Proceedings of the First European Conference on Space Debris, Darmstadt, Germany, 5-7 April 1993 (ESA SD-01)

Analysis of Near-Misses Between Operational Spacecraft and Catalogue Objects

H. Klinkrad

Mission Analysis Section, ESA/ESOC
Darmstadt, Germany

Abstract

The underlying concepts are reviewed for predicting proximity events between objects from the USSpaceCom Catalogue and operational spacecraft on representative target orbits. The ESA controlled sun-synchronous ERS-1 orbit ($h = 780$km, $i = 98.5°$) and the Space Station type EURECA orbit ($h = 450$km, $i = 28.5°$) with well-known orbit determination uncertainties are used as test cases. Orbit accuracies of ELSETs from the Catalogue are deduced by comparison with precise reference data for ERS-1 and EURECA, and they are then used to define a collision warning ellipsoid around the moving target spacecraft.

Near-miss statistics and fly-by geometries for ERS-1 and EURECA are given for 1-week analysis time intervals in Oct.1992. The number of close encounters, and the corresponding collision risk is then put into perspective with statistical debris flux estimates.

A historic near-miss event of STS-48 Discovery with a Proton upper stage on 16-Sep-91 is employed for the verification of methods and algorithms which have been implemented in a software for proximity event analysis at ESOC.

1. Introduction

Some 3,400 launches to date have been producing more than 22,000 objects which entered the USSpaceCom Catalogue. About 7,000 of these objects are still in orbit, most of which are remnants of 113 fragmentation events of rocket upper stages and of spacecraft. In its operational mode, the USSpaceCom Space Surveillance Network (SSN) can track objects down to 10cm in LEO. Experimental observation campaigns indicate that at the lower end of the SSN detection threshold (for 10cm $\leq$ d $\leq$ 1m) the derived Catalogue may be incomplete by a factor 2. Objects in the size class 0.3cm $\leq$ d $\leq$ 0.6cm, which could still disable or destroy an unshielded spacecraft, are likely to outnumber the Catalogue by a factor of 65. Debris of diameters d $\geq$ 1cm, which cannot be shielded with current spaceborne techniques, are estimated to be between 5 to 20 times the current Catalogue population (35,000 to 140,000 objects).

As a consequence of the steady growth of space debris, the resulting collision risk which is imposed on large-size orbiting targets has in recent years become a non-negligible factor for launch and on-orbit operations. For Space Shuttle, USSpaceCom in cooperation with NASA are routinely performing collision-free launch window determinations (ORBWIN software, Ref.3), and computations of near-misses between Space Shuttle and members of the Catalogue population (COMBO software: Collision Or Miss Between Orbits, Ref.7). The decision to monitor and forecast near-miss events of Catalogue objects with respect to Space Shuttle was taken after the Challenger STS-51L accident. Based on studies of orbit determination accuracies for Space Shuttle and for Catalogue objects, an STS operational flight rule was established (JSC-12820, Rule 4-61) which calls for collision avoidance manoeuvres if the predicted miss distance is within an alert ellipsoid of 5km x 2km x 2km (along-track, radial, cross-track), and if neither payload nor mission objectives are compromised (Ref.9). This collision ellipsoid corresponds to an accepted residual risk of 1 in 100,000. Statistical estimates indicated that for an STS mission of standard altitude, inclination, and mission duration about 1 avoidance manoeuvre can be expected every 10 missions. This forecast figure matches well with operational records: Since the STS-51L accident, there were 31 Shuttle flights, 3 of which necessitated an active avoidance manoeuvre (STS-48 on 17-Sep-91, STS-44 on 29-Nov-91, and STS-53 on 8-Dec-92).

More recent publications (Ref.7) define an STS manoeuvre ellipsoid of 10km x 2km x 2km (along-track, radial, cross-track) to trigger collision avoidance manoeuvres. This more elongated volume seems to better accommodate drag uncertainties in orbit propagations. It shall hence be adopted as reference for the forthcoming analysis.

2. Computation of Proximity Events

2.1 Collision Warning Ellipsoid

In order to associate miss distances between any two Catalogue objects with a corresponding collision risk, one must have some knowledge of the uncertainty which is attached to the predicted positions of the objects. ESA is routinely performing operational orbit determinations for their spacecraft, which to them are cooperative targets (equipped with transponders). Two ESA LEO missions shall serve as benchmark tests for Two-Line Element sets (denoted as ELSETs or TLEs by NASA and ESA, respectively) which are acquired by ESA/ESOC from NASA under a NASA/ESA letter agreement.

