Deterministic method for Active Debris Removal target selection

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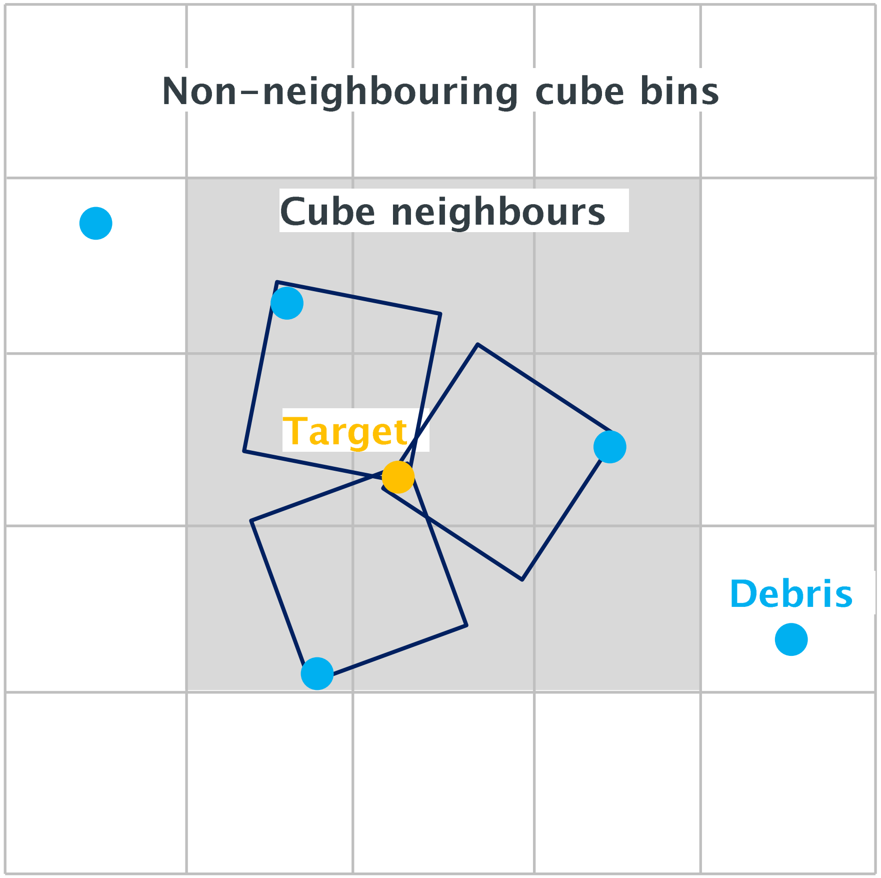
The importance of ADR target selection

1. Cannot remove everything due to financial constraints
2. Want to remove objects that will cause collisions and pollute the environment
3. ∵Should focus on specific objects to increase the benefit AND reduce cost

Targets selection: the modelling approach

- An algorithm, e.g. the Kernel, is used to compute the collision probability $P(C)$ – multiple "snapshots" taken each year to estimate $P(C)$
- This can give two lists of targets
  - Based on a given year projections only, used for ADR simulations
  - Based on all the Monte Carlo runs and long-term projections – gives the "worst" objects

Kernel snapshot in two dimensions



Modelling target lists inapplicability

- The DAMAGE long-term target list's composition is approximately constant. It intuitively make sense from "risk to the environment" standpoint
  - Large (high $P(C)$)
  - Densely populated orbits (even higher $P(C)$)
  - Heavy (many potential new debris)
- The short-term list's order is not constant and it does not converge regardless of the cube size, time step etc.[1]
- ∵ The current "modelling approach" will never provide an accurate estimate of the objects that should be removed in the near-term

1 – S.J. Johnston, N.S. O'Brien, H.G. Lewis, E.E. Hart, A. White and S.J. Cox, Clouds in Space: Scientific Computing using Windows Azure, Journal of Cloud Computing: Advances, Systems and Applications, Vol. 2, No. 2, 2013

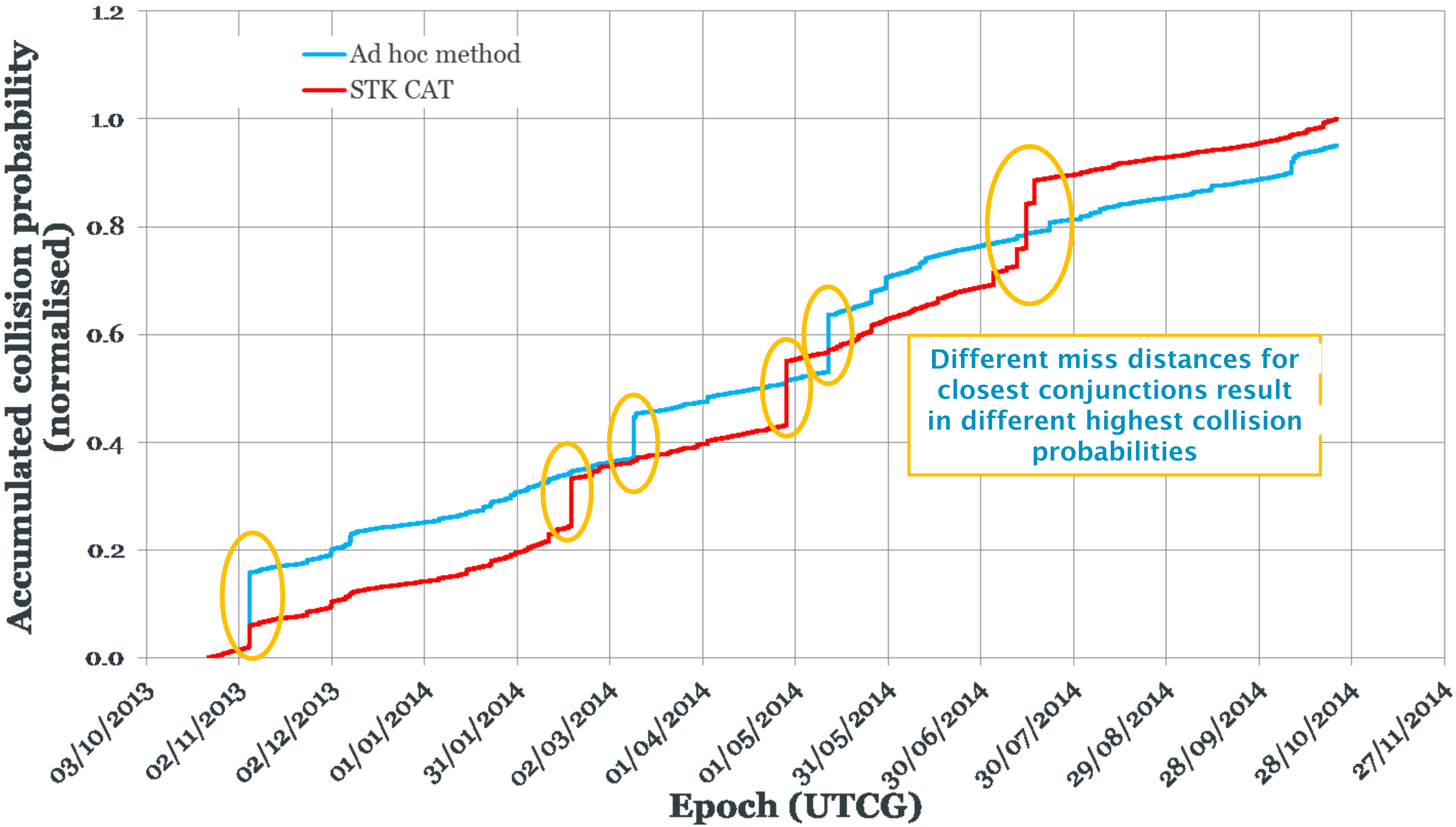
How do we address the issue of target selection if we are to fly an ADR mission?

