UTILISATION OF THE BIRD SATELLITE AFTER ITS END OF OPERATIONAL LIFE

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ABSTRACT

The small satellite BIRD has successfully demonstrated the combination of ambitious science and innovative but not necessarily space-proven components in design to cost. BIRD’s payload is still fully functional. Its pointing accuracy depends on the still working attitude control components. Future missions based on BIRD experience and design are planned. We suggest a continued on-demand use of BIRD as a test bed for their development. New algorithms and strategies can be tested on BIRD by software upload before taking risks on its successors. Magnetorquer attitude control can be tested and improved. The long time behaviour of the battery stacks and electronics will be evaluated. Non-propulsive orbit control techniques can be evaluated and tested in conjunction with atmospheric measurements.

1. CURRENT SITUATION

1.1. Administrative Circumstances

The operational end of life of DLR’s very successful small fire-detection satellite, BIRD, has again been announced for the end of 2007. This end, after the previous cut of dedicated funding several years ago, was due to the several years of severely impaired pointing ability of the satellite. With the loss of the satellite’s operationally useful pointing capabilities, this announced end appears reasonable, despite the still fully functioning payload.

However, with the widespread use of BIRD technology for two new series of DLR satellites and potentially others, a new operational factor has arisen which merits a reconsideration of the decision to ground BIRD at the end of last year. The driving programmes using technology first established in the BIRD effort are the DLR Agentur’s OOV/TET (*O*n-*O*rbit *V*erification / *T*echnologie*e*rprobungs*t*räger) programme which intends to provide an orbital bus for collections of various technological and engineering experiments, and DLR’s own new SSB (*S*tandard *S*atellite *B*us) platform intended to provide easy and cost-efficient access to orbit for dedicated payloads proposed or lead by the scientific community within DLR. The first models of these series are in phase CD and phase A, with launches intended in 2010 and 2011, respectively.

1.2. On-board Technical and Ground Segment Operational Status

BIRD operations have in recent years only been maintained through a skilful and serendipitous combination of personal and institutional efforts. These include housekeeping data harvesting for the OOV/TET development effort, engineering interest in the long-term behaviour of infrared sensors and mechanical coolers within the payload, and most of all, personal interest and tenacity combined with the willingness to try data takes at very low chances of full success and non-negligible risk to flight hardware on the part of the last ground staff assigned to BIRD satellite operations, aided by the need to track objects on the verge of becoming space debris. The in-house study of late 2006 from which this document has been developed represents the first dedicated involvement of the SSB effort in the reuse of BIRD and its engineering data.

As of 2008 Apr 24, and based on day-to-day ground operator experience, BIRD suffers from at least the following critical failures and design flaws:

- Of the eight common pressure vessel batteries each containing two cells, at least two cells are weak. Great operational care is required to avoid cell reversal in these two aged cells that would lead to their quick destruction. By design, there are no sufficient indicators implemented in flight hardware to enable full individual monitoring of each common pressure vessel element, let alone of each cell. Power management planning is entirely dependent on operator experience to interpret the information available from the few sensors available, some of which have drifted considerably, even out of range. Also, the design of the power converters does not allow for a deep discharge of the battery, leading to a conservative safe mode trigger level battery voltage. This level is reached quickly after the failure of very few cells of the battery even if all others remain in good condition.

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- Of the four reaction wheels installed on board, two are considered dead. The third wheel may still have a probably very limited capability, combined with a quality problem that is mechanical and/or command interface induced, but has not been tested thoroughly enough to determine the most likely cause of failure; it also has not been switched on for a long time. The last wheel is possibly still available and may not have suffered mechanical damage, but has also remained essentially untested for a long time. Mechanical problems in the wheels were originally caused by a failure of the on-board flight control and wheel controller hardware and software to intercept commands that lead to spin rates way beyond the mechanical wheel design's capabilities. A late budgetary decision to use unsuitable low-grade material wheel bearings reduced these mechanical capabilities substantially and likely contributed to the mechanical effects of the failures. Another contribution may have come from coil resin that has moved out of the wheel motors due to mobilization by excessive heating during this event.

- The firmware (internal software) of the star trackers can not be updated. The flight release firmware suffers from two serious problems. Most importantly, the firmware crashes when internal interrupts caused by data transfer requests from the outside occur at a point in time inconvenient to the firmware. The time windows of communication convenient to the firmware are known, but since the quartz clocks of the star trackers and the main computers are not synchronized, the timing will always diverge over time. The relative time difference and its rate are not known and can not be estimated. The time difference will accumulate to a critical level within very few days. Recovery from these failures requires a full reset and restart of the star trackers. Since an automated mechanism such as a periodical reset of the star trackers is not implemented in the current flight software, they are not in the attitude control loop and are used only to reference captured images. Also, misleading data occasionally appear in the output when the dark sky is occulted by the Earth, the Moon, or other bright images such as internal reflexes caused by the optical surfaces.

- The sun sensors are installed such that one of their three dual redundant orthogonal photocells is in parallel with the deployed solar panels. The attempt to point the satellite for maximum power input at the Sun causes sunlight to shine at a near 90° angle of incidence on these photocells, and grazing on all others. The cosine shape of the signal per photocell causes the well lit cell to be insensitive to attitude changes, while the low level of light on all others causes them to be very sensitive for sources of light other than the Sun. The resulting error of the indicated direction to the Sun can easily exceed 20° at certain parts of the orbit. This deviation does not correspond to the direction to the equivalent effective point source of radiation integrated over the hemisphere visible to the photovoltaic cells on the solar panels. It is also unpredictable because a major contribution arises from albedo differences on Earth, such as cloud patterns. Both effects cause a drop in solar power input that due to the aged batteries and solar panels has become operationally relevant.