- ERS-1: The First European Remote Sensing Satellite is operating on a sun-synchronous orbit at $h = 780$km and $i = 98.5°$. Operational orbit determination is performed by ESOC using Kiruna range and Doppler data, augmented by global radar altimetry (at 'Fast Delivery Product' level). Orbit determination position accuracy (1σ values): 10m × 1m × 2m (in along-track, radial, cross-track direction).
- EURECA: The European Retrievable Carrier is operating on a Space Station like orbit at $h = 450$km and $i = 28.5°$. Operational orbit determination is performed by ESOC using Maspalomas and Kourou Doppler data (only descending passes at Kourou). Orbit determination position accuracy (1σ values): 100m × 10m × 20m (in along-track, radial, cross-track direction).

The larger uncertainties in case of EURECA can be attributed to the reduced amount of tacking data, to the poorer observation geometry, and to increased airdrag.

For ERS-1 (91-050A), which is in orbit since 21-Jul-91, 371 TLE states were transmitted to ESOC by 26-Jan-93. 101 of these were within a period of minor manoeuvre activities (07-Oct-92 to 26-Jan-93), which was adopted for the comparison of ESOC and USSpaceCom orbit determinations. For EURECA (92-049B), which was released by STS-46 Atlantis on 02-Aug-92, a period of no orbit manoeuvres between 02-Aug-92 and 26-Jan-93 yielded 37 TLE states for comparison. The combined analysis results are listed in Tab.1, where apart from position errors, also velocity and Kepler element errors are given.

For the selected analysis time intervals, the 1σ TLE position error ellipsoid (along-track, radial, cross-track) was 2.3km × 0.2km × 0.8km for ERS-1, and 2.4km × 0.4km × 0.9km for EURECA. The poor tracking geometry for EURECA is showing in the somewhat worse radial and out-of-plane accuracy, while along-track errors are of similar magnitude. Maximum position errors for ERS-1 (driven by a few isolated TLE outlayers) went up by a factor of 4 to 5, whereas for EURECA the increases were limited to factors of 2 to 3. The 1σ uncertainties in semimajor axis increase with a decrease in altitude (increase of drag effects). With $\Delta a_{1\sigma} = 76$m for EURECA, the error is about 130% of the one for ERS-1, and about 50% of the $\Delta a_{1\sigma}$ of a frequently observed re-entry object (e.g. Salyut-7/Kosmos-1686). If analysis time intervals with major orbit maintenance or orbit change manoeuvres are chosen for deriving mean TLE orbit determination errors, then the 1σ uncertainties typically increase by a factor of 2.

The orbit determination accuracy assessment just described was using interpolated ESOC states of well defined accuracy for epochs of TLE orbit determinations (at ascending nodes). Thus, TLE propagation errors were eliminated. Both concurrent states were then transformed to osculating cartesian states in a true-of-date equatorial system using the SGP-4 orbit theory for the TLE transformations.

When comparing the known ESOC orbit determination accuracies with the derived TLE state uncertainties, the ESOC error contributions to a combined RSS uncertainty can be regarded as negligible. Defining a mean 1σ position uncertainty ellipsoid from the complementary ERS-1 and EURECA TLE orbit errors leads to roughly 2.5km × 0.3km × 0.6km in along-track, radial, and cross-track direction for a single orbit. By mapping onto this ellipsoid an uncertainty ellipsoid of the same size under a typical collision azimuth (e.g. 45°), and by forming an RSS combined position error with some along-track margin for drag uncertainties, one can establish a collision alert ellipsoid with 1σ extensions along-track, radial, and cross-track of about 5km × 2km × 2km (which is the JSC-12820 guideline). For prediction time intervals larger than 1 day, and at strongly drag affected altitudes, a 10km extension along-track seems advisable (Ref.7) and will be adopted as reference hereafter.

2.2 Processing of Proximity Events

For the present analysis, proximities of any member of the USSpaceCom Catalogue with respect to ESA's LEO spacecraft ERS-1 and EURECA shall be determined. The analysis time intervals in both cases shall be on the order of 1 week. A proximity event shall be defined as a transition of a Catalogue object through a collision warning ellipsoid of dimensions $\Delta r_v \times \Delta r_u \times \Delta r_w$ (along-track × radial × cross-track), which is centered on the target spacecraft.

The proximity detection algorithm which is used by ESOC is closely following the processing steps outlined in Ref.5. The following successive sieves are used to determine potential near-miss or collision events:

1. Epoch Filter: rejection of all TLE states which have an epoch which is more than Δt_{TLE} days before the reference epoch (e.g. $\Delta t_{TLE} = 30$d)
2. Altitude Filter: rejection of all TLE states which (including altitude decay) do not intersect the altitude band between initial apogee and final perigee of the target orbit within the analysis time span.
3. Plane & Geometry Filter: rejection of all TLE orbits which at the intersection of the chaser and target orbit plane have position separations larger than the maximum extension of the collision warning ellipsoid ($\Delta r_{sph} = \Delta r_v$)
4. Orbit Phase Filter: rejection of those TLE orbits which at times of possible near-misses do not yield orbit positions within Δr_{sph} of the target spacecraft
5. Ellipsoid Pass Check: rejection of near-miss events which pass through the target proximity sphere of radius Δr_{sph}, but which are outside the collision warning ellipsoid $\Delta r_v \times \Delta r_u \times \Delta r_w$

