments would be generated. If these fragments were large enough, they too could generate additional debris through further collisions.

Up to now only one operational spacecraft, the French Cerise reconnaissance satellite, has been hit by another catalogued object, being struck in 1996 by a fragment from the third stage of an Ariane launcher that had exploded ten years earlier. Evidence of the degrading nature of the space environment, however, is provided by the increasing numbers of close encounters in space. Several times per week, the flight path of ESA’s ERS-2 Earth-observation satellite is carefully examined for potential close encounters or collisions with catalogued objects. If the chance of a collision exceeds a certain tolerance, a collision-avoidance manoeuvre is carried out. ESA performed two such evasive manoeuvres with the ERS-1 spacecraft in June 1997 and March 1998. The most recent collision-avoidance manoeuvre, with the International Space Station (ISS), took place on 15 December 2001, when Space Shuttle ‘Endeavour’ increased the Station’s altitude by 1 km to avoid a collision with a Russian SL-8 upper stage launched in 1971.

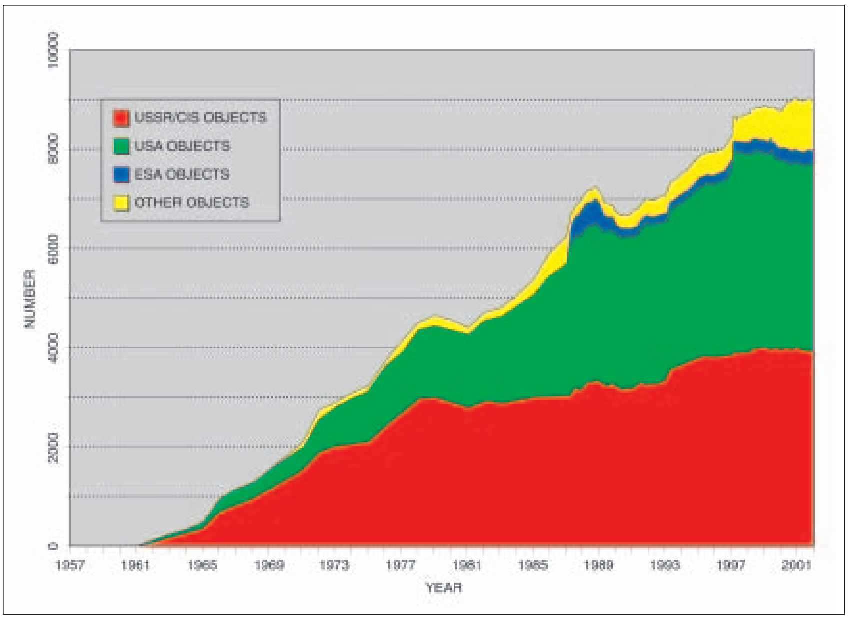


Figure 1. History of catalogued objects in orbit

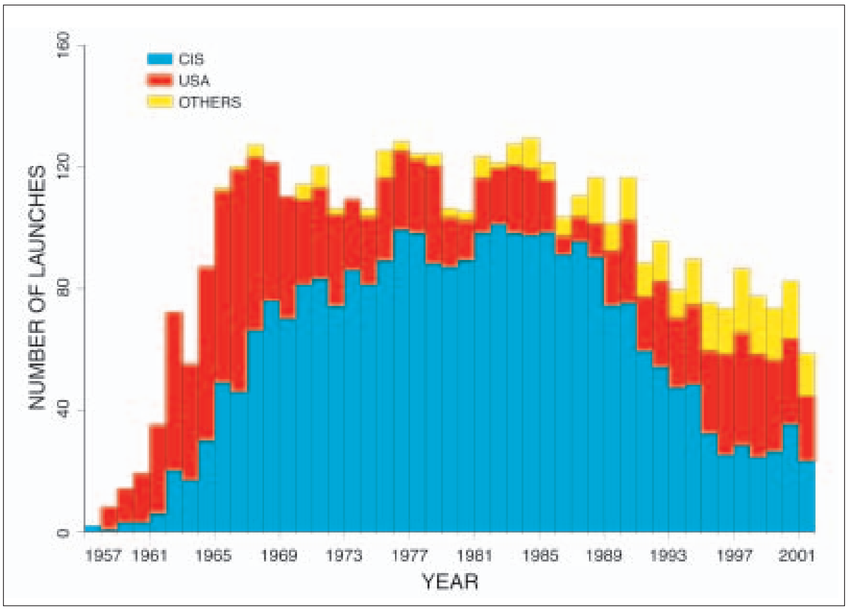


Figure 2. History of successful rocket launches

The natural meteoroid environment does not pose a serious hazard to most spacecraft in Earth orbit. Exceptions are meteor streams with high Earth-approach speeds such as the Leonids, which were traveling at 71 km/s, which may necessitate special safety measures for operational spacecraft.

The FGAN system