- Payload data can only be stored in volatile memory within the payload data handling unit which does not support a low power data retention mode. Hence, data takes can only be attempted when the power situation does not force the satellite into safe mode before the data have been downlinked and the payload data handling has been shut down in a controlled fashion.

- Magnetometer and GPS data are not used sufficiently by the on-board attitude control software to augment attitude information to provide a vector other than the sun vector for true three-axial attitude control.

- The IMU is no longer available after a relatively early failure, although it has exceeded its design life.

Due to the termination of dedicated funding, only one pass per day is presently used for ground contact activities. The power situation has to be evaluated from pass to pass. It is highly dependent on the random orientation with which the satellite comes out of eclipse. Although the magnetorquer-only attitude actuation regime is capable of roll rates of 90° in 10 minutes, the time it takes to re-orient the satellite fully towards the Sun is significant with respect to the total time of insolation per orbit.

The error of the sun vector generated by the sun sensors depends not only on ephemeral patterns such as cloud cover and surface albedo on Earth, but also on reflections of these from the satellite that emanate from surfaces able to produce glints and flares. It is not possible to separate solar radiation from any of the other sources. Because there is no solar input to the sun sensors while in eclipse, the residual drift accumulates during this period and counteraction only begins at satellite sunrise. This induces a step response behaviour at the beginning of insolation and every time the sun vector is reacquired. The variability of secondary sources of light and their modification by directly attitude dependent reflections induces additional time-variable errors that can also excite oscillations of the attitude control system. At times, these oscillations grow so much that data takes become impossible for lack of power. The behaviour of these oscillations is not well understood and may well remain entirely unpredictable for the purpose of mission planning because of the contribution by factors such as cloud cover.

Although BIRD is three-axis stabilized by design, and even by the sensors and actuators still available, the satellite is hence effectively in a tumbling roll stabilization. The roll axis, the Sun vector, and the solar panel normal frequently but not always come to drift within a common cone half angle of some 20°.

When data takes are attempted, the roll about the perceived sun vector causes the line sensors of the payload cameras to be at a random and unknown orientation with respect to the direction of motion and the ground track. This orientation is constrained only by the very general limits resulting from a power situation deemed sufficient for imaging, and the previous attitude control behaviour and stability required to achieve it. Depending on the deviation of the sensor line from a right angle to the direction of motion considered acceptable, the imagery acquired has a fairly low chance of being useable in general. Since the orientation of the perceived sun vector deviates in two dimensions, the chance of actually hitting a target area on the ground is much lower again.

Values given based on the requirements of operators used to non-small satellites for these chances are on the order of 5 % and 0.01 %, respectively. The chances of achieving generally useable imagery imply the definition of a required angle between the line sensors and the direction of motion of > 85°. The definition of a required general pointing error may be estimated by assuming that the surface of the Earth is hit at all, taking into account BIRD's initial orbital altitude of 572 km. This would imply an error of < 5° along track and across track required to hit a square target area, or < 0°.25 across track required for sufficient coverage of an infinite length swath. The latter values correspond to approximately one quarter and one seventieth, respectively, of the nominal swath width of BIRD. While the first value would seem very relaxed for an operational requirement, the latter seems typical for the high quality standards previously achieved in other Earth observation programmes. Experience shows that sometimes, indeed, the horizon is well visible in the image product, and the pointing error that still can be achieved by BIRD may consequentially be even larger.

2. TESTABILITY

Currently, the resources for close to real life simulations and testing available to satellite development efforts are very limited both in scope and number, and yet, very expensive. For small satellites, the common budgetary constraints further restrict the technological envelope of testing resources, and even those options readily available to financially larger projects may not be available at all.

Many crucial operational factors, such as radiation exposure and the effects of prolonged weightlessness, meaning that which lasts longer than about five seconds, remain virtually untestable on the ground, regardless of the financial effort. For the possible failures in the estimation of consequences of these factors, the launch of a satellite possibly worth hundreds of millions of euros still is nothing but a huge leap of faith, despite the experience accumulated in fifty years of space flight.

Ideal testing would include factors as these, and provide reliable data by simulating over time scales of at least the same order of magnitude as that expected as a reasonable functional lifetime of the satellite to be launched. Of course it is impossible to achieve this, especially in the one-off world of European science payloads, for it would mean to launch a test craft for every operational spacecraft.

But still, this approach has been used widely. All procedures to be uploaded to the Voyager 2 spacecraft for its highly successful Uranus and Neptune encounters were implemented and rigorously tested on Voyager 1 which was headed to empty space after its close encounter with Saturn's moon, Titan. These procedures included extremely risky endeavours such as out-of-spec operation of the hydrazine thruster engines or the disengagement of the second redundant computer to free up computational capacity for image compression, which had not yet been invented when these probes were launched. Indeed, both spacecraft were across the board driven to performances way beyond their pre-launch specifications. Their successful operation beyond Saturn would not have been possible without the use of Voyager 1 as a mission-identical test-bed. [1] Similar methods were used on several less well known spacecraft series, such as those based on the American Agena and (former) Soviet Zenit platforms. Both were highly serialized spacecraft buses, and sometimes, several operationally decommissioned spacecraft were still available in orbit at a time. [2][3]

Now, for the first time outside the U.S. and the former Soviet Union (and possibly China), there arises the opportunity to have a conceptually and in many functions nearly identical test bed in a real space environment. It would also be fully available around the clock to the mission design teams concerned, and in hardware, it is already paid for.