For a 1 week analysis of near-miss events of ERS-1 in Oct.1992, 6790 TLE sets were submitted for processing. 474 (7%) of these were rejected due to TLE epochs which were older than 30 days (most of them of HEO and GEO type), 3954 (58%) of the TLE population were rejected by the altitude band filter, 540 (8%) did not pass the orbit plane and geometry filter, 1825 (26.5%) were rejected by the orbit phase filter and collision ellipsoid pass check, and only 44 objects (0.5%) passed through a collision warning ellipsoid of dimensions 100km × 20km × 20km.

The orbit states of the target spacecraft and of the remaining Catalogue population were transformed from the original TLE format (in SPG-4 mean elements) into corresponding singly averaged states according to Ref.6. Time rates of change of the mean Kepler state were transformed accordingly (propagation with J_2, J_2^2, J_3, J_4, and decay rate $\dot{a} = \mathrm{fct}(n)$). After an initial estimate of near-miss location and time in terms of mean elements, a more precise iterative improvement was performed by recovery of first order (J_2) osculating states.

3. Discussion of Results

3.1 Review of STS-48 Avoidance

After the STS-51L Challenger accident, and after the re-initialisation of Shuttle operations (with revised flight rules) in Sep.1988, at least 4 proximity events with Catalogue objects showed miss-distances which were within a 5km × 2km × 2km manoeuvre ellipsoid according to STS flight rule 4-61. These were (Ref.1, 8, 9):

- STS-27 Atlantis, Dec.2-7, 1988
- STS-48 Discovery, Sep.17, 1991
- STS-44 Atlantis, Nov.29, 1991
- STS-53 Discovery, Dec.8, 1992

Three out of the four events were associated with an inclination of almost 57°, which is near the maximum declination envelope for STS orbits. These missions, due to higher spatial densities of Catalogue objects with higher declinations, passed through an environment of increased collision risk as compared with STS orbits of 28.5° inclination (see Fig.1).

For STS-27, due to inadequate warning time and potential compromises of mission objectives, no evasive manoeuvre was executed. STS-48 was predicted to have a near miss with a Proton upper stage at 2.2km, and STS-44 had a predicted fly-by of a Vostok upper stage at 5.8km. For both Shuttle missions an avoidance manoeuvre was performed which yielded a save miss distance. STS-53 was the first mission to raise an alert due to a potential collision with a fragmentation debris. Again, a successful evasive manoeuvre was performed.

In order to test ESOC's proximity event prediction software, the STS-48 (91-063A) close encounter of a Proton upper stage (77-091B) shall be used as a reference case. The Proton stage of mass ≈ 1,500kg and length × diameter ≈ 3.8m × 2.6m, had injected Kosmos 955. At the time of encounter, the Proton stage was on a near-circular orbit at $h = 540 \pm 24$km and $i = 81.2°$, while STS-48 was at $h = 567 \pm 4$km and $i = 56.9°$.

A screening of the full Catalogue population for proximity events with STS-48 during Sep.14-16, 1991, successfully identified the fly-by of the Proton stage (77-091B) within a distance of 2.59km on Sep.16 at 04:06:50.75 UTC (see Tab.2). This predicted closest approach was under an azimuth angle of 47.5° almost within the local horizontal plane (elevation − 3.2°). The geometry and geographic location of the encounter (578.5km above the Lesser Slave Lake) are shown in Fig.2. Information released by NASA (Ref.1) indicated a fly-by distance of 2.2km (1.2 n.mi.) for the same epoch.

Tab.2 indicates the change of predicted time and geographic location of closest encounters with updates of STS-48 TLE state vectors between Sep.14 and Sep.16. Initially (for 4 out of 5 predictions on Sep.14), a closest approach was anticipated one orbit earlier, at 02:31 UTC, and at $\lambda = 85.9°$W and $\phi = 56.7°$N. As of the morning of Sep.15, the predicted closest approach moved one orbit ahead to 04:06:55.41 UTC at $\lambda = 109.88°$W and $\phi = 56.43°$N, with a miss distance of initally 55.7km at $t_{enc} - 23.5$ hrs. This fly-by distance steadily decreased down to 2.59km for an STS-48 TLE state vector from $t_{enc} - 9.2$ hrs. The fly-by time only shifted by -4.7sec during these updates. To complete the picture, Tab.3 shows all proximities of STS-48 and 77-091B within ± 1 orbit of the 2.59km near-miss.