The main subsystems of the FGAN Tracking and Imaging Radar (TIRA) are: a 34-m parabolic antenna (Fig. 3), a narrow-band mono-pulse L-band tracking radar, and a high-resolution Ku-band imaging radar. The sophisticated, fully computer-controlled, 34-m parabolic Cassegrain-feed antenna is mounted on an elevation-over-azimuth pedestal. It is shielded from atmospheric influences by a rigid 49 m-diameter radome.

The L-band radar is used primarily for the detection and tracking of space objects. Using a double-Klystron power stage, it generates high-frequency pulses of typically 1 to 2 MW peak power and 1 ms pulse length. The signal-processing concept supports target tracking in angular direction as well as in range and range rate. In this operating mode, up to 30 statistically independent observation vectors per second are measured with the tracking filter. The main components of an observation vector are: time, azimuth and elevation angles, range, range rate, echo amplitude and phase, and the transmitted peak power.

The Ku-band radar's main application is in the imaging of space objects, being operated simultaneously with the tracking radar on the same target. Typically, linear frequency-modulated radar pulses of 13 kW peak power, 256 microsec pulse length and 800 MHz bandwidth are generated by a travelling wave tube. The signal processing is based on the de-ramp principle, and the matched-filter operation is realised by fast Fourier transformation in a post-processing mode. Up to 400 range profiles per second are acquired with 25 cm resolution (Hamming window applied) in imaging mode.

The main space applications of TIRA are:
- searching for and tracking space objects (orbit determination)
- characterisation of the space-debris environment
- validation of space-debris models
- tracking re-entering (risk) objects
- imaging space objects (verification of operational procedures, attitude determination, emergency operations, damage and fragmentation analysis)
- radar measurements of meteoroid streams.