3. PRODUCTIVITY INCREASE BY NEW USE

Propagations of BIRD's orbit over the range of solar activity to be expected until mid-2016 show that it is very likely to survive in orbit until late 2010 even under expected worst case conditions. These would be effected by the highest expected, +3σ prediction of the 2011/12 solar maximum hitting BIRD's full aerodynamic cross section, by ways of radiation-induced expansion of the upper atmosphere. Careful attitude management could extend BIRD's time until re-entry by about two to three years even under the most adverse solar conditions, and luck, in the shape of lower than maximum estimated solar activity may easily see BIRD through to mid-2016 and beyond. This is longer than the longest requested lifetime of any payload presently under consideration for a SSB launch in 2011, and most likely covers at least the initial phases of flights to come.

3.1. Ambitious Theory and Humble Practice

BIRD, and its bus components in particular, could thus in theory stand ready to serve as a testbed for new mission software for all subsequent flights based on its technology. Temporary loss of BIRD due to a malfunctioning software experiment may be more easily tolerable than the same occurring to an operational TET or SSB spacecraft.

In practice, however, several important factors would have to be met first. Most critical is the power situation. As long as the present situation of two weak battery cells continues, near normal operation would be possible if battery charging could be achieved reliably, and the time between image taking and downlink were short enough. However, the unreliable attitude control presently causes an equal lack of reliability in solar panel pointing. Since payload power can only be drawn from the surplus beyond the needs of vital functions, it is essential to expand this margin.

A first step to enable reuse of BIRD has to be the development of a new attitude control and star tracker management software suite that integrates all available information into the control loop; continuous star tracking with occultation filtering and periodical timing management also to replace the IMU, GPS localization, magnetometer data, and sun sensor information. On the actuator side, the availability and condition of the wheels would have to be assessed once a reliable magnetorquer-only recovery has become possible. If at least one wheel remains operative, it may be used. If not, and to ward against further failures of these aged components, an optimized magnetorquer-only actuation mode has to be included. The use of the magnetorquers to maintain the satellite's attitude at an improved precision will most likely require practice and fine tuning of control loop parameters. The total effort for this is probably comparable to a new software development of a similar scale in the present TET or SSB efforts. If this is correct, it would still be an order of magnitude cheaper than the development of a new satellite for the same purpose as BIRD.

Imaging does not necessarily require nadir pointing which reduces the power input from the solar cells at the most critical time of demand. If a reduced resolution can be accepted by stepping down from the very high quality levels usually required by operators and customers of non-small satellites, slant imaging becomes possible. The satellite will then scan the ground without departing from its attitude of optimal insolation. In return, the ground resolution drops according to the increased distance to the area imaged, but this area also grows in exchange, yielding the same number of pixels. Slant projections of the field of view onto the globe will require additional postprocessing and unstretching of the image content, but this effort is very small compared to that of developing a new satellite. Similar software is used to map and mosaic flyby images of interplanetary probes with fields of view extending to the local horizon of the celestial bodies photographed from close range.

A new critical situation will then only arise if more battery cells become weak, or if more than two of the still healthy or weak battery cells fail completely by internal short circuit, or if one battery cell fails by open circuit. The limit for the number of weak cells is set by the low battery voltage trigger level that causes the satellite to switch into safe mode. It is not clear whether this limit can be readjusted or ignored, hence it is assumed as fixed. Once the limit of weak or shortened battery cells is exceeded, a safe mode will occur every time the satellite passes into eclipse. It may be possible to handle even this situation if a fast bootstrapping process can be implemented in the software to be uploaded, and some measure of data retention is possible. The satellite would then have to wake up at every sunrise, if necessary get its position and epoch by GPS, and follow a preset per-orbit routine as long as it is in daylight. It may also be sent to sleep in a controlled fashion, by reducing the roll rates as far as possible before sunset, to increase the likelihood of good solar panel pointing at sunrise despite the unconscious drift period in eclipse. Thermal conditioning may become a part of this day and night routine, as well, by controlled preheating of critical systems while in daylight to compensate for the uncontrolled coldsoaking in eclipse.

Successful camera payload operation becomes very unlikely in this regime because image taking and downlinking would have to occur within one period of insolation, but it would not be entirely impossible. Windows of availability would be restricted to orbits and target areas with a suitable S-band ground station, each, uprange from the area to be imaged for commanding image takes, and downrange for dumping image data.

The most likely use in the situation of effective loss of the battery would involve the collection of housekeeping data on a few suitable orbits and passes from time to time, and magnetorquer attitude control experiments or practice.

Activities using BIRD even in a very restricted fashion will end once the solar panels no longer develop sufficient charging power to lift the degraded battery stack above the safe mode threshold voltage. This will occur if several battery cells develop hard shorts instead of just becoming weak cells. Until then, using BIRD is a matter of informed decision, not technical fate.

3.2. Potential Gain

The main benefits differ for the SSB payloads presently under consideration, but all can easily benefit from a suitable extension of BIRD's mission. These benefits can be reaped before launch during the design and construction phases, as well as after launch during commissioning and operations, and most of all, for trouble-shooting at all times - assuming that BIRD can be made available as suggested above.