Since the predicted fly-by at 04:06:50.75 UTC was well within the Shuttle alert ellipsoid, NASA decided to manoeuvre STS-48 in accordance with Rule 4-61. At 23:30 UTC on Sep.15, an along-track ΔV of 0.6 m/s was applied which shifted the point of closest approach behind and above Discovery at a distance of 14.7km. This predicted miss with a state vector from 02:00 UTC was confirmed by a post-event TLE state from 08:30 UTC. All of these results are in good agreement with NASA mission reports, and they give confidence in the implemented algorithms, which will hereafter be applied to ERS-1 and EURECA.

3.2 ERS-1 and EURECA Near-Miss Results

The proximity detection method just outlined has been applied to two operational spacecraft under ESA control: EURECA (92-049B) on a Space Station like orbit at $h = 450$km and $i = 28.5°$, and ERS-1 (91-050A) on a sun-synchronous orbit at $h = 780$km and $i = 98.5°$. Both orbits are near-circular. The analysis time intervals for both spacecraft spanned about 1 week (EURECA: 1-8 Oct.1992, ERS-1: 8-14 Oct.1992), with epochs chosen such that a maximum number of TLE state vectors was available from the USSpaceCom Catalogue.

Statistical assessments of collision risk on the EURECA and ERS-1 orbit for Oct.1992 indicated a Catalogue flux of 4.0×10^{-7} m^{-2} yr^{-1} and 3.3×10^{-6} m^{-2} yr^{-1}, respectively. This corresponds to about 1 and 9 passes per week through a collision warning ellipsoid of extensions 20km × 4km × 4km. Comparing these estimates with the deterministic results listed in Tab.5 (showing 1 and 13 passes/week, respectively) gives a good agreement.

Of 19 proximity events within a 100km × 20km × 20km ellipsoid around EURECA, none of the passes were within an adopted manoeuvre ellipsoid of 10km × 2km × 2km. The closest miss in the time interval Oct.1-8 occurred on Oct.1 at 04:12:15.42 UTC with a fly-by of 79-067A (Kosmos 1116) at a distance of 3.7km almost verically above EURECA.

As could be expected from the statistical risk estimate, the number of proximity events for ERS-1 according to Tab.5 is about one order of magnitude larger than for EURECA, since spatial densities of the Catalogue objects increase both with the higher mean altitude, and with the larger inclination of ERS-1 (see Fig.1). During the analysis time period Oct.8-14, ERS-1 had 184 passes of Catalogue objects within 100km × 20km × 20km, 52 passes through an ellipsoid scaled by 1/2 (which is a Shuttle warning envelope according to Ref.8), and still

4 near-miss events within 10km × 2km × 2km (size of the Shuttle manoeuvre ellipsoid).

Tab.4 gives a detailed break-down of times, geographic locations, and encounter geometries of the closest ERS-1 fly-bys by Catalogue objects between Oct.8 and Oct.14, 1992. All of these events are within 20km × 4km × 4km. The accuracy with which the proximities are determined is directly related to the quality of the TLE orbit determination (assessed in 2.1) and to the time separation between TLE epoch and encounter (see last columns in Tab.4). Some of the listed events allowed updates to be performed as new ERS-1 or Catalogue object state vectors became available. In case of Δt's within $\pm$ 2d, the updates show very consistent results, while for object 72-069A, with a Δt of 4 days between two updates, there is a noticeable discontinuity in the fly-by results. While some of the near-misses are singular events, objects 83-103B and 86-030B (upper stages of Kosmos 1503 and 1741), both of which are on near-circular orbits at $i = 74.0°$ with orbit periods close to ERS-1, exhibit proximities with respect to ERS-1 on the ascensing and descending arcs at near-symmetric latitudes and fly-by geometries.

The three closest misses of ERS-1 were determined for object 86-030D (Kosmos 1741 rocket body fragment) at $\Delta r = 0.23$km, for 81-053JN (Kosmos 1275 collision fragment) at $\Delta r = 1.28$km, and for 86-030B (Kosmos 1741 rocket body) at $\Delta r = 1.96$km. Considering the related uncertainties in position predictions, any of these passes could have created a direct hit.

6. Summary and Conclusions

The risk of a direct hit of an operational spacecraft of cross-section 30m^2 by a Catalogue object in LEO (with d > 10cm) is on the order of 1 in 10,000 on a typical sun-synchronous orbit (ERS-1), and 1 in 100,000 on a Space Station type orbit (EURECA). The corresponding risk of a catastrophic collision with an object of diameter d > 1cm can be 10 to 20 times larger, and thus attains a magnitude which takes a noticeable effect on the overall mission reliability.

LEO objects with diameters d < 10cm are not regularly observable by the operational SSN of USSpaceCom, and these objects hence cannot be actively avoided by an operational spacecraft. The Catalogue population above this tracking threshold possibly represents only 5% to 10% of all debris which could disable or catastrophically destroy a spacecraft upon impact. A collision between large-size Catalogue objects and oerational spacecraft will, however, generate an unprecedented amount of small-size collision fragments which could agrevate the tendency towards collisional cascading in some LEO altitude bands (e.g. near the ERS-1 orbit). Taking active measures to avoid such collisions by monitoring and forecasting proximity events and by planning avoidance manoeuvres is something that can be done and should be done whenever possible.