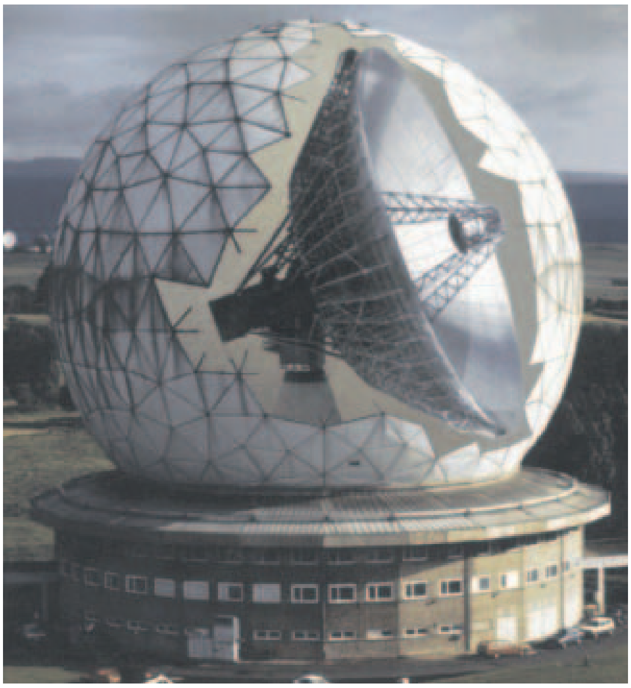


Figure 3. The TIRA facility

Searching for and tracking space objects

For space-object tracking, there is generally a priori information available, such as some orbital elements and the approximate size of the object (radar cross-section). The radar beam is pointed to a pre-determined position in space and after detection the object is tracked and observation vectors are collected, from which its orbital parameters and radar signature can be computed. The latter provides clues as to the object's intrinsic motion (rotation or tumbling rate). This mode of observation is called 'target-directed' and is used when the uncertainty in the knowledge of an object's orbit is unacceptably high and more precise information is required, for instance for collision-avoidance manoeuvres for operational spacecraft and for reentry predictions for potentially dangerous objects.

Another application is for tracking support during the launch and early operations phases of a mission, which may include confirmation of reaching the nominal orbit after launch, or searching for spacecraft and determining their actual orbits following a non-nominal launch.

Characterisation of the space-debris environment

An important tool in the characterisation of the small-size debris population are so-called 'beam-park' experiments. In this operating mode, the radar beam is maintained in a fixed direction with respect to the Earth and all objects that pass through the beam are registered. In the course of one day, the Earth's rotation scans the beam through 360 deg in inertial space. From the backscattering of the radar signal, the size of the object and some of its orbital parameters can be determined. The FGAN radar is sensitive enough to detect 2 cm-sized objects at a distance of 1000 km. This primarily statistical information on the small-size terrestrial debris population in the LEO region can be used to validate space-debris models.

Several US radars are carrying out beam-park experiments from Haystack (Mass.), Goldstone (Calif.), and Kwajalein (in the Pacific). Until recently, the Haystack radar was the only data source for objects as small as about 2 mm. Between 1990 and 1994, space debris was observed for more than 3000 hours and the results of these measurements have influenced most space-debris models.

The first European beam-park campaign was carried out in 1993. During a 10-hour experiment, the TIRA L-band radar's ability to detect small-size debris in LEO was successfully demonstrated. The first operational measurement campaign was subsequently performed on 13/14 December 1994, when the FGAN L-band radar was operated in beam-park mode for 24 hours and the Fylingdales Phased-Array Radar (UK) also participated for 24 hours. The Herstmonceux 20 cm telescope (UK) also operated for 3 hours with good weather conditions, but the Zimmerwald 50 cm telescope in Switzerland unfortunately experienced bad observation conditions. All sensors were pointed at the centre of the same observed volume.

Within the framework of ESA/ESOC study contracts with FGAN, hardware modifications were introduced in 1995/1996 to improve TIRA's sensitivity: new low-noise amplifiers (0.3 dB) were fitted to the L-band receiver's front end and directly connected to the switched limiters. On the transmitter side, two modulation decks were reconstructed in order to operate the transmitter at higher peak power levels (increased from 1 to about 2.5 MW) with reduced inter-pulse noise. These modifications roughly doubled the distance at which objects can still be detected.

With the more powerful radar in place, a third measurement campaign was performed on 25 November 1996. This time the TIRA L-band radar was operated in bistatic 'COoperative BEAM-park mode' for 24 hours. A second data-collection system was installed at the World's largest steerable, 100 m parabolic antenna, at Bad-Münstereifel Effelsberg in Germany, operated by the Max-Planck-Institute of Radio Astronomy in Bonn, and about 21 km from the TIRA system. On the same day, the Haystack radar in the USA, and during the same week the TRADEX radar on Kwajalein, were also operated. This COBEAM campaign (Fig. 5) showed that the FGAN L-band radar can indeed detect 2 cm objects at 1000 km distance. When combined with the Effelsberg radio telescope as a secondary receiver, objects as small as 0.9 cm can be detected at the same distance. Pointing the Effelsberg antenna in azimuth to 90 deg E (or 90 deg W) provides an unambiguous relationship between Doppler frequency measurements and orbital