ADR MISSION IMPLEMENTATION

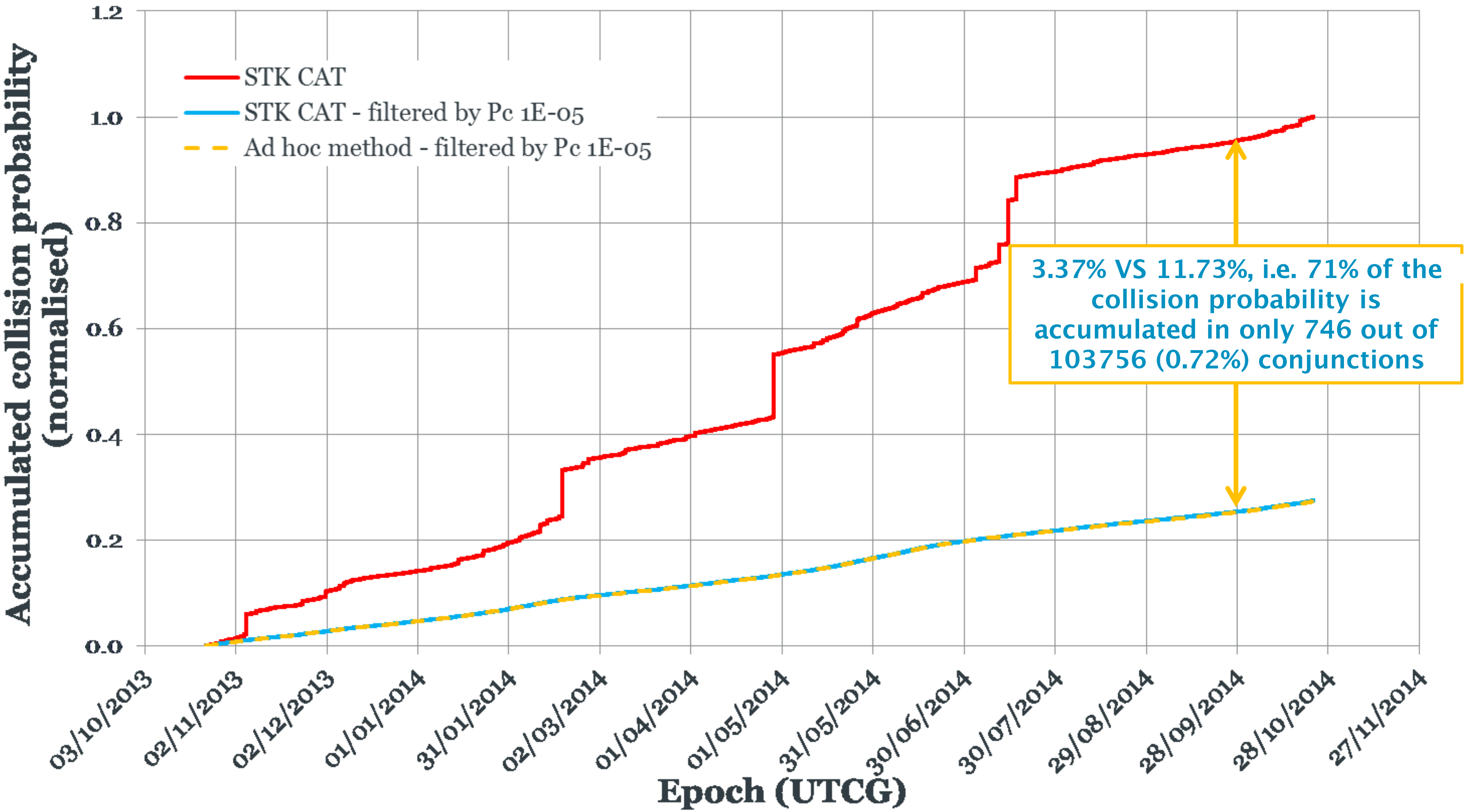
An alternative method

- Find "all" conjunctions closer than a given threshold
  - Use an adaptation of the "smart sieve"
  - Base the detection on SGP4-generated ephemerides and the public TLE catalogue
- No covariance data for TLEs
  - Compute the maximum collision probability for all the conjunctions
  - Assume spherical position errors to remove conjunction geometry bias
  - Use a database of physical objects' radii (kindly provided by T.S. Kelso)

Comparison to STK CAT – one year of conjunctions experienced by Envisat



Comparison to STK CAT – one year of conjunctions experienced by Envisat



Sensitivity studies: default object size

- Look at four classes of objects that are distinguished between in the three-line element sets and MASTER 2009 population