3.2.1. AsteroidFinder/SSB

The experience gained by BIRD's exposure to a higher and growing lifetime radiation dose can extend the upper limit of the orbit altitude envelope for SSB satellites. It is presently still that set for BIRD before its launch in 2001, at 850 km with regular excursions to about 900 km allowed if caused by an eccentricity of no more than 0.03. The extension of the upper limit would allow for higher and better illuminated Sun-synchronus dawn-dusk orbits, and for less interference in limb-grazing observations of near-Sun asteroids from a more frequently available 10..11:00 SSO. The combination of BIRD's radiation hardness and orbital decay data may further the optimization of the initial orbital altitude in a way to ensure a very long orbital life at a minimum radiation dose. By this, the payload could benefit from its inherent potential of low risk due to mechanical failures. It could well outlast several solar maxima in an operationally useful state for long-term observations. Also, the number and variety of the secondary payload launch opportunities available to this payload may rise considerably with the clearer definition of the range in initial orbital altitudes.

BIRD's aged avionics and the upcoming rise in solar activity from its present minimum to the next maximum expected in 2011/12 will provide the opportunity to gain the experience necessary to build even more reliable single event upset recovery procedures. These can be tested in a real environment, and may thus immediately extend the SSB's safe envelope of operations yet again, even for missions already under way. This further relaxes launcher constraints, and it expands the field of payloads that can be acquired for flights on a SSB.

However, BIRD has so far proven fairly insensitive to the most commonly cited source of radiation-related single event upsets in small satellites, the South Atlantic Anomaly (SAA). [4][5] Earlier preliminary analyses of the geographical location of these upsets in BIRD do not show the SAA at all in data from the first 36 days of 2003. There seems to be a slightly higher density of upsets near the northern aurora oval, and near mid latitudes. [6] If this trend were to continue during the upcoming rise in solar activity, the desired radiation sensitivity data would remain largely elusive. It may then still be stated that the radiation protection strategies used in the development of BIRD were effective, and that small satellites do not necessarily have to be overly sensitive to a typical low Earth orbit space radiation environment.

If an active cooling scheme has to be employed for the focal plane array on AsteroidFinder, one of the options is the use of Stirling cycle coolers similar to those used on BIRD. Continued operation of these coolers on BIRD will provide an extended base of data for reliability calculations, and may also highlight the first points of failure in operation to focus efforts to improve the design of mechanisms used.

3.2.2. CHARM/SSB

Unlike the other SSB payloads under discussion, CHARM benefits exclusively from an as low as possible orbit. At the same time, the payload is likely to impose strong constraints on the attitude of the satellite. During the solar maximum of 2011 and thereafter, the atmosphere will expand with the growing intensity of the Sun's radiation. Its influence will therefore reach to higher altitudes, including the lower portion of the SSB's envelope of orbital altitudes. A high quality characterization of the atmospheric and radiative drag effects on a SSB-type satellite is therefore highly desirable, including the effects of aged surfaces. Detailed knowledge of the effects on BIRD's orbital altitude and on the loading of the attitude control system in particular are vital for the planning of CHARM's observations since an orbit trim propulsion is presently not available on the SSB. CHARM's orbit will therefore with its continuous decay alternate between highly repetitive and highly non-repetitive modes of ground coverage. If other constraints require an intermittent mode of operation of its high-power Differential Absorption LIDAR (DIAL) payload, a tight prediction of the orbit will provide a clear indication as for the choice of the most favourable scheduling of operations. BIRD will most likely lead CHARM in its orbital decay by a margin useful for continuous mission planning. This will be the case for almost all scenarios except for an extremely weak solar maximum combined with the strict implementation of an altitude-saving attitude mode on BIRD's side, and hence, a lower initial orbit altitude of CHARM when launched on time in 2011.

3.2.3. LiveSat/SSB

A major fraction of LiveSat's sub-payloads requires exposure to space radiation. By the same mechanisms as described for AsteroidFinder, but for the diverging requirements of the highest radiation dose at a short lifetime, an intentional launch into a more intense radiation environment may become feasible if the SSB's survivable dose is raised by BIRD's experience to be gained. BIRD has so far performed extremely well during several intense solar storms, some of which were strong enough to seriously upset other satellites built exclusively from space-qualified and radiation-hardened parts, unlike BIRD. Experience from at least two serious breakdowns early in BIRD's mission has been incorporated into the on-board software and ground operations, and the existing data may again be analyzed to learn even more lessons.

It may be possible to implement a regular temporary shut-down routine in LiveSat/SSB to reduce the risk of single event upsets while the satellite passes through high-radiation zones at apogee, or within the South Atlantic Anomaly. This would be similar to the sunrise bootstrap and controlled shutdown mechanisms discussed earlier, and should be tested extensively, because recovery to normal operations has to occur reliably *after* the risk-inducing exposure. These tests are only possible in the real environment, using BIRD.

On the other hand, it may be possible to implement a non-propulsive orbital decay and re-entry control regime, if LiveSat/SSB was to be launched to a fairly low orbit to increase the re-entry capsule's efficiency by decreasing its propellant mass fraction. If the satellite was intentionally allowed to decay naturally to a very low Earth orbit, below approximately 180 km before separating the re-entry capsule, a substantial increase in scientific payload could be achieved by reducing the size of the de-orbit motor. The variable forces necessary to control the descent can be provided by modulating atmospheric and radiative drag by changing the satellite's attitude relative to the direction of orbital motion and the Sun, respectively. Although it is impossible to achieve a set date for re-entry, a control margin seems to exist for every timescale concerned if the satellite's cross section is at least as variable as that of the present TET envelope viewed from all aspects.