In order to perform evasive manoeuvres before a predicted collision or near-miss between an operational spacecraft and a Catalogue object, an alert or manoeuvre initialisation ellipsoid must be defined. Taking into account orbit uncertainties, a tolerated residual risk per event (1 in 100,000 for Shuttle), and typical collision geometries, NASA established a 5km × 2km × 2km manoeuvre ellipsoid for STS missions (Ref.9). Such definitions and related proximity prediction and avoidance procedures as adopted by NASA for STS flights could eventually also be applied to ESA missions at LEO altitudes. The fuel expenditure for avoidance manoeuvres (which should be performed 2 or 3 orbits before predicted miss) is mostly less than 1 m/s.

Acknowledgements

I wish to thank my colleagues Dr. J.Dow and Dr. R.Zandbergen of ESOC's Orbit and Attitude Division for providing orbit determinations for ERS-1 and EURECA.

References

1. anon.
Aerospace Daily, press release, Sep.17, 1991

2. J.Bendisch, D.Rex
Collision Avoidance Analysis
Paper **AIAA 90-1338**, AIAA/NASA/DOD Orbital Debris Conference, Baltimore/MD, Apr.16-19, 1990

3. G.D.Bredvik, J.E.Strub
Determination of Acceptable Launch Windows for Satellite Collision Avoidance
Paper **AAS 91-373**, AAS/AIAA Astrodynamics Specialist Conference, Durango/CO, Aug.19-22, 1991

4. K.J.Ernandes
A Mission-Preserving Evasion Technique for Near-Circular, Low-Altitude Orbits
Paper **AIAA 88-4278-CP**, 1988

5. F.R.Hoots, L.L.Crawford, R.L.Roehrich
An Analytical Method to Determine Future Close Approaches Between Satellites
Celestial Mech. 33 (1984), p.143-158

6. J.J.F.Liu, R.L.Alford
A Semi-Analytic Theory for the Motion of a Close-Earth Artificial Satellite with Drag
Paper **AIAA 79-0123**, 17th Aerospace Sciences Meeting, New Orleans/La., Jan.15-17, 1979

7. J.P.Loftus, A.E.Potter, P.Anz-Meador, R.Reynolds
Orbital Debris Mitigation Techniques
COSPAR Paper **B.8-M.3.05**, World Space Congress, Washington/DC, 28.Aug-5.Sep, 1992

8. D.McKnight (ed.)
Space Shuttle Performs Another Avoidance Maneuver
in **Space Debris Monitor**, Vol.5(1), p.18, Jan.1, 1992

9. F.Vilas, M.Collins, P.Kramer, G.Arndt, J.Suddath
Collision Warning and Avoidance Considerations for the Space Shuttle and Space Station Freedom
Paper **AIAA 90-1337**, AIAA/NASA/DOD Orbital Debris Conference, Baltimore/MD, Apr.16-19, 1990

TLE Orbit Determination Accuracy Assessment for ERS-1 and EURECA

Object	Position Error, km (wrt. ESOC state)						Velocity Error, m/s (wrt. ESOC state)					
	along-track		radial		out-of-plane		along-track		radial		out-of-plane	
	RMS	Max	RMS	Max	RMS	Max	RMS	Max	RMS	Max	RMS	Max
ERS-1	2.318	11.801	0.212	0.775	0.226	0.784	0.220	0.800	2.437	12.576	0.488	2.903
EURECA	2.445	5.802	0.419	1.545	0.906	1.775	0.484	1.730	2.575	6.674	0.276	0.605

Object	Δa(m)		$\Delta e \times 10^3$		$\Delta i(°) \times 10^3$		$\Delta\Omega(°) \times 10^3$		$\Delta\omega(°)$		$\Delta f(°)$	
	RMS	Max	RMS	Max	RMS	Max	RMS	Max	RMS	Max	RMS	Max
ERS-1	57.184	198.61	0.027	0.097	3.748	22.299	1.831	6.327	1.487	5.223	1.486	5.212
EURECA	76.130	161.79	0.048	0.099	2.072	4.528	15.850	30.999	11.658	51.361	11.652	51.315

Tab.1: Assessment of TLE orbit determination accuracies for ERS-1 (91-050A) and EURECA (92-049B). Interpolated ESOC orbit determinations were used as references (related RMS position uncercainties along-track, radial, and out-of-plane were 10m × 1m × 2m for ERS-1, and 100m × 10m × 20m for EURECA).