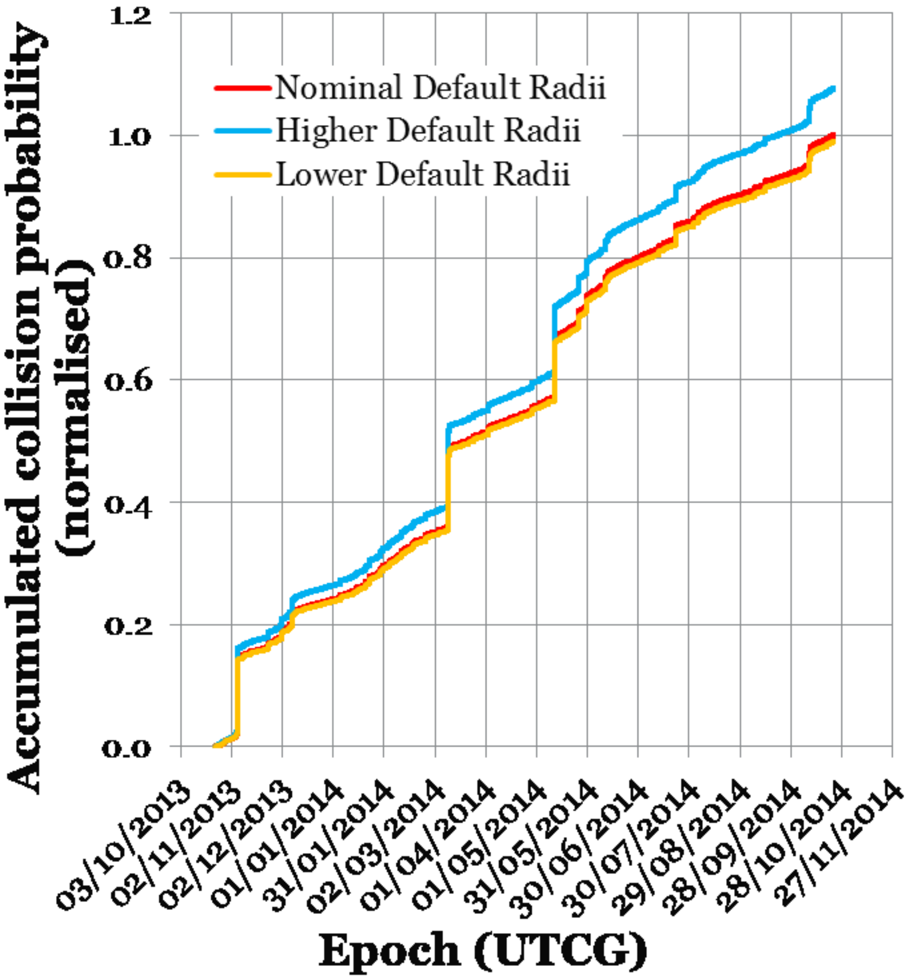
MASTER2009 objects' radii by type

Object Type	R/B	P/L	MRO	DEB	All
MASTER Object ID	1	2	3	4	1, 2, 3, and 4
Average radius (m)	1.7691	1.0350	0.5385	0.1558	0.3470
Standard deviation (m)	0.8145	0.7824	0.7219	0.5545	0.7803

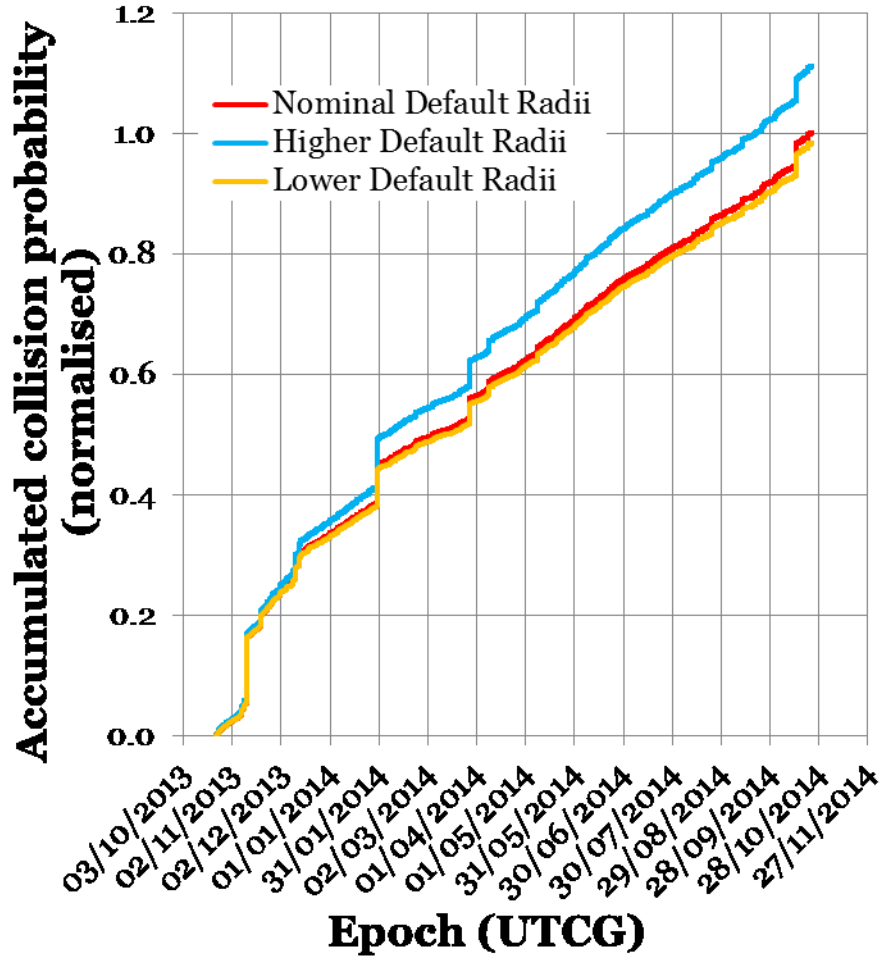
- Use two targets from the top of the list from DAMAGE runs
  - Envisat
  - Zenit-2 R/B (SSC 27006)
- Compare results for
  - Average radius
  - Average + 1 standard deviation
  - Average – 1 standard deviation (or 5 cm if standard deviation > average)