Also, experimental use of the magnetorquer coils as magnetosails to generate a very low thrust may be possible. This method of propulsion is discussed for interplanetary spaceflight, but seems also useable within strong magnetospheres. If a measurable effect could be produced using a small satellite, this would be significant in that surplus power may be even used for minute changes in the orbit. If the effect were measurable, its control could be exercised.

Both mechanisms can be tested and quantified in the real world, using BIRD. In fact, if it were to last long enough, BIRD's re-entry may be used as a demonstration, and for studies in conjunction with ground-based observations by a meteorite tracking network, such as the European fireball network operated in part by DLR (PF BA).

For LiveSat/SSB, both approaches may be combined in a high-eccentricity orbit, if it were available as a launch option.

The complex payload arrangement of LiveSat will require a very intense flow of payload, bus, and pointing commands, some of which are to be sent via independent links by third parties, such as DLR's School Lab. This mode of operation will require extensive testing of these mechanisms and safe recovery methods. The latter will have to include emergency pointing and reaction wheel unloading through the magnetorquers. The latter are still available on BIRD, but their use requires considerable attitude control and mission design experience. BIRD can provide the necessary set-up for sustained proficiency training of personnel to be involved in the operation of future SSB and TET satellites, and for the fine tuning of automatic mechanisms which will have to work reliably beyond the reach of ground control networks.

3.2.4. BIRD

Apart from in many ways serving as a very useful retro-SSB test-bed, or indeed retro-TET just as well, there are also intrinsic benefits that can be gained by a continued availability of BIRD. The past European, Californian, and Australo-Asian fire seasons have yet again demonstrated the value of information provided by means similar to BIRD's infrared payload.

Although continued expenses for a continuous operation seem unwarranted due to the precarious attitude control situation, the option to quickly reactivate the satellite to an operational status in case of emergency has to be kept alive and imprved upon in the ways mentioned earlier, for several reasons:

First, there is continued interest in several BIRD follow-on concepts, including several entries in the competition leading to the selection of the three SSB payloads selected for phase 0 studies mentioned above. However, while a generally available but presently unreliable, yet powerful route of information still generates interest in the time pressure of a major disaster management situation, a proposal for future missions will not. Hence, even if BIRD due to its present or improved condition fails more often than not to provide overhead imagery of the disaster area, it will still be included in the effort and in the post-situation assessments by trying alone. Any successful imaging, even at greatly reduced resolution, will still surpass that presently available from other satellites. It will also provide instant relief, and opportunity for publicity, while the demand to improve the reliability and quality of this service in case of intermittent failure to image the target area will provide a well documented incentive to follow up on follow-on missions. Temporary unavailability may by the contrast of the sorely missed item actually be a promotional factor for future fire detection missions.

Then, if these follow-on missions come to pass, the continued monitoring of the performance of critical components aboard BIRD will increase the experimentally proven reliability of those, and the design approach itself. Prolonged experience in the operation of mechanical components such as the active payload coolers, or the semiconductor sensors, and data on their wear and ageing in a real space environment will be valuable to any new design. Since a low altitude orbit offers benefits for many Earth observation technologies, the extension of these data to very low altitudes will be useful. Of interest is the specific environment of the lower ionosphere with its high ionized atomic oxygen component, as well as a higher total dose of radiation. Both can be provided at the same time by BIRD, due to its natural orbital decay and the latter's coincidence with the upcoming solar maximum.

Finally, permanently shutting down a satellite payload which observes effects of interest for human-induced climate change, biodiversity issues, and ecological research in general, simply is bad publicity. Continued operation even at a low level of intensity will provide a data bridge over time for future missions and scientific studies.

3.2.5. Others

If it survives in a condition that would still allow for attitude control, the final phase of BIRD's orbital decay could also be used to try out a non-propulsive re-entry control technique that may be applicable for all satellites with an at least partially working attitude control system. As mentioned above, initial testing of the available mechanisms, drag modulation and magnetospheric magnetosailing, can be done some time before BIRD's final decay phase. The data generated would directly be applicable for the TET and SSB efforts.

However, the principle has a wider use in the de-orbiting of numerous small, low density, as well as rare heavy, high-density satellites. The natural decay of the growing number of small satellites without a propulsion system could be speeded up, reducing the number of targets for the generation of orbital debris avalanche growth. For larger satellites, the amount of propellant to be reserved for de-orbiting may be reduced if other force-generating mechanisms are available and proven. Also, the risk posed to the ISS by any one satellite without a propulsion system while being at the same altitudes with crossing orbits can be reduced, if this altitude band is passed quickly in a controlled high-drag mode. Coordination with NORAD, ESA, and other space debris tracking efforts may be possible, and the published data be used to reduce the risk for the satellite concerned to collide with uncontrolled space debris by inducing a different rate of orbital decay.

The effects attainable by these low-thrust, low-drag methods may be small, but they may reach a useful order of magnitude if accumulated over time or used when most efficient. The variation of drag may be just large enough as a force difference at very low altitudes to within the last few days or weeks shift the predicted most likely point of re-entry away from high-risk areas such as the continents, to lower-risk areas. The latter include the Pacific-Atlantic common longitudes for high-inclination and sun-synchronous orbits, the Arctic Ocean, or Antarctica, and the circumantarctic parts of the major Oceans for mid-inclination orbits. In light of the recent successful satellite intercepts by ground-based missiles, these mechanisms may also be used to trim the orbit so that favourable conditions exist at a missile range offering these services.