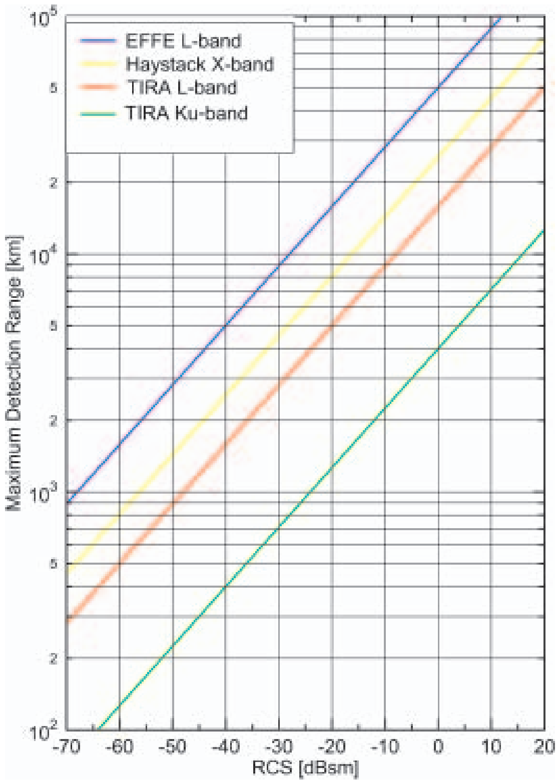


Figure 4. Range performance for bi-static radar operation with the 100 m Effelsberg radio telescope, for the FGAN L-band and Ku-band radars, and for the Haystack X-band radar. The plots are for single-pulse processing with a signal-to-noise ratio of 3 dB

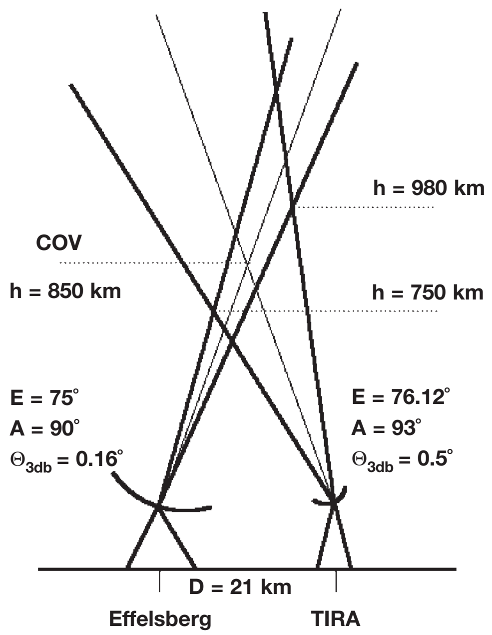


Figure 5. The 'beam-park' experiment geometry

inclination of detected targets for circular orbits. Together with the corresponding pointing angles for the two antennas, there was an altitude overlap of more than 200 km.

During the 24-hour COBEAM observation campaign, 371 objects were detected by Effelsberg and 317 by FGAN. 189 objects were seen by both sites and the total number of objects detected was 499. The many detections around 900 km altitude are most likely due to the NaK droplets from RORSATs. The increased detection rate at 600 km is probably due to debris generated by the explosion of a Pegasus hydrazine auxiliary propulsion stage five months prior to the COBEAM experiment. This explosion of the Pegasus stage illustrates the highly dynamic nature of the space-debris environment, which means the beam-park experiments must be frequently repeated to monitor the constantly changing (mainly increasing) risk of collisions as a function of the altitudes and orbital inclinations of operational satellites. Four more 24-hour experiments have therefore been conducted in the meantime, and one or two such campaigns per year are planned for the future.

Due to improved data-processing capabilities, the observation windows of the campaigns in 2000 and 2001 were extended to cover distances from 350 to 2000 km. As a result, nearly 500 objects are now detected by FGAN in 24 hours, i.e. one every three minutes. Figure 6 shows an altitude versus Doppler inclination plot for the 471 objects detected in October 2000. Only 94 of these objects appear in the US Space Command Catalogue. Various clusters such as the NaK droplets at 900 km and 65° inclination, and the Globalstar constellation at 1400 km and 55° inclination, are clearly apparent.

