Innovative orbit determination and catalogue building methods for LEO and GEO objects

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References

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Introduction

- With the advent of the European SSA initiative there is the need for advanced concepts in tracking and cataloguing of space debris
- The Celestial Mechanics group of the University of Pisa developed advanced methods for preliminary orbit determination of asteroids AND space debris.
- These methods, widely tested in the NEO field, proved to be extremely efficient also for the space debris case in GEO.
- Together with an innovative telescope design they provide the core of an optical surveillance network for *high LEO*.

Algorithms for preliminary orbit determination

- Virtual debris algorithm based on the concept of admissible region
- Keplerian integral method based on the 2-body energy, $\mathcal{E}$, and the angular momentum, **c**, constancy, and **generalized for the J_2 problem.**

Virtual debris algorithm

- The admissible region replaces the conventional confidence region as defined in the classical orbit determination procedure.
- The admissible region is found by imposing conditions to ρ, $\dot{\rho}$
  1. $\mathcal{C}_1 = \{(\rho, \dot{\rho}) : \mathcal{E}_E < 0\}$ ($\mathcal{D}$ is a satellite of the Earth) ;
  2. $\mathcal{C}_2 = \{(\rho, \dot{\rho}) : \rho_{MIN} < \rho < \rho_{MAX}\}$ (the distance of the object from the observer is in the interval (ρ_{MIN}, ρ_{MAX})) .

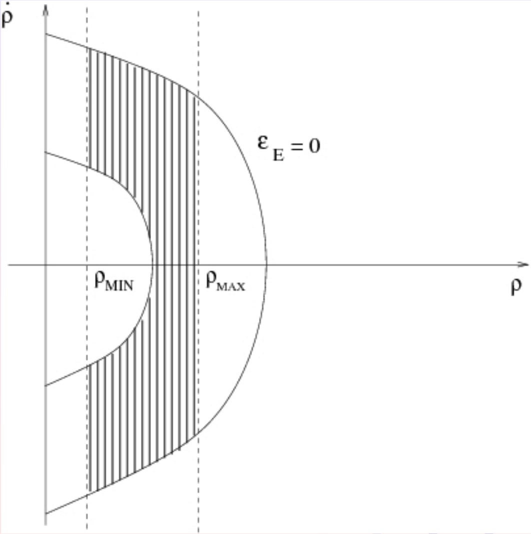
Definition

Given an attributable A_{opt}, we define as **admissible region** *for a space debris* $\mathcal{D}$ the set

$$\mathcal{C} = \mathcal{C}_1 \cap \mathcal{C}_2 \, .$$

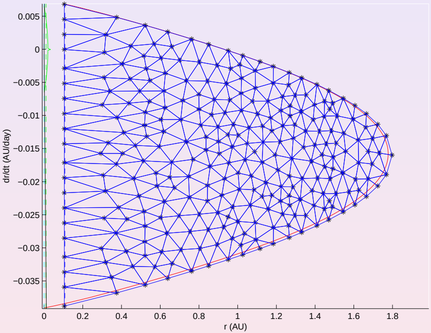
Admissible region with one connected component

It is possible to modify condition (1) to exclude "just launched" objects imposing a lower bound on the energy.



Sampling the Admissible Regions

- The AR is still an infinite set.
- Nonetheless it can be sampled with a finite number of points (Virtual Debris).
- The orbit represented by one of the VDs is a good approximation of the orbit of the real object.
- The sampling can be performed with a Delaunay triangulation (optical observations) or by a cobweb (radar observations).



Solar radiation pressure algorithm

An adaptive non-gravitational perturbations semi-empirical model was developed:

- For observed arcs either of total duration ≤ 0.01 days, or with less than 3 tracklets, we use no non-gravitational perturbation model, thus we solve for each set of correlated observations for only 6 orbital elements.
- For observed arcs with at least 3 tracklets and total duration > 0.01 days we use a model with direct radiation pressure, only the anti-Sun component, and with a free A/M parameter thus we solve for at least 7 parameters.
- For observed arcs with at least 4 tracklets and total duration > 2 days we use a model with an additional secular along track term giving quadratically accumulated along track displacement, with a free multiplicative parameter with the dimension of A/M (to ease comparison with the other term) thus we solve for 8 parameters.