Time Evolution of a Near-Miss Event Between STS-48 and 77-091B

Debris Obj. ID	STS TLE Epoch, UTC		Fly-By Epoch, UTC		Fly-By Geometry			Fly-By Location		
	day'91	hh:mm:ss.s	day'91	hh:mm:ss.s	Δr(km)	Azi(°)	Ele(°)	h(km)	λ(°)	ϕ(°)
77-091B	Sep.14	01:30:00.00	Sep.16	02:31:04.07	4.26	-96.73	-81.61	578.52	-85.89	56.71
77-091B	Sep.14	05:20:27.40	Sep.16	04:06:53.20	30.77	46.54	-5.99	578.53	-109.85	56.57
77-091B	Sep.14	11:44:30.00	Sep.16	02:31:20.54	34.92	45.78	-8.11	578.50	-85.81	56.52
77-091B	Sep.14	14:56:33.50	Sep.16	02:31:22.82	62.12	47.36	-3.84	578.49	-85.74	56.38
77-091B	Sep.14	18:08:35.60	Sep.16	02:31:22.80	61.90	47.36	-3.85	578.49	-85.74	56.38
77-091B	Sep.15	04:38:37.60	Sep.16	04:06:55.41	55.71	48.32	-0.87	578.52	-109.79	56.43
77-091B	Sep.15	12:15:00.00	Sep.16	04:06:52.22	18.89	48.11	-1.42	578.53	-109.88	56.62
77-091B	Sep.15	16:32:31.70	Sep.16	04:06:51.13	6.47	47.81	-2.29	578.54	-109.91	56.69
77-091B	Sep.15	18:51:03.00	Sep.16	04:06:50.75	2.59	47.50	-3.23	578.54	-109.92	56.71
STS-48 man.	Sep.15	23:30:00.00	→	ΔV=0.6m/s						
77-091B	Sep.16	02:00:00.00	Sep.16	04:06:49.22	14.76	-133.63	6.44	578.54	-109.96	56.80
77-091B	Sep.16	08:30:00.00	Sep.16	04:06:49.27	14.37	-133.76	6.81	578.54	-109.96	56.80

Tab.2: Time evolution of a near-miss event between STS-48 (91-063A) and a Proton upper stage (77-091B) on 16-Sep-91 as a function of the available orbit determination states of STS-48 Discovery.

Evolution History of a Near-Miss Event Between STS-48 and 77-091B

Debris Obj. ID	STS TLE Epoch, UTC		Fly-By Epoch, UTC		Fly-By Geometry			Fly-By Location		
	day'91	hh:mm:ss.s	day'91	hh:mm:ss.s	Δr(km)	Azi(°)	Ele(°)	h(km)	λ(°)	ϕ(°)
77-091B	Sep.15	18:51:03.00	Sep.16	02:31:04.07	150.71	-131.28	-0.78	578.57	-86.26	57.50
77-091B	Sep.15	18:51:03.00	Sep.16	03:19:01.42	110.92	125.32	-24.51	538.54	81.82	-57.25
77-091B	Sep.15	18:51:03.00	Sep.16	04:06:50.75	2.59	47.50	-3.23	578.54	-109.92	56.71
77-091B	Sep.15	18:51:03.00	Sep.16	04:54:47.89	69.78	-18.28	-40.90	538.11	58.15	-56.46
77-091B	Sep.15	18:51:03.00	Sep.16	05:42:37.42	156.24	48.46	-0.60	578.49	-133.60	55.92

Tab.3: Evolutions history of a near-miss event between STS-48 (91-063A) and a Proton upper stage (77-091B) on 16-Sep-91 at 04:06 UTC.