With variable drag forces, parameters sensitive to along-track variations can be trimmed, such as decay rate or eccentricity. By these, and given enough time to accumulate changes, the ground track and position at a point in time can be altered. Depending on the satellite orbit's inclination, magnetic forces can also work in the cross-track and radial directions, while a substantial solar panel might allow the generation of lift as well as drag, the combined vector of which can be steered arbitrarily within a cone in the leeward hemisphere. Time-sequenced modulation of both drag and magnetic forces allows for quite sophisticated approaches. These might have sufficient efficiency to control a satellite's re-entry within a relatively brief period around the re-entry date progressively set by long-term variations in atmospheric drag due to solar activity while the satellite continues to decay naturally.

This is far from being a point landing control required for capsule recovery such as in LiveSat/SSB. At best, the most likely time and hence location of re-entry can be tuned within the greater frame of events imposed by the solar and atmospheric aspects of nature. However, this would be entirely satisfactory if the safest possible disposal of a satellite is the only requirement. This is of particular interest for satellites with high-density components such as large engines, heavy batteries, or X-ray mirrors, for example of the Wolter type used on

ROSAT. These are likely to survive re-entry, and may cause damage on the ground if they come down over inhabited areas. A functioning attitude control system may in this way be considered as a zero-mass secondary backup system. Over time, and after sufficient testing on other missions, this method may even develop into a replacement for dedicated de-orbiting equipment. It would require, and maybe become a technology driver for long term reliability in attitude control systems. This would also benefit many exotic future space missions for which this kind of reliability is essential.

The decaying orbit of such a satellite could in time be drag-modulated into a shape of some eccentricity that positions its perigee where a re-entry trajectory would lead into a safe area most of the times, at the most likely time of re-entry. This can be achieved by a high atmospheric drag orientation near the initial apogee to dip the perigee, a low drag attitude near the latter to maintain as much of the apogee altitude as possible, and the perigee if necessary. In other phases of the orbit, for example, a high solar radiation pressure attitude may be used to collect or dispose of a little orbital energy when necessary and not interfering with the aforementioned drag generation. Then, just before the final phase of re-entry, the satellite could be turned into a minimum drag position to only just hold out until the Earth has turned the safe area to lie underneath the ground track, and then be switched to a maximum drag orientation to ensure re-entry within very few perigee passes. The accidental magnetosailing properties of the onboard harness and electronics may additionally be used in the same way, if the effect were substantial enough, or alternate cabling routes be incorporated into the harness to further these effects using bulk current from the main supplies to the main consumers.

Small satellites without components likely to survive re-entry as hazardous objects could in the same way be steered towards a designated re-entry are entirely without safety concerns. Then, their re-entry could be observed for scientific and other purposes. Examples are atmospheric studies, calibration experiments in meteoritics, re-entry engineering, and public relations fireworks extending over many hundreds of kilometres along track. Every satellite that is as closely tracked on its final days as it would be necessary for a satellite undergoing a semi-controlled re-entry in this way, inherently is a scientifically valuable probe for continuous studies of the upper atmosphere and its variability on short timescales.

4. RETAINING BEST POSSIBLE USE OF AN INVESTMENT MADE WHILE AVOIDING ADDITIONAL EXPENSES

A bare minimum tracking of BIRD will be required even after the end of all operations, due to the concerns about space debris. The only way to shorten the time and expenditures of this effort would be to speed up orbital decay by continuously exposing the maximum cross section of the satellite to atmospheric drag. This only becomes impossible with the end of all operations, be it for irrecoverable technical reasons as proposed, or by an earlier decision not related to such considerations. However, due to its orbit and mode of operation, BIRD already exposes a rather large cross section, and hence the gain available by this method is small; indeed, it may well be within the range of long-term modelling inaccuracies for several of the cases considered.

If, on the other hand, the option of continued use is retained, the time of availability can greatly be extended by choosing an attitude that with a minimum drag provides just enough power for the safely continued collection of engineering data on BIRD's ageing. Since many of the people who designed and operated BIRD remain involved in the similar TET and SSB efforts, the only effort to be made to implement this proposal is to not dispose of all items necessary to operate BIRD in a full-on mode, be they communications and control hardware, software, or documentation. Especially critical is the BIRD-proprietary uplink equipment within the German network of ground stations for its non-standard modulation, increased data rate command interface.

This non-effort may indeed constitute a saving in itself, as opposed to a regular decommissioning process.

With the above, it appears clearly recommendable that this non-effort be made. While it merely appears technologically sound and prudent from the engineer's perspective, and will probably serve the public relations profile of DLR, it may in itself actually be a financially viable decision, too.