Data set

- Surveys observations of the year 2007, from the ESA Space Debris Telescope (provided by AIUB), optimized to search for small-size debris in the GEO region and the geostationary transfer orbit region (GTO), *with the main objective to derive statistical information.*
- Follow-up observations of the year 2007, used to maintain a catalogue of debris objects to allow for detailed analysis of physical characteristics.
- **Surveys were not designed in a way to serve as a test for a "survey only" catalogue build-up and maintenance strategy.**

Data set

The data set contains 3 177 tracklets, among them

- 977 uncorrelated tracklets,
- 747 correlated tracklets of 349 correlated objects ("correlated" = correlated with USSTRATCOM TLE catalogue),
- 1 453 tracklets from intentional follow-up observations of 240 objects.

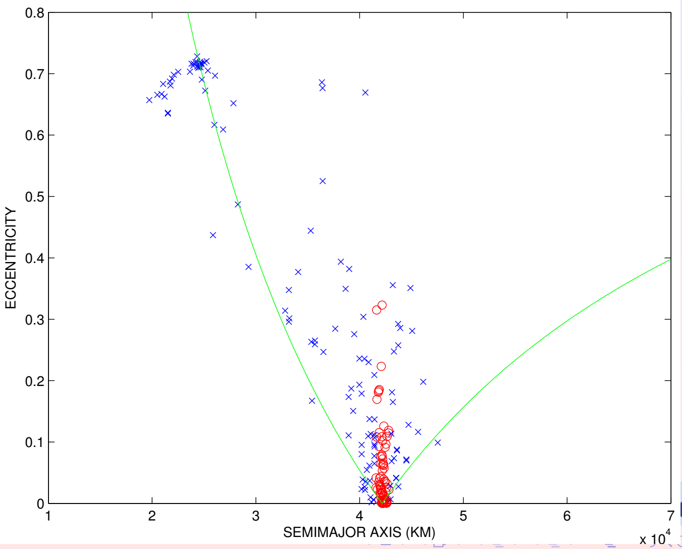
The surveys covered the GEO region rather homogeneously but were not optimized to re-observe objects, e.g., from night to night. These 977 uncorrelated tracklets could belong to 300 – 500 objects.

Study motivation

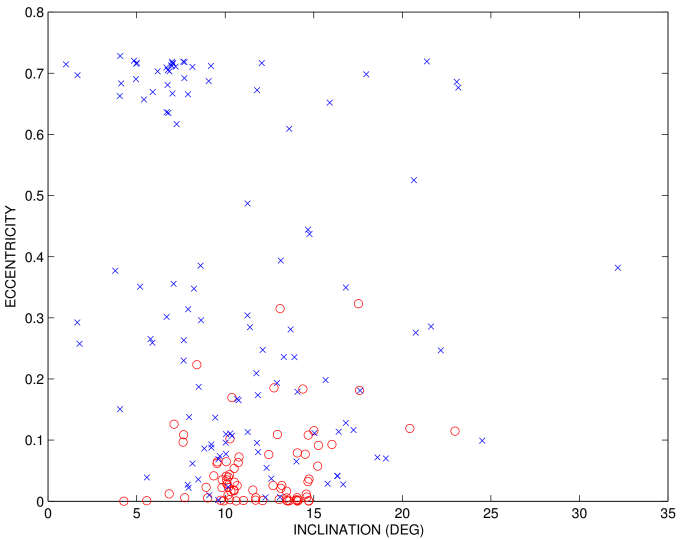
- The new algorithms and SW were applied to the data set.
- The purpose was to show that these algorithms are adequate for a future catalog buildup activity by ESA.
- Thus we selected a time interval long enough that we can presume a future SSA survey would have observed all target objects within such a period, and short enough to allow for accurate orbit determinations with our semi-empirical non-gravitational perturbations model.
- We selected the lunation as a kind of natural time unit for observations. The tracklets of objects observed several times within one lunation should be correlated. On the contrary, objects observed only once per lunation may not be correlated, because this is well beyond the SSA specifications.