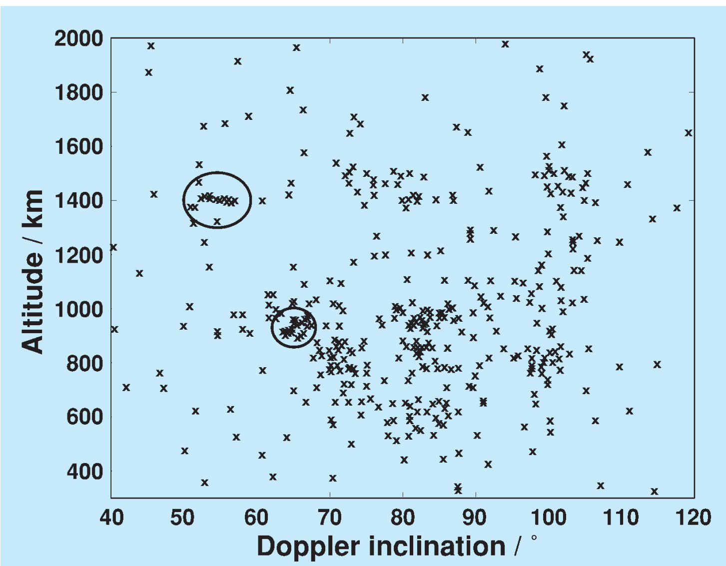


Figure 6. Altitude versus Doppler inclination for objects detected during the October 2000 beam-park experiment

The main results of these beam-park experiments, however, are the comparisons provided with the space-debris models. Every 24-hour experiment in the past confirmed that our understanding and modelling of the space-debris environment was incomplete; in some orbital regions, twice as many objects were detected as were predicted by the models. The observational data have been and will continue to be used to improve our space-debris models.

Validation of space-debris models

In order to describe the spatial distribution of the debris population that is not yet catalogued, mathematical models have been developed. ESA's reference model for space debris and meteoroids, called 'MASTER', was jointly developed with researchers at the Technical University of Braunschweig in Germany. The most recent model, MASTER 99, is based on the catalogued population, the known historical fragmentations and non-fragmentation debris. Particles as small as 1 micron are taken into account. It also contains the Divine-Grün-Schaubach meteoroid model, which provides directional fluxes.

For the construction of a meteoroid and debris reference model, several assumptions have to be made which introduce uncertainties. Most models take the cataloged population as a basis and add fragments from known breakups in the micron to 50 cm size regime to account for the incompleteness of the catalogue. For sizes larger than 50 cm, the breakup model parameters are calibrated such that the theoretical population fits the catalogued population. For the size range between 1 mm and 50 cm, however, observational data are sparse and the uncertainties in the models increase considerably with decreasing object size. However, validation of the models in the size range from a few millimetres to 50 cm can be achieved with special ground-based measurement campaigns using high-performance radar facilities like TIRA.

Tracking re-entering (risk) objects

Since Sputnik I was launched, more than 17 000 catalogued objects have reentered the Earth's atmosphere and most did burn up completely. In the case of compact and massive spacecraft, the melting and evaporation process will not be complete and fragments of the vehicle may reach the ground, as has been the case with Skylab, Kosmos-954 and Salyut-7/ Kosmos-1686. The standard procedure for large objects for which re-entering fragments constitute a safety hazard on the ground, is to carry out a controlled re-entry in an uninhabited oceanic area. Recent examples are the de-orbiting of the Russian Mir space station and of NASA's Compton gamma-ray spacecraft.