Sensitivity studies: default object size

Envisat



Zenit-2 R/B

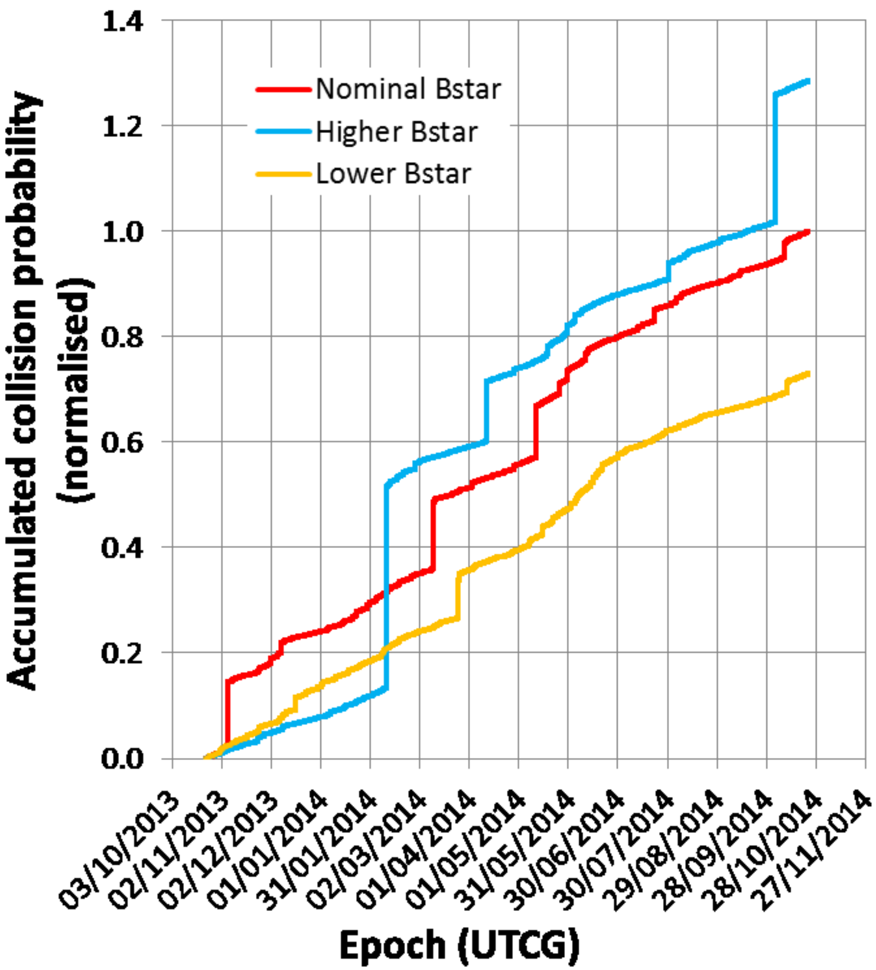


Sensitivity studies: solar activity

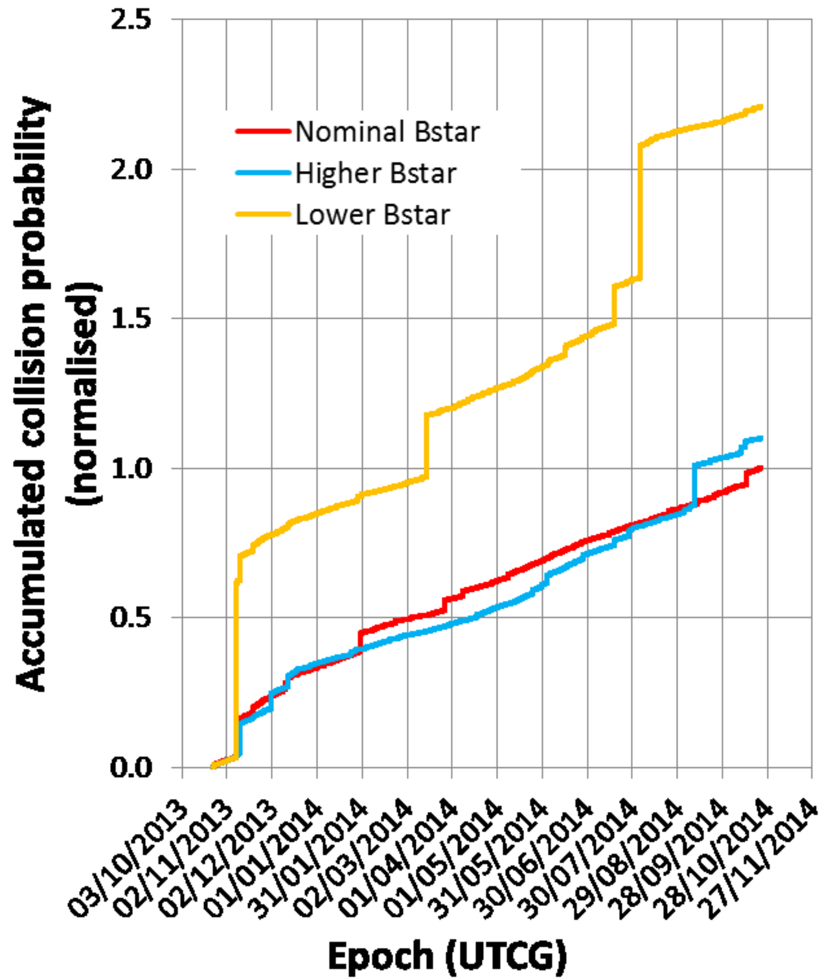
- Solar activity ⇒ atmospheric density ⇒ drag ⇒ orbit path
- Effects of solar activity on atmospheric density are not currently modelled in this work
- But a TLE component, $B^* = \frac{1}{2}\rho_0 C_D \frac{A}{m}$, is linearly proportional to density
- ∵ vary the density by varying the B^* coefficient of all the objects in the two test-cases
  - 70% nominal B^*
  - Nominal B^*
  - 130% nominal B^*

Sensitivity studies: solar activity

Envisat



Zenit-2 R/B



Lists of targets comparison: settings

- Compare long-term DAMAGE list to the *ad hoc* one
  - 200 years, 100 Monte Carlo runs for DAMAGE
  - 1 month for *ad hoc*
- Conjunctions closer than $\sqrt{300}$ km
- Select targets purely based on collision probability – no mass data for the TLE catalogue
- Use actual and maximum collision probabilities