5. METHODS

The orbit predictions used herein are based on a simple satellite properties model using static and/or average attitudes and cross-sections with respect to the direction of motion in Earth orbit, and to the direction to the Sun, respectively. The individual simulation runs were started from BIRD's present orbital altitude, calculated from a set of two-line elements as of 2007 Oct 15. BIRD's effective mean operational atmospheric drag cross section was established by comparing the mean semi-major axis of simulation runs from launch on 2001 Oct 22 at the epoch of the two-element set used with the actual value. Using identical solar-atmospheric conditions and drag coefficients for these runs, it was found that the actual atmospheric drag cross-section is about one tenth larger than calculated on the base of BIRD's advertised capability and mode of operations. This increase most likely is due to a lower duty cycle of observations, and the resulting extension of the idle and battery-charging attitude time. It may be inferred that BIRD decays faster because it is underused, as an unexpected surfacing of the paradigm use it or lose it. It is also noted that while this is true within the model, BIRD seems to decay slower than expected according to propagations made early in its operational life. The reason for this has not been investigated, but likely involves different models of solar activity.

The decay time to altitudes below 450 km is of special interest for the CHARM/SSB payload proposal. Decay dates beyond 2016 May 31 are coarsely estimated by typical dh/dt values taken from internal data of the decayed simulation runs for the respective activity expectation, i.e. assuming continued nominal or lowest expected activity beyond mid-2016.

The orbits were propagated using a dedicated mission analysis tool for low Earth orbit (LEO) satellites, implementing a numerical orbit propagation based on a high accuracy force model. For the propagations to be completed within a reasonable time, the Earth's gravity field was simulated to an order and degree of 20, only, with 2 to 120 being possible. Third-body perturbations due to the Sun and Moon, tidal forces of the Earth, and non-gravitational forces due to atmospheric drag, solar pressure, and geomagnetic forces are included in the model. The Jacchia-Gill Earth atmosphere model was used, and the effects of the possible variations of solar activity were included through solar flux tables of the actual activity and predictions, from 1994 Apr 01 to 2016 May 31, also covering a five year SSB mission from mid-2011 onwards. These were provided for a minimum, nominal, and maximum prediction after the actual data until 2005 Jun 06 as of 2006 Sep 12, and from those scaleable by a user defined interpolation. Orbital and geometry parameters were generated in a file format suitable for direct analysis as well as automated plotting, using one-step-per-orbit runs.

Residual lifetime predictions are subject to a set of uncertainties. The major contributors to these are the actual, day-to-day, shorter time scales, and local variations of atmospheric density due to variations in the solar flux. Drag cross-section and coefficient may become additional major contributors once attitude control of the decaying object is lost. Even with these included, it has been shown in [7] that predictions of the residual lifetime of an uncontrolled object based on NORAD two-line elements, only, can be accurate to within about 10 % of the time to re-entry, if several atmospheric models can be used and the time to re-entry is within 0.5 to 10 days. Peak errors of the prediction can however rise up to about 25 % of the time until actual re-entry if only one model is used, or predictions are run on a very short time to re-entry. On an absolute scale, however, the predictions converge reliably enough for a closely monitored object. For the last orbits, high-percentage relative errors were mainly due to differences in altitude (±10 km) and time (±7 min) definitions of the reference time of re-entry becoming relevant. Ten days before re-entry, all models were on the safe side, within 0 to -2 days off, and three days prior to re-entry converging to within ±few orbits of the actual time of re-entry. This would be sufficient for an object to hit the largest albedo features of Earth if the re-entry is constrained along track by a sufficient eccentricity of the orbit and argument of perigee in the hours before actual re-entry.

Better results are likely possible for objects more closely monitored than a randomly chosen spent Vostok upper stage launched in 1978, on an in time sufficiently eccentricity-tuned orbit.

6. DRAG MODULATION POTENTIAL OF A LARGE SATELLITE, ROSAT

To gain an impression of their possible utility in a wider context, the methods used to estimate the orbital development of BIRD and the potential of drag modulation by attitude control as a non-propulsive tool for re-entry control may be applied to a large satellite. As an example without a propulsion system for re-entry control but with potential interest for a controlled or at least risk-reducing re-entry, the vintage German X-ray astronomy satellite, ROSAT, was chosen. Unlike for the satellites based on the BIRD concept discussed above, only the lower print-out time resolution propagation was run for a lifetime estimate, since the internal resolution of the propagation remains unchanged by the output file settings. The time difference in the results is of one orbital period plus one second, or less. This simplified approach has earlier been verified by comparison of various SSB propagation test runs.

The orbital lifetime estimate for ROSAT from an altitude of 200 km was derived by going backwards in the data record produced until reaching the last entry with an orbital altitude above 200 km. The actual altitude at this point was approximately within -0/+5 km of this value due to the lower resolution in time in the data files generated. The results given in the tables below were hence rounded in a way to make this difference inconsequential.

7. REFERENCES

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8. TABLES

Solar maximum intensity until 2016 May 31	attitude mode	aerodyn. / rad. cross-section, m²	lower than 450 km after, date	altitude 2016 May 31, km	approx. decay date
highest expected	max. drag	0.88 / 0.61	2Q 2010		4Q 2010
highest expected	operational avg.	0.58 / 0.85	4Q 2010		2Q 2011
highest expected	min. drag	0.30 / 0.61	4Q 2011		3Q 2013
nominal expected	max. drag	0.88 / 0.61	1Q 2011		4Q 2011
nominal expected	operational avg.	0.58 / 0.85	1Q 2012		2Q 2016
nominal expected	min. drag	0.30 / 0.61	3Q 2016	453	~ 2020
lowest expected	max. drag	0.88 / 0.61	~ 2022	483	~ 2028
lowest expected	operational avg.	0.58 / 0.85	~ 2025	499	~ 2030
lowest expected	min. drag	0.30 / 0.61	> 2025	509	> 2030