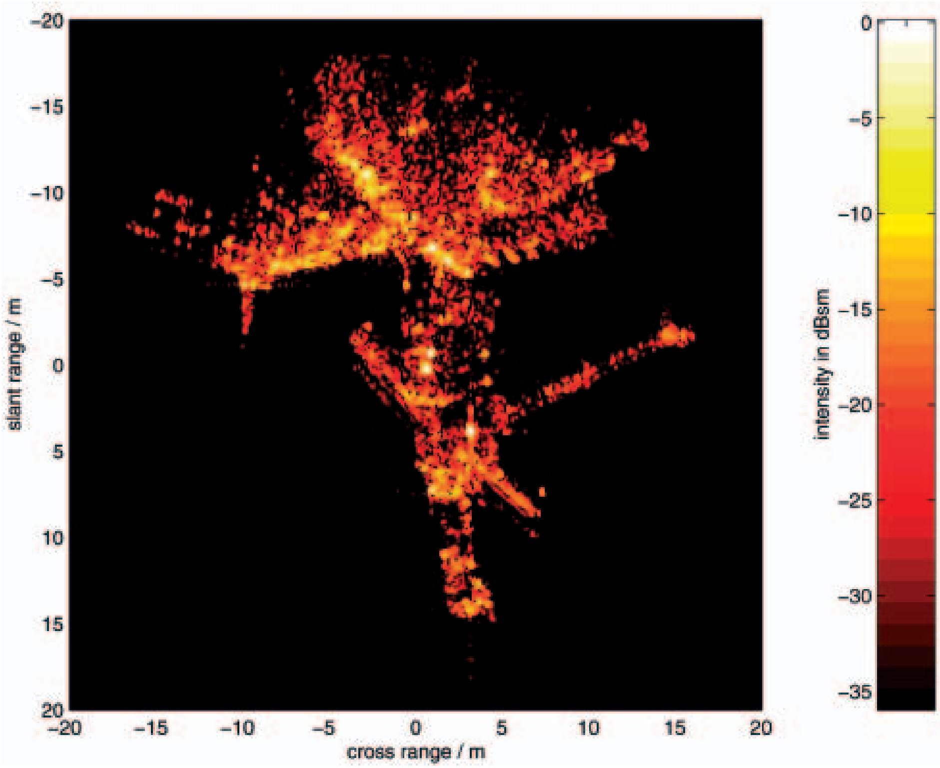


Figure 7. Radar image of the Mir space station

If a massive space vehicle becomes uncontrolled at low altitude, the task of determining the re-entry window (time and location) and the dispersion of the re-entering fragments along the ground track will be very difficult. Also in the case where the re-entering object is still controllable, but the available propellant for the de-orbit manoeuvre is very limited, the orbit-prediction task will be fraught with difficulties. The main reason is that aerodynamic forces will increasingly influence the trajectory, which cannot then be modelled with sufficient accuracy. Other factors that limit the prediction accuracy are changes in atmospheric density and the attitude of the space vehicle.

Radar tracking of re-entering risk objects is thus of paramount importance. It allows us to determine the changes in the orbit parameters and hence to calculate the re-entry window in time and along the ground-track. Recent examples of re-entering objects for which FGAN has provided this support to ESA are Salyut-7/ Kosmos-1686, Kosmos-398, China-40 and the Mir space station (Fig. 7).