Lists of targets comparison

DAMAGE

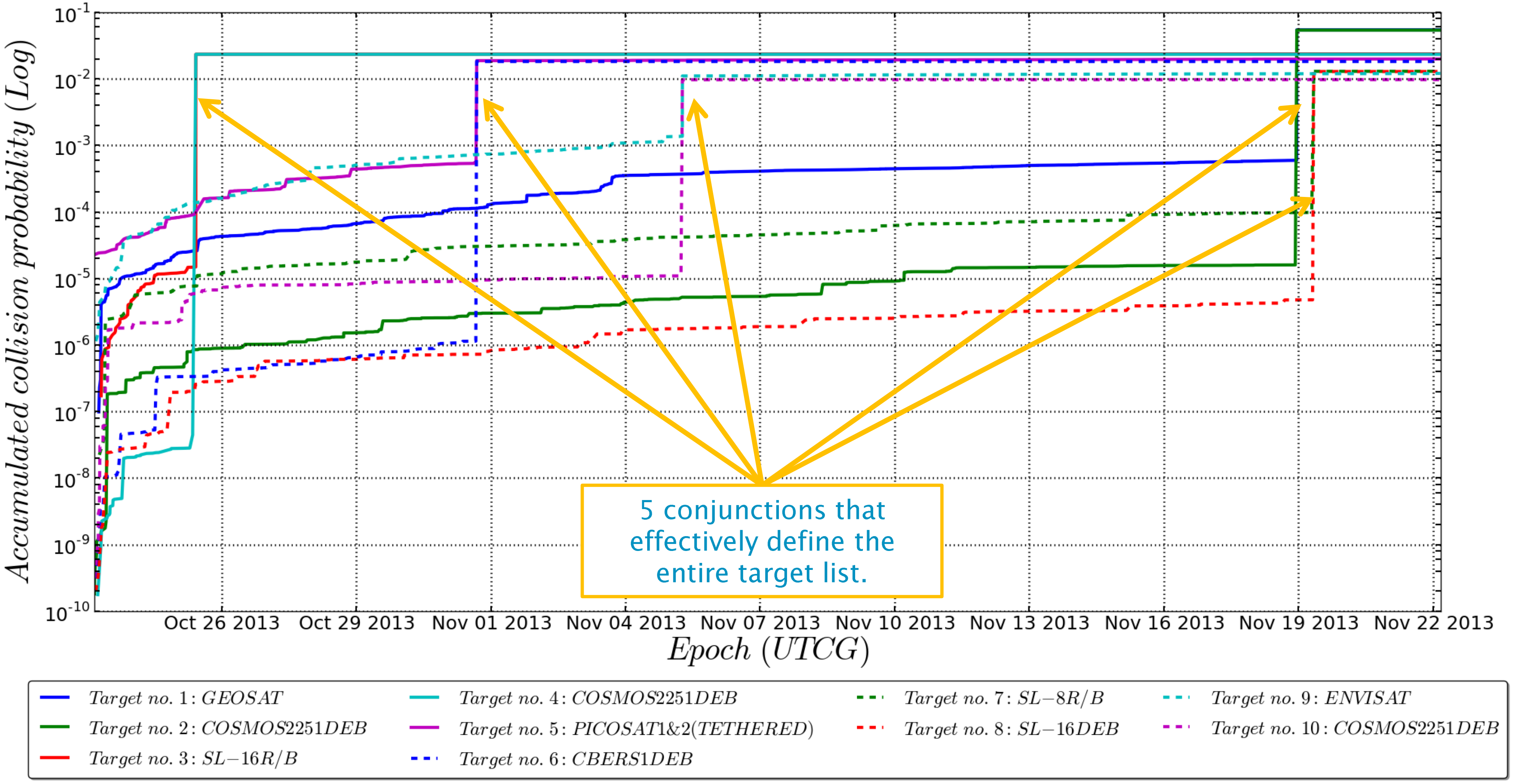
Priority	Object Type	Target	Pc	No. conjunctions
1	Other	ESA-16054	28.0416%	632
2	Other	ESA-16872	24.5130%	437
3	Other	ESA-14168	22.6456%	304
4	R/B	ESA-3693	18.8974%	1672
5	R/B	ESA-2400	18.4698%	1637
6	R/B	ESA-3927	18.2484%	1551
7	R/B	ESA-2886	17.9807%	1606
8	R/B	ESA-2219	17.8328%	1599
9	R/B	ESA-2535	17.7423%	1661
10	R/B	ESA-2789	17.7263%	1525

Ad hoc method

Priority	SSC	Name	Pc	No. conjunctions
1	15595	GEOSAT	5.4566%	3943
2	35836	COSMOS 2251 DEB	5.3906%	2227
3	25400	SL-16 R/B	2.3713%	2281
4	33812	COSMOS 2251 DEB	2.3349%	1021
5	26080	PICOSAT 1&2	2.0095%	1967
6	32066	CBERS 1 DEB	1.8204%	2822
7	7350	SL-8 R/B	1.2976%	1342
8	22374	SL-16 DEB	1.2850%	1301
9	27386	ENVISAT	1.2267%	2192
10	34552	COSMOS 2251 DEB	0.9708%	2270

- Current evolutionary models observations
  - Underestimate number of conjunctions
  - Collision probability appears largely underestimated as well but this is due to actual and maximum collision probabilities being compared
  - When both models are set to use the same probability metric the results agree
- No targets in either list match
  - Difficult to relate MASTER to SSC, but here mostly R/B on one list and DEB on the other
  - Importance of short time-scale behaviour

Lists of targets comparison: highest probability objects



Conclusions

1. We can get an idea about the objects that should to be removed from current evolutionary models, but even without them
2. The evolutionary models lack the resolution (spatial and temporal) to enable the most important, w.r.t. collision probability, conjunctions to be identified
3. Fine detail of the conjunctions can change the whole target list entirely
4. Use an *ad hoc* target selection approach rather than removing the targets selected using evolutionary models to:
   - Minimise the number of ADR missions to be performed
   - Ensure that most in-orbit collisions are avoided
   - Still probabilistic but would increase ADR efficiency

Acknowledgements:

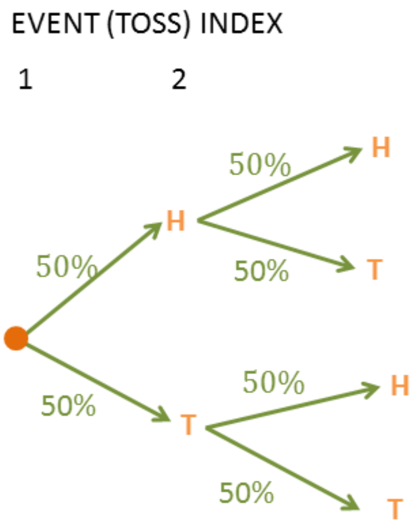
- MASTER population was kindly provided by the ESA Space Debris Office
- Objects' radii database was kindly provided by T.S. Kelso (Clestrak)
- A publically available SGP4 implementation from Celestrak was used
- Conjunction detection and collision probability estimation methods were validate using STK CAT from AGI.