GEO results: *a* vs. *e*

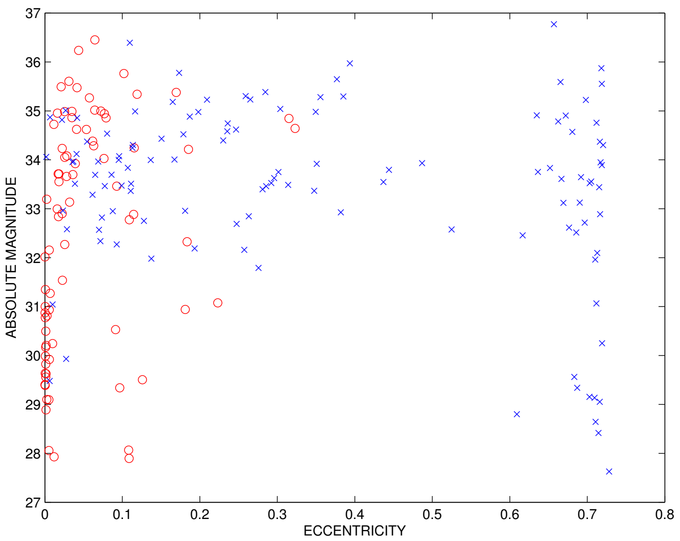
Out of 3 177 input tracklets, 1 503 were correlated, 1 674 left uncorrelated.



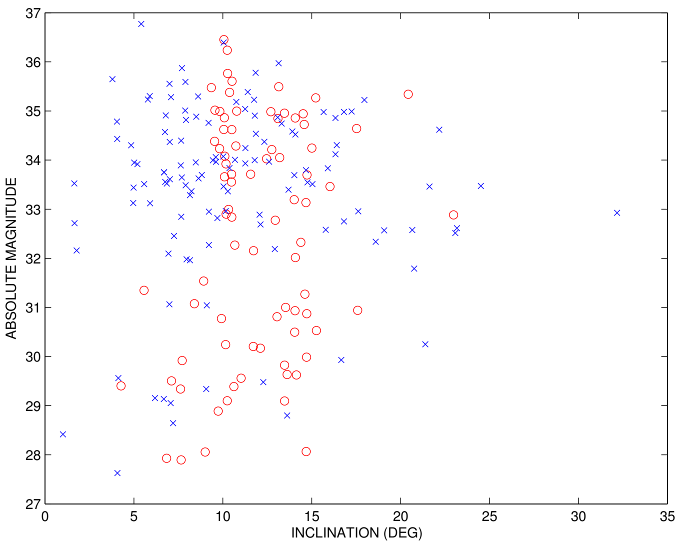
GEO results: i vs. e



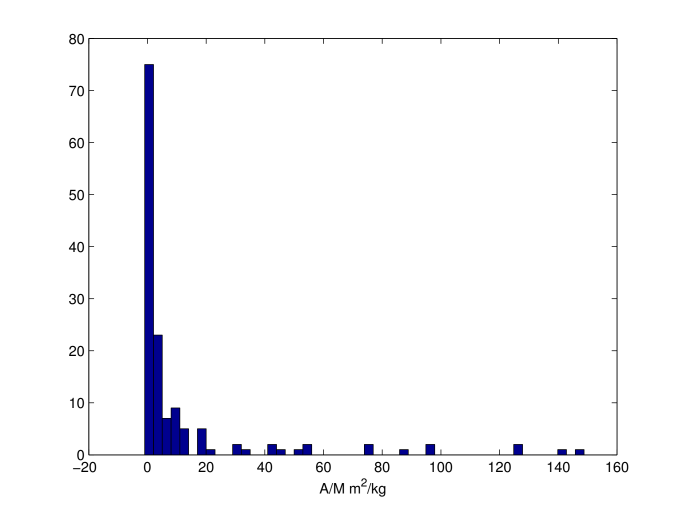
GEO results: *e* vs *H*



GEO results: *i* vs *H*



GEO results: high A/M objects



Assessment of the results

Summary of the comparison with AIUB for the first lunation. Between parenthesis is the number of occurrences where we identified the reason for the smaller or missed correlations with an observation strategy not optimized for our algorithms.