Table 1 - Rough estimates of BIRD's orbital lifetime depending on attitude and solar activity

Solar radiation intensity	attitude mode	aerodyn. / rad. cross-section, m²	first time below 130 km after, d	theoretical impact after, d
highest expected maximum	max. drag	1.16 / 0.41	0.1049	0.1361
highest expected maximum	mid drag side	0.41 / 1.16	0.3063	0.3493
highest expected maximum	min. drag	0.30 / 1.16	0.4056	0.4660
lowest expected minimum	max. drag	1.16 / 0.41	0.1625	0.1903
lowest expected minimum	mid drag side	0.41 / 1.16	0.4618	0.4917
lowest expected minimum	min. drag	0.30 / 1.16	0.6382	0.6625

Table 2.1 - Drag modulation effect on immediate re-entry, SSB from near-circ. 150 km orbit

Solar radiation intensity	attitude mode	aerodyn. / rad. cross-section, m²	first time below 130 km after, d	theoretical non-fragm. impact, d
highest expected maximum	max. drag	1.16 / 0.41	1.0806	1.1087
highest expected maximum	mid drag side	0.41 / 1.16	3.0658	3.1005
highest expected maximum	min. drag	0.30 / 1.16	4.1959	4.2276
lowest expected minimum	max. drag	1.16 / 0.41	2.3615	2.3789
lowest expected minimum	mid drag side	0.41 / 1.16	6.5926	6.6364
lowest expected minimum	min. drag	0.30 / 1.16	8.9788	9.0182

Table 2.2 - Drag modulation effect on immediate re-entry, SSB circular 200 km orbit

parameter, variable, unit	BIRD	BIRD
epoch of initial cond., YY/MM/DD.fod	01/10/22.2152	07/10/15.3537
semi-major axis, A, km	6945.857	6904.8904398
eccentricity, E, 1	0.001299	0.0016554
argument of perigee, AOP, °	210.026	15.0449
mean anomaly, M, °	0.00	345.1295
right ascending node, RAAN, °	8.177	48.0569
inclination, I, °	97.772	97.7497
satellite mass, MASS, kg	92	92
area, aerodynamic drag, AREA_CD, m²	(calc. 0.53)	from succ. approx. 0.58
area, radiative drag, AREA_CR, m²	0.85	0.85
aerodynamic drag coefficient, CD, 1	2.30000	2.30000
radiative drag coefficient, CR, 1	1.30000	1.30000

Table 3.1 - BIRD initial mean orbital elements and satellite drag parameters

parameter, variable, unit	SSB/TET 150 km	SSB/TET 200 km
epoch of initial cond., YY/MM/DD.fod	07/10/01 ; 11/01/01	07/10/01 ; 11/01/01
semi-major axis, A, km	6528.000	6578.000
eccentricity, E, 1	0.002277957	0.00
argument of perigee, AOP, °	90.00	270.0000
mean anomaly, M, °	0.00	180.0000
right ascending node, RAAN, °	96.8373 ; 191.1048	96.8373 ; 191.1048
inclination, I, °	96.1263	96.2936
satellite mass, MASS, kg	110	110
area, aerodynamic drag, AREA_CD, m²	0.30 ; 0.41 ; 1.16	0.30 ; 0.41 ; 1.16
area, radiative drag, AREA_CR, m²	1.16 ; 1.16 ; 0.41	1.16 ; 1.16 ; 0.41
aerodynamic drag coefficient, CD, 1	2.30000	2.30000
radiative drag coefficient, CR, 1	1.30000	1.30000

Table 3.2 - Re-entry control initial mean orbital elements and satellite drag parameters

Solar maximum intensity until 2016 May 31	attitude mode	aerodyn. / rad. cross-section, m²	last time above 200 km, days before re-entry	approximate decay date
highest expected	max. cross-sct.	20.00 / 11.90	1.16	4Q 2008
highest expected	side cross-sct.	10.71 / 11.90	1.80	3Q 2009
highest expected	min. cross-sct.	5.07 / 11.90	2.31	2Q 2010
nominal expected	max. cross-sct.	20.00 / 11.90	1.28	1Q 2009
nominal expected	side cross-sct.	10.71 / 11.90	1.41	4Q 2009
nominal expected	min. cross-sct.	5.07 / 11.90	3.21	4Q 2010
lowest expected	max. cross-sct.	20.00 / 11.90	1.80	1Q 2010
lowest expected	side cross-sct.	10.71 / 11.90	2.50	4Q 2010
lowest expected	min. cross-sct.	5.07 / 11.90	4.37	1Q 2013

Table 4.1 - Rough estimates of ROSAT's orbital lifetime and theoretical drag modulation effects depending on attitude and solar activity

parameter, variable, unit	ROSAT, 401 km
epoch of initial cond., YY/MM/DD.fod	07/10/22.5308
semi-major axis, A, km	6779.911
eccentricity, E, 1	0.0002108
argument of perigee, AOP, °	207.6211
mean anomaly, M, °	152.4687
right ascending node, RAAN, °	342.9523
inclination, I, °	52.9994
satellite mass, MASS, kg	2421.10
area, aerodynamic drag, AREA_CD, m²	5.07 ; 10.71 ; 20.00
area, radiative drag, AREA_CR, m²	11.90
aerodynamic drag coefficient, CD, 1	2.30000
radiative drag coefficient, CR, 1	1.30000

Table 4.2 - ROSAT initial mean orbital elements and estimated satellite drag parameters