Thank you

Questions?

Sum of individual probabilities VS accumulation: analogy and method

Coin toss' analogy



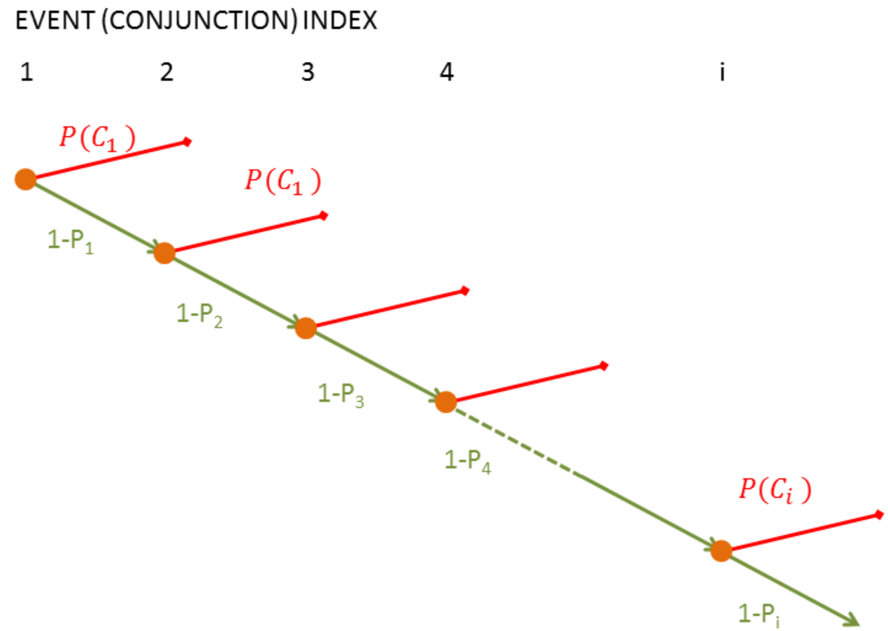
$P(HH) = 0.5 \times 0.5 = 25\%$

$P(HT) = 0.5 \times 0.5 = 25\%$

$P(TH) = 0.5 \times 0.5 = 25\%$

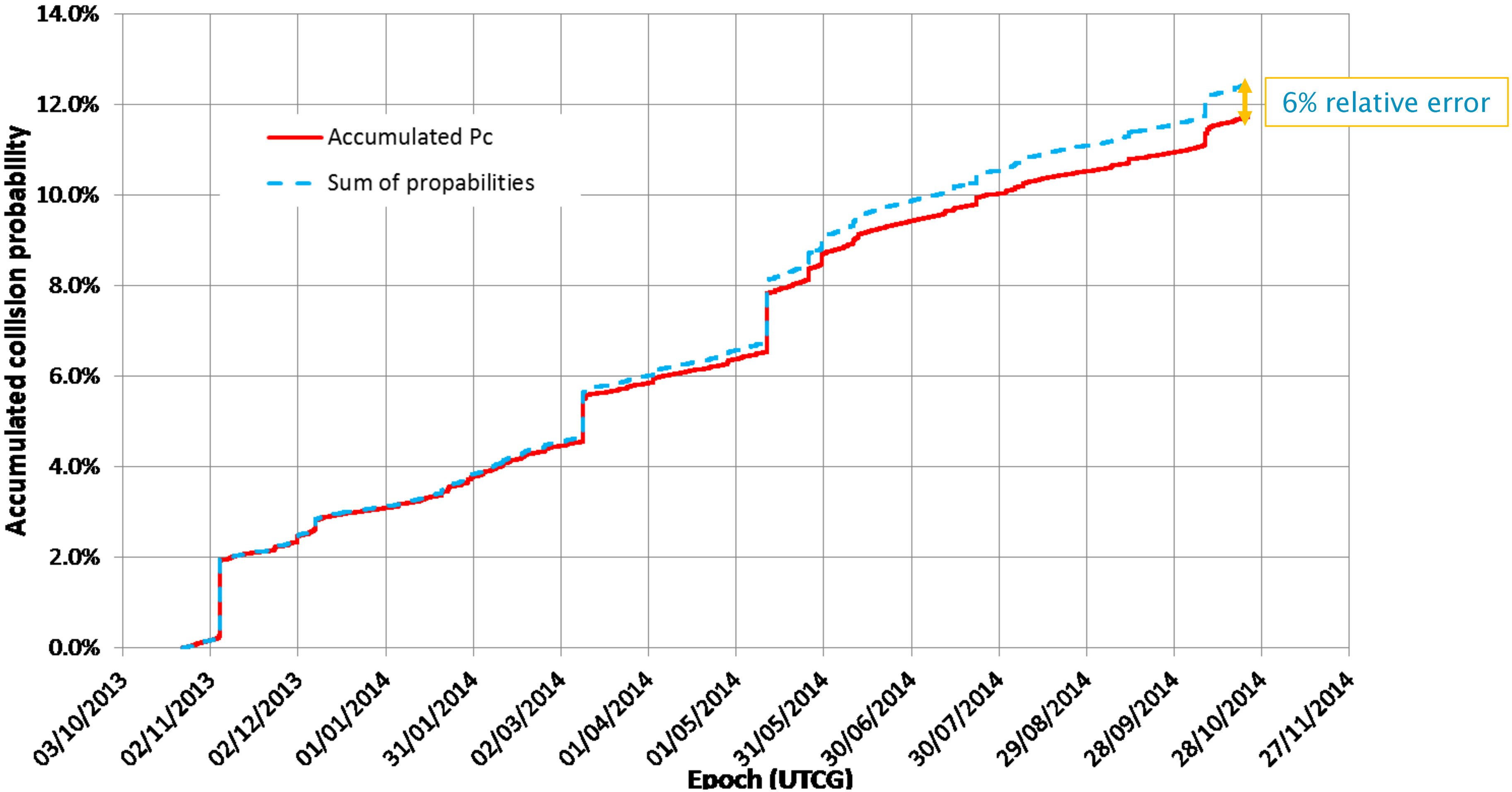
$P(TT) = 0.5 \times 0.5 = 25\%$

Application to collisions

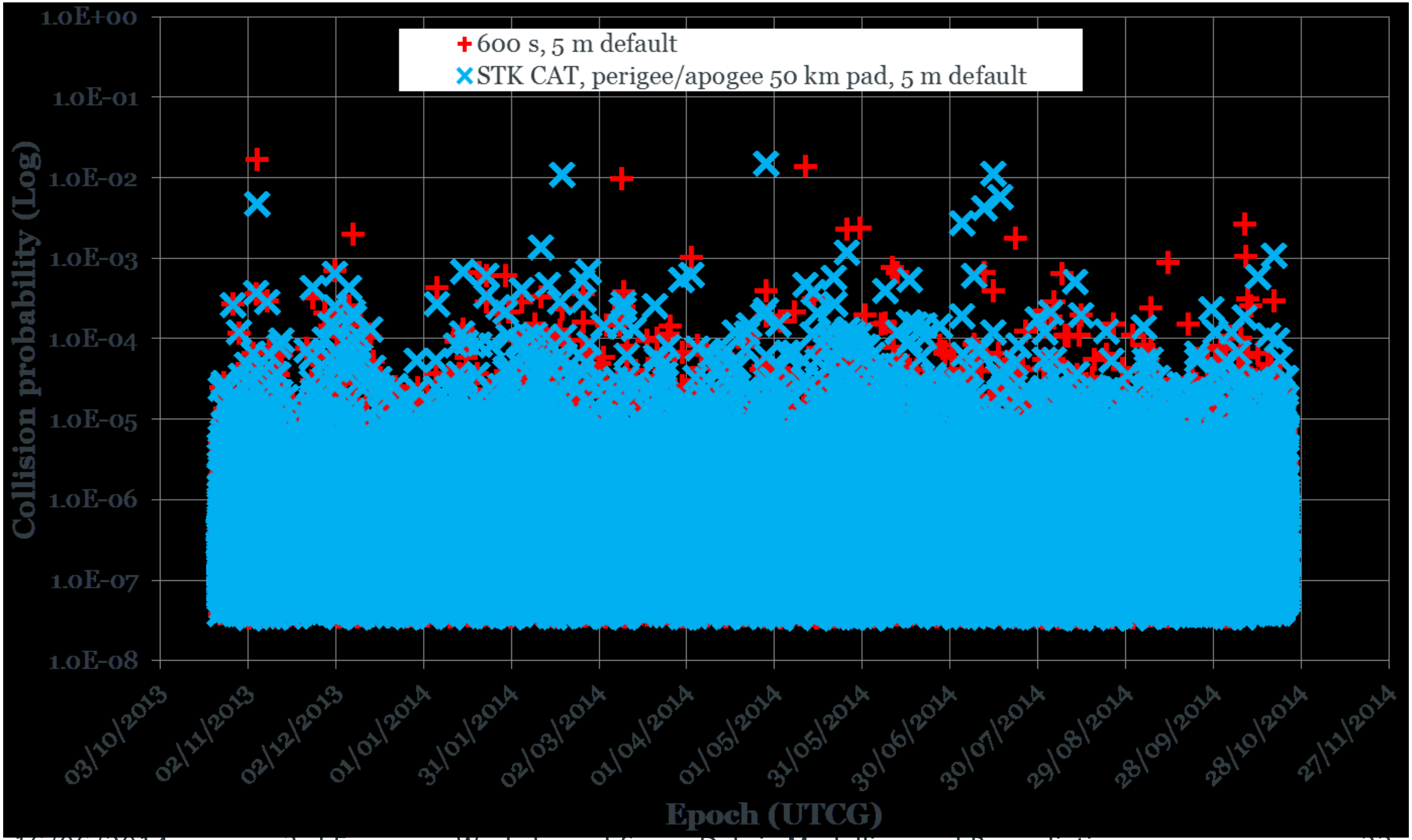


$$P(\textbf{any out of } N) = 1 - P\left(\bigcap_{i=1}^{N} \neg C_i\right) = 1 - \prod_{i=1}^{N}\left(1 - P(C_i)\right)$$

Sum of individual probabilities VS accumulation: Envisat test case



Comparison to STK CAT – one year of conjunctions experienced by Envisat



Proposed ADR workflow