Number of Tracklets	Equal	Larger	New	Smaller	Missed	Mixed
16	-	-	-	-	-	1
10-11	1	-	-	1	-	-
7-8	7	1	1	-	-	-
4-6	7	3	-	1	1 (1)	-
3	4	3	2	3 (3)	1 (1)	-

Assessment of the results

- Some of the smaller and missed correlations could be traced back to the observation strategy.
- The observation strategy was not intended for the exploitation of the used algorithms
- In particular the requirement of avoiding the singularities and of the limiting time span of the methods was of course not considered
- 2-tracklet correlations were deemed not reliable (typical RMS in *a* were thousands of km for observations taken in the same night.) The probability of being true if a longer time span was available is judged to be very low. A comparison among the 2-tracklet correlations proposed by AIUB and the new method shows a very large fraction of disagreement $\Longrightarrow$ 2-tracklet correlations are to be considered as an intermediate data product.

GEO study conclusions

- The new methods allowed the determination of six-parameters orbits from a standard dataset of optical observations.
- The VD algorithm to be applied for short time intervals between observed arcs (a few orbital periods). KI used for longer time spans (several orbital periods).
- No a-priori information nor simplified assumptions (such as circular orbits) were required.
- The observation strategy was completely independent from the design of the methods and not optimized for their use.
- Even the most demanding cases of high A/M objects were successfully treated.

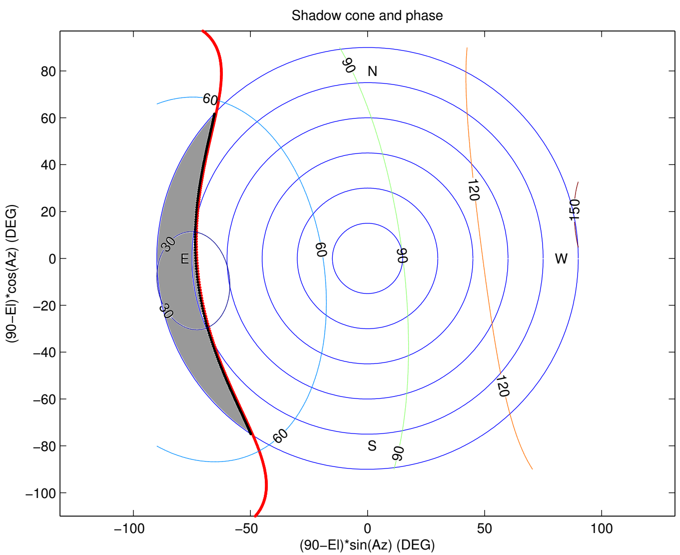
SARA Study motivation

- Complement radar measurements in LEO above $\sim$ 1100 km, to lower the power requirements (and costs).
- Identify and test a suitable network of optical instruments with a full scale simulation of the measurement process

Stations and telescopes

- The network is dictated by a tradeoff between geopolitics science and meteo reasons. It includes 7 stations with 3 telescopes each:
  - 3 in the equatorial area
  - 2 in the northern hemisphere
  - 2 in the southern hemisphere
- Telescope with a primary mirror of 110 cm diameter (equivalent aperture 100 cm), fast moving.
- Fly eye concept, with single CCD chips cameras well separated, with a private focal plane segment for each one.
- Large field of view: 45 square degrees (24000 $\times$ 24000 arcsec)

Data processing assumptions



Dynamics fence chasing optimal phase angle conditions.

Tropical station at solar time 19:00 hours.

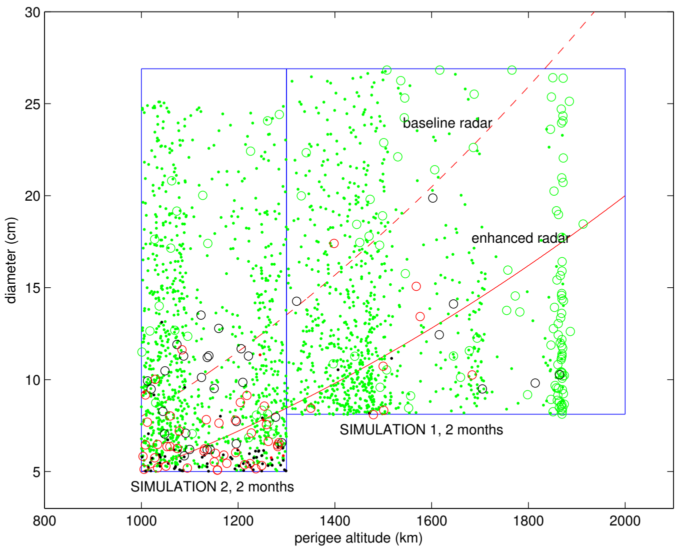
Data processing assumptions

- Dynamics fence chasing optimal phase angle conditions.
- Image processing software detecting trails.
- Astrometric reduction algorithms which allow for sub-pixel accuracy.