Near-Miss Events for ERS-1 (91-050A, time span: 8-14 Oct, 1992)										
Debris Obj. ID	Fly-By Epoch t_{ref} (UTC)		Fly-By Geometry			Fly-By Location			$\Delta t(d) = t_{TLE}-t_{ref}$	
	yy-mmm-dd	hh:mm:ss.s	Δr(km)	Azi(°)	Ele(°)	h(km)	λ(°)	ϕ(°)	Δt_{ERS}	Δt_{obj}
69-062B	92-Oct-08	01:21:46.36	4.66	-69.77	48.04	808.99	118.79	-64.56	-0.763	-5.033
80-056A	92-Oct-08	05:24:12.66	3.81	-87.31	88.07	788.44	-109.08	32.98	-0.932	-11.352
70-086B	92-Oct-08	17:37:17.64	2.39	164.79	-87.47	787.95	-98.84	42.77	-1.441	-11.931
69-082BE	92-Oct-10	16:14:27.79	5.01	-143.34	-19.25	792.86	74.97	65.23	-1.480	-1.190
update	→	16:14:27.71	5.93	-143.34	-16.65	792.86	74.96	65.23	+0.197	-1.190
83-103B	92-Oct-11	14:37:32.44	2.29	86.33	-44.27	790.02	-63.82	-12.99	-0.736	-0.415
update	→	14:37:32.40	2.35	86.33	-45.54	789.94	-63.82	-12.99	+0.312	-0.415
83-103B	92-Oct-11	15:27:45.48	4.33	-86.28	21.99	786.12	103.71	12.44	-0.771	-0.451
update	→	15:27:45.45	4.36	-84.14	23.02	786.20	103.71	12.44	+0.277	-0.451
86-030D	92-Oct-13	07:59:47.66	1.81	-67.93	-14.55	795.83	-172.94	73.61	-0.574	-1.354
update	→	07:59:47.63	1.85	-68.89	-13.94	795.85	-172.95	73.61	-0.364	-1.354
update	→	07:59:47.33	0.23	132.96	-70.08	795.84	-172.91	73.59	-0.364	+0.896
81-053JN	92-Oct-13	10:33:35.07	1.48	-57.15	-51.53	812.19	-67.01	-80.73	-0.680	-0.120
update	→	10:33:35.01	1.28	-57.06	-64.64	812.16	-67.03	-80.72	-0.471	-0.120
91-041B	92-Oct-13	22:44:17.09	2.38	-86.15	-54.16	786.92	-3.68	0.96	-1.187	-1.927
update	→	22:44:17.04	2.23	-86.15	-54.38	787.03	-3.68	0.97	-0.978	-1.927
update	→	22:44:17.08	2.45	-86.17	-48.83	787.03	-3.68	0.97	-0.978	+0.312
81-053AW	92-Oct-13	23:20:51.56	6.35	167.53	-17.18	789.02	176.68	47.45	-1.213	-0.713
update	→	23:20:51.53	7.13	167.67	-14.13	789.06	176.68	47.45	-1.003	-0.713
update	→	23:20:51.51	3.69	167.64	-32.92	788.79	176.68	47.42	-1.003	+0.317
72-069A	92-Oct-14	03:12:14.84	3.37	-8.68	-6.44	807.57	94.98	-59.19	-1.374	-3.864
update	→	03:12:14.69	2.28	-8.66	-7.92	807.59	94.98	-59.18	-1.137	-3.864
update	→	03:12:15.48	10.00	171.19	-1.44	807.64	94.97	-59.12	-1.137	-0.507
update	→	03:12:15.42	11.42	171.19	-1.25	807.62	94.97	-59.12	+0.442	-0.507
86-030B	92-Oct-14	07:42:13.43	1.96	83.70	-56.02	792.03	53.45	53.06	-1.352	-1.132
update	→	07:42:13.36	2.11	83.68	-53.40	791.96	53.45	53.06	+0.255	-1.132
86-030B	92-Oct-14	08:32:28.80	3.40	96.10	71.35	805.72	-138.99	-53.37	-1.387	-1.167
update	→	08:32:28.72	3.41	96.67	74.67	805.79	-138.99	-53.36	+0.220	-1.167

Tab.4: Summary of near-miss events between ERS-1 (91-050A) and Catalogue objects in a 1-week analysis time span (8-14 Oct.1992). All encounters are within an ERS-1 centred alert ellipsoid of 20km × 5km × 5km (along-track, radial, cross-track).

Statistics of ERS-1 and EURECA Near-Misses Within 1 Week				
Number of Fly-Bys Inside Collision Warning Ellipsoid	Ellipsoid Definition: along-track (km) × radial (km) × out-of-plane (km)			
	100 × 20 × 20	50 × 10 × 10	20 × 4 × 4	10 × 2 × 2
ERS-1, 8-14 Oct 1992	184	52	13	4
EURECA, 1-8 Oct 1992	19	1	1	–

Tab.5: Near-miss statistics for ERS-1 (h = 778km, i = 98.52°) and EURECA (h = 450km, i = 28.5°), when exposed to the USSpaceCom Catalogue population of Oct.1992 for one week.