1. Run long-term predictions, track highest-probability conjunctions and prevent the ones with collision probability above some threshold.

2. Use ephemerides with known covariance to support the decision-making. But need to be wary of the "probability dilution" – maximum probability is useful.

3. The highest-accuracy ephemerides should be used or some collisions can be missed anyway, e.g. Cerise – Ariane Debris collision maximum collision probability was only O(1E-06) based on the most-recent TLEs.[1]

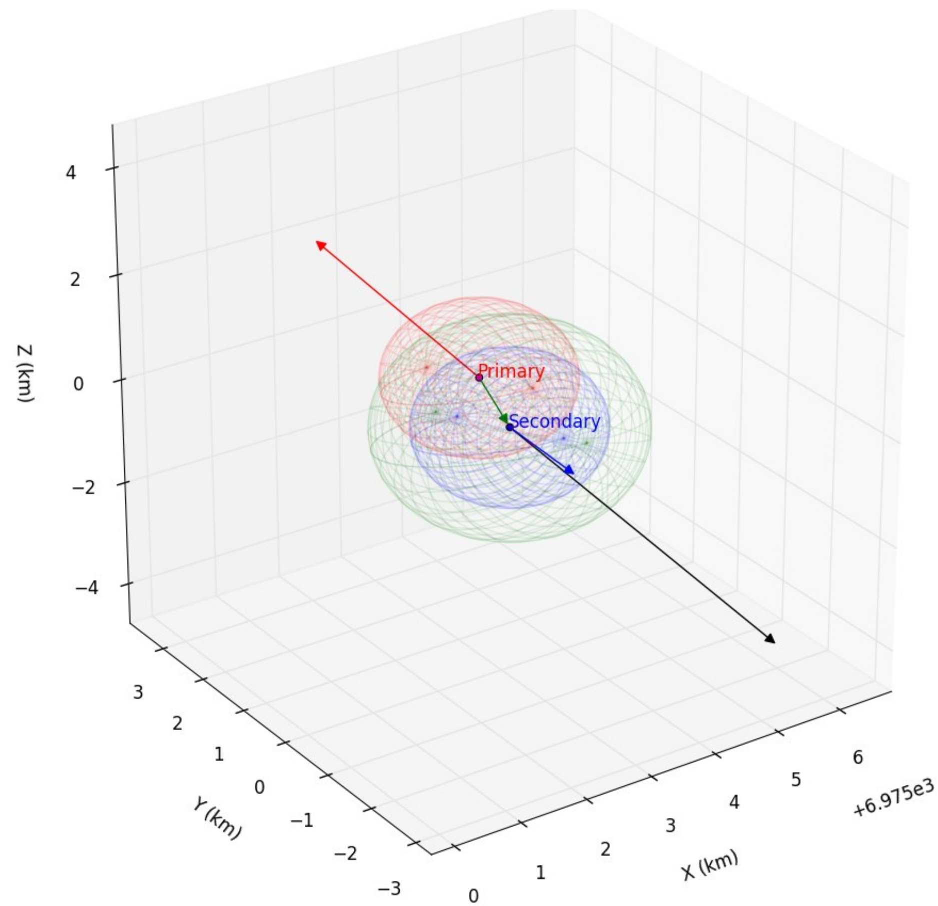
1 – N. Berend, Estimation of the Probability of Collision Between Two Catalogued Orbiting Objects, Adv. Space Res., Vol. 23, No. 1, pp. 243–247, 1999