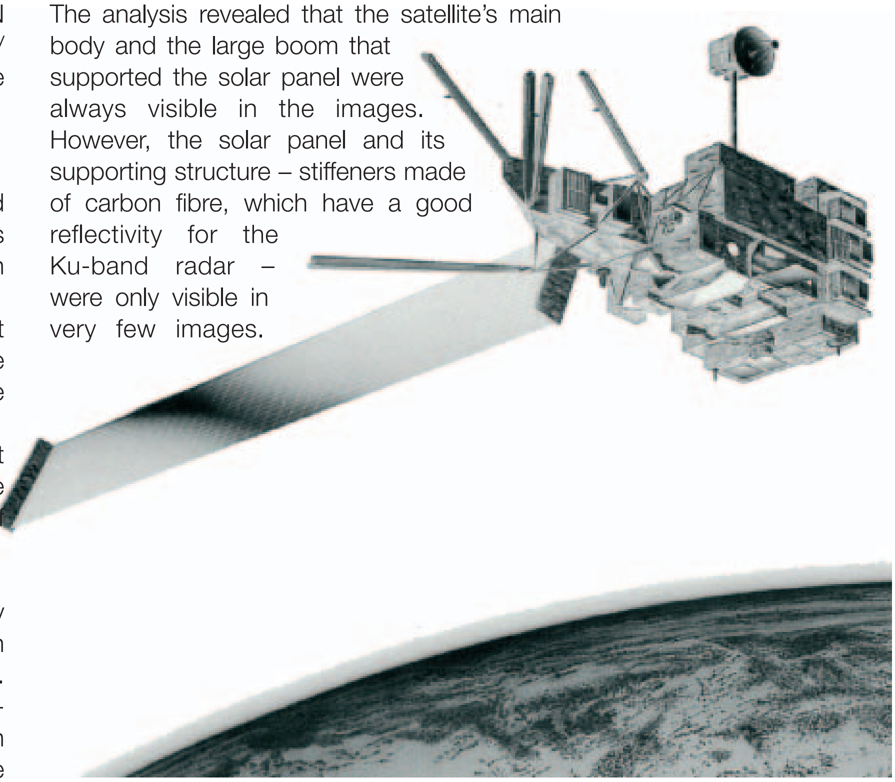
Imaging space objects

The imaging capability of the TIRA Ku-band radar is not only of relevance for space-debris research, but also for space operations in general. Its main applications are:

– in the support of Launch and Early Orbit Phases (LEOPs), including verification of the deployment of moveable elements of a space vehicle, and
– as a diagnostic tool in the event of spacecraft anomalies, including determination of the attitude, shape and configuration of the spacecraft.

An example of just such an emergency situation was provided by the Advanced Earth Observation Satellite, ADEOS (Fig. 8). Launched on 17 August 1996 into a 797 km-altitude circular orbit with 98.6 deg inclination and designed for a lifetime of more than three years, ADEOS operations had to be terminated on 30 June 1997 due to loss of electrical power. The spacecraft's main body was 4 x 4 x 7 m^3 and it had a 3 x 24 m^2 and 0.5 mm-thick solar panel. Several passages of ADEOS were observed on 7 and 14 July 1997 with TIRA. From the Ku-band measurements, images were computed to investigate the cause of the malfunction. For the altitude assessment, a three-dimensional wire-grid model was constructed and two-dimensional projections of this model were overlayed on the images. The analysis revealed that the satellite's main body and the large boom that supported the solar panel were always visible in the images. However, the solar panel and its supporting structure – stiffeners made of carbon fibre, which have a good reflectivity for the Ku-band radar – were only visible in very few images.