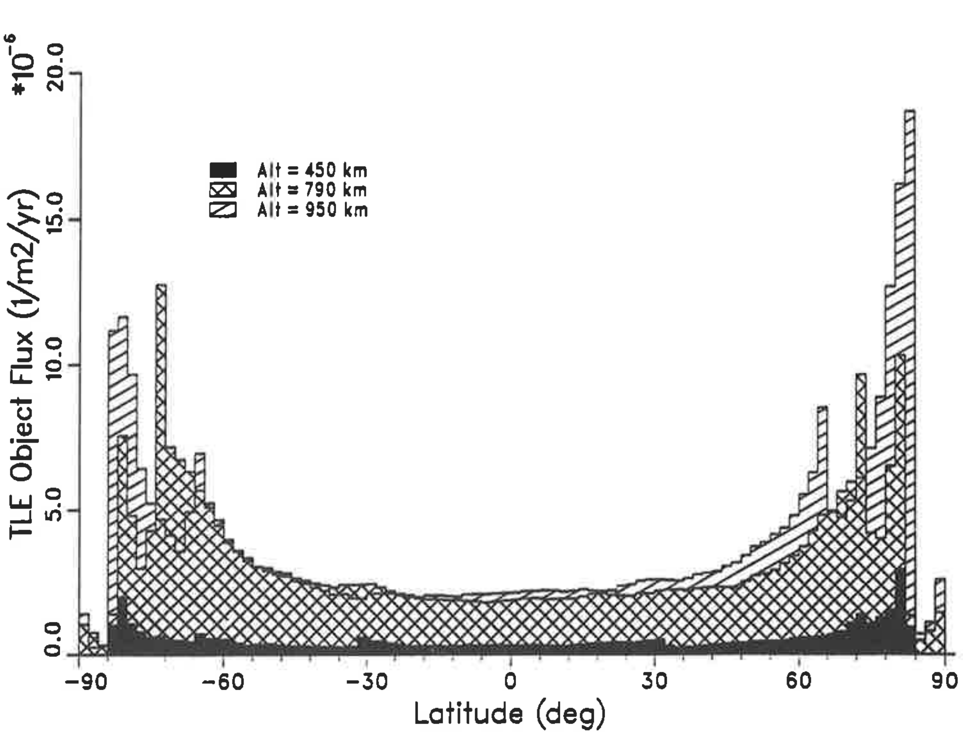

Fig.1: Catalogue object flux on an inertially stationary, spherical target at altitudes of 450km (SSF, EURECA), 790km (ERS-1, SPOT), and 950km (RORSAT reactor graveyard orbits), as a function of latitude. (TLE Catalogue data of July 1992)

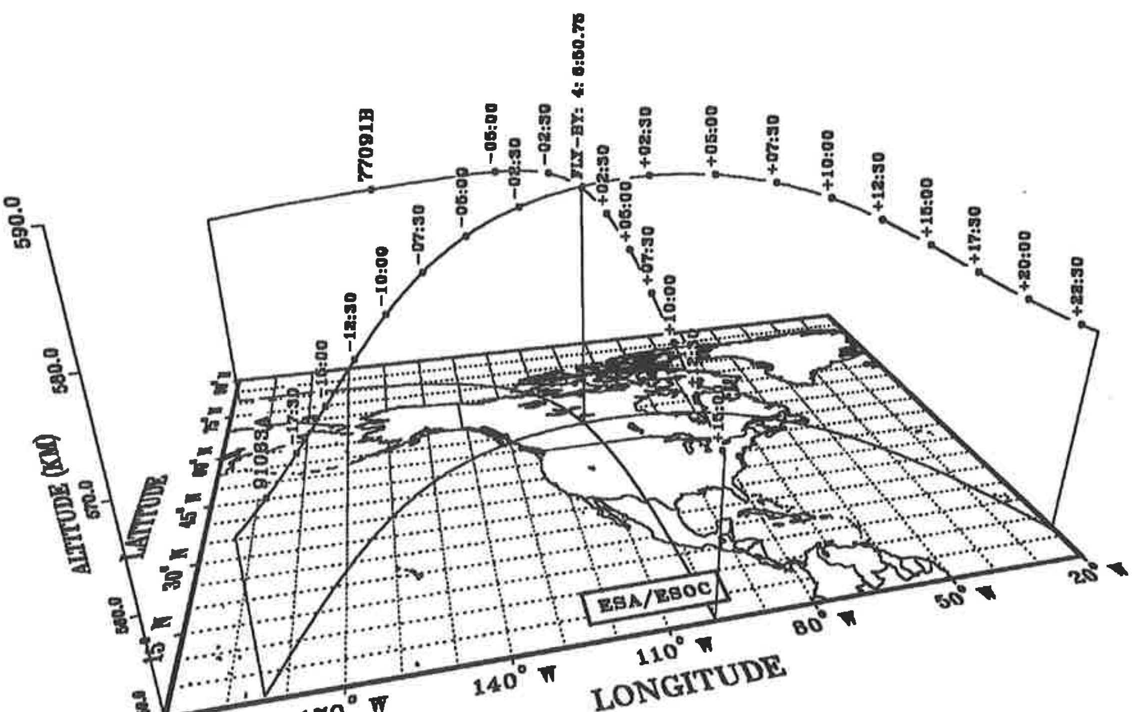

Fig.2: Fly-by orbit geometry of STS-48 Discovery (91-063A) and a Proton upper stage (77-091B) which launched Kosmos 955. The near-miss would have occurred on 16-Sep-91 at 04:06:49 UTC at a distance of 2.59km, in a geodetic altitude of 578.54km above the Lesser Slave Lake. 4.5h prior to the encounter, a $\Delta V = 0.6$m/s avoidance manoeuvre increased the miss distance to 14.8km.