Collision probability estimation

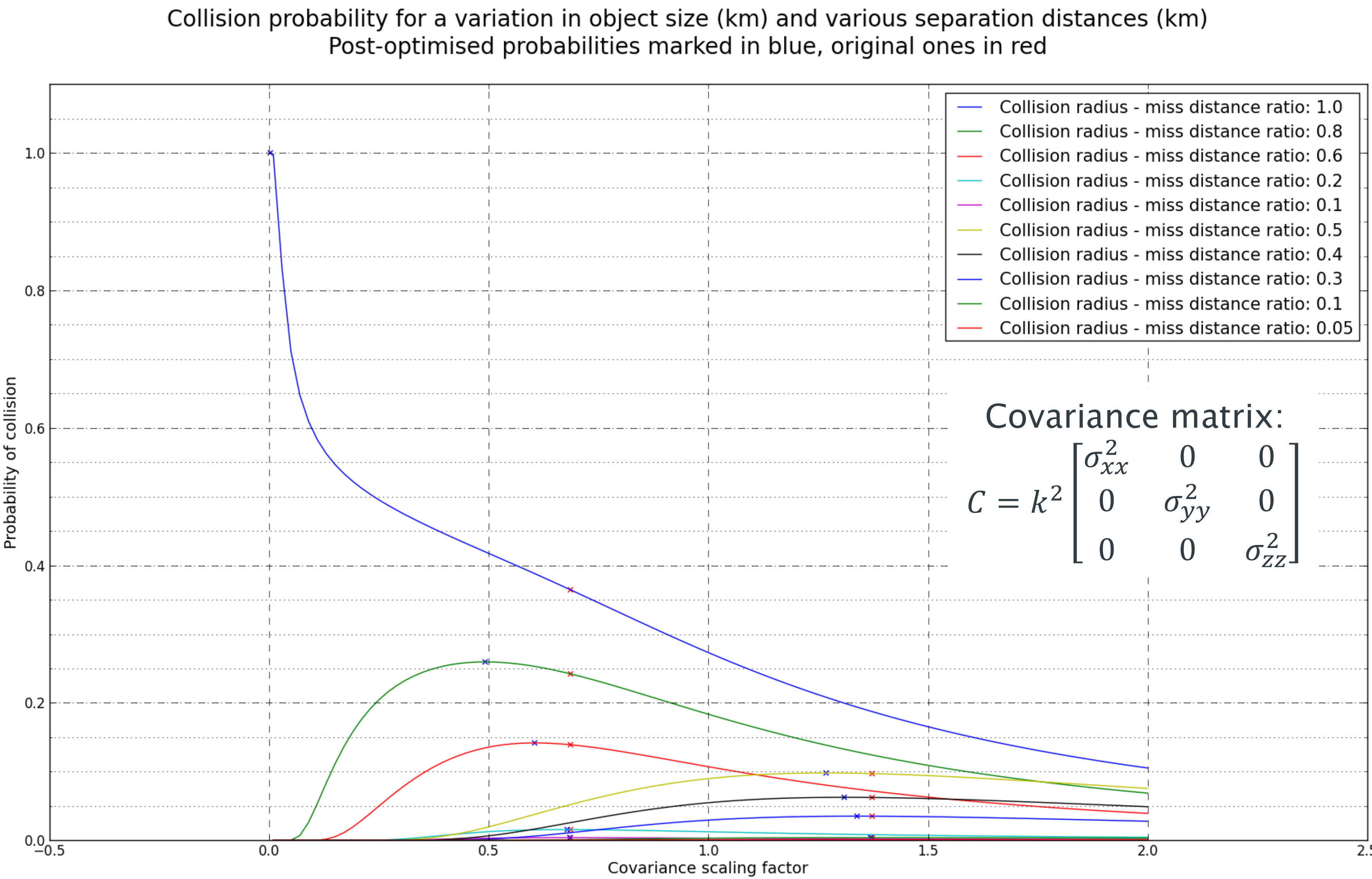
Method

1. Project actual (or worst-case) covariance matrices onto the B-plane
2. Combine covariance matrices around the secondary
3. Formulate a position Probability Density Function (PDF, maximum at the secondary)
4. Integrate over a circle with radius equal to the combined collision radius centred on the primary

Relative geometry in ECI



Maximum collision probability



$$C = k^2 \begin{bmatrix} \sigma_{xx}^2 & 0 & 0 \\ 0 & \sigma_{yy}^2 & 0 \\ 0 & 0 & \sigma_{zz}^2 \end{bmatrix}$$

Lists of targets comparison: settings

- Conjunctions closer than $\sqrt{300}$ km
  - For consistency with DAMAGE
  - limit the amount of data
  - It has been shown that it is the very close conjunctions that have the most overall effect
- T.S. Kelso's database + MASTER 2009 radii
- Nominal B^* values as quoted in the TLEs
- One month simulation
  - computationally expensive to run longer simulations
  - Little extra insight added by longer simulations
  - TLEs only accurate for several days
- Select targets purely based on collision probability – no mass data for TLE catalogue

Lists of targets comparison: DAMAGE settings

- Conjunctions closer than $\sqrt{300}$ km (cube side length of 10 km)
- Objects larger than 10 cm from MASTER 2013
- 1st January 2005 to 31st December 2013 launch traffic repeated
- No explosions
- No manoeuvres
- 95% compliance with Post Mission Disposal ("25-year rule")
- 100 Monte Carlo runs
- Actual collision probability, not maximum

Future work

- Compare effects of using maximum VS actual collision probability
- Incorporate objects' masses into the conjunction assessment
- Build a framework for periodic prediction of dangerous conjunctions