Figure 8. Schematic of the ADEOS spacecraft



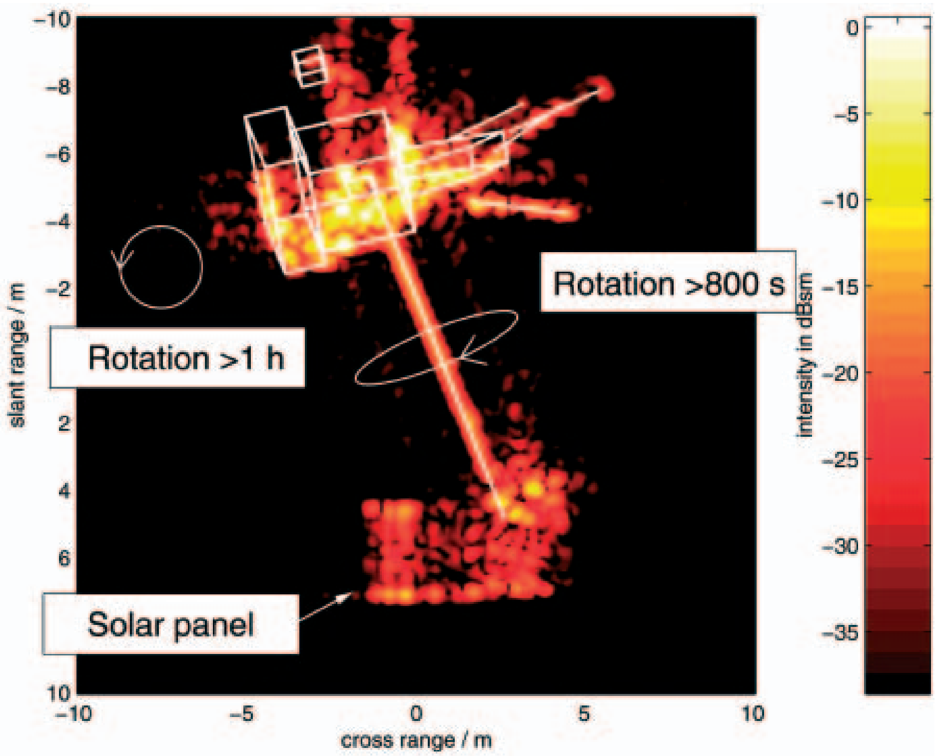


Figure 9. Radar image of ADEOS with overlayed wire-grid model and the results of intrinsic motion and damage analysis

Instead a cluster of scatter centres at the end of the boom was always visible. It is therefore assumed that the solar panel was snapped off at the base near the spacecraft's main body. Figure 9 clearly shows the dislocated solar panel at the end of the boom.

The analysis of the intrinsic motion of ADEOS identified basically two rotation components: one around the satellite's main body with an angular velocity of approximately 0.1 deg/s, and another around the satellite's boom with an angular velocity of about 0.4 deg/s.

Radar measurements of meteoroid streams

Another application of the TIRA system is the detection of meteors, in particular during meteoroid streams. As we marvel at the sight of visible meteors, not everybody is aware of the fact that for every one we see there are many much smaller ones that cannot be seen with the naked eye, but are detectable by high-power radar systems. Owing to their high speed, even these naturally occurring small meteoroids, which typically range from a fraction of a micron to a few millimetres in size, are potentially hazardous to Earth-orbiting spacecraft. The situation is particularly critical in the case of high-speed meteor streams such as the Leonids.

Because the progenitor of the Leonids, Comet Tempel-Tuttle, had passed through perihelion in February 1998, strongly enhanced meteoroid activity was expected with the Leonid shower of 17/18 November 1998. The very high approach velocity of the Leonids (more than 70 km/s) compensates for their small size and they thus constitute a real safety hazard for satellites. ESA therefore took special safety measures to protect its own spacecraft in orbit against potential impacts. It also warned other European satellite operators of the hazards and advised them on how to reduce the risk. In the event, on 17/18 November 1998 over a period of about 25 hours the Earth passed through a shower of relatively large meteoroids, which arrived at a rate of some 200 per hour (zenithal hourly rate, ZHR). This was the most severe shower since the previous Leonids meteor storm in 1996.

The question of how many radar-detectable meteors can be expected in a meteor storm like the Leonid event was the motivation for a measurement campaign with the FGAN L-band radar in 1999. The Leonids meteor storm was observed from 23:30 UT to 12:00 UT during the night of 17/18 November. A total of 176 meteor tracks were detected that night which, given the small 0.5 deg field of view of the TIRA system, is quite impressive. However, a closer analysis of the angular distribution of the meteor trails showed that very few of the meteors detected actually belong to the Leonids, the vast majority subsequently being assumed to form part of the sporadic background.

In order to understand better the measurements that were made in 1999, in 2001 another campaign was initiated that was designed specifically to measure the number of background meteors. On 18 November 2001, a ZHR of about 2000 was recorded. The data collected during the background campaign are still under investigation, but preliminary results indicate that the radar-detected meteors are indeed dominated by the sporadic background.

Another interesting aspect of the TIRA observations is the radar detection of meteoroids that arrive at speeds higher than 80 km/s. Particles arriving at these speeds cannot originate within our Solar System, and must be coming to us from interstellar space. As the highly sensitive dust detector on ESA's Ulysses spacecraft already detected such interstellar particles back in 1992, the TIRA detections of such fast meteors are credible. Therefore, high-power radars like TIRA can not only provide valuable information about space debris, but can also be used for high-quality space-physics observations.