Simulation setup

- Two simulations:
  1. 912 objects with absolute magnitude between 35.857 (diameter 26.828 cm) and 38.458 (diameter 8.098 cm) and with altitude of perigee $q > 1300$ km (from MASTER)
  2. 1104 objects, with absolute magnitude between 36 (diameter 25.118 cm) and 39.5 (diameter 5.011 cm) and $1000 \leq q \leq 1300$ km.
- Orbit propagated and synthetic observations generated (assuming albedo of 0.1).
- Meteo effects: realistic cloud coverage model, based on actual weather satellite data (cloud coverage totally correlated within one night)
- Orbit determination: Keplerian integrals method, with J_2 add-on

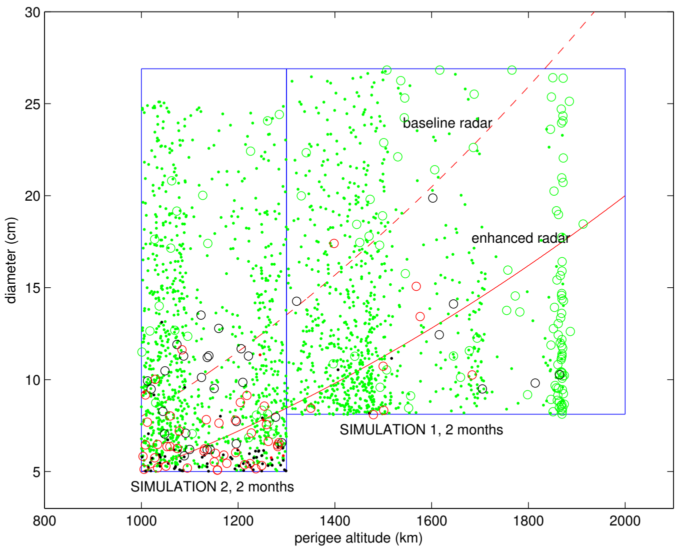
Results of the 2-month simulation



$$d_{min} = \sqrt{\frac{h^4}{h_{ref}^4} d_{ref}^2}$$

$d_{ref} \sim 5$ cm
$h_{ref} \sim 800$ km

Results of the 2-month simulation



Dots = resident LEO

Circles = transit objects

Green: catalogued

Red: no observations

Black: there are observations but no orbit.

Results of the 2-month simulations

SIMUL 1	Total	LEO	PLEO	LTO
No. Objects	912	796	97	19
Orbits Computed	894	793	95	6
Obj. without orbit (with 1-2 Tr.)	10 (3)	3 (0)	2 (0)	5 (3)
Obj. not observed	8	0	0	8

SIMUL 2	Total	LEO	PLEO	LTO
No. Objects	1104	1014	62	28
Orbits Computed	965	942	21	2
Obj. without orbit (with 1-2 Tr.)	92 (13)	67 (9)	16 (2)	9 (2)
Obj. not observed	47	5	25	17

Efficiency of the 2-month simulations

Efficiency = ratio between the number of reliable orbits computed (with at least 3 trails) and the total number of objects.

SIMUL 1	Total	LEO	PLEO	GTO
Eff. Catalog	98.1%	99.6%	97.9%	31.6%
Eff. above radar	98.6%	99.8%	97.2%	71.4%

SIMUL 2	Total	LEO	PLEO	GTO
Eff. Catalog	82.8%	86.6%	37.5%	7.1%
Eff. above radar	93.7%	98.9%	97.2%	25.0%

Orbit improvement

The same telescopes and stations are used for follow-up.

The numbered orbits are accurate enough to perform follow-up with no trailing loss
(most signal concentrated on a single pixel (1.5×1.5 arcsec)).

After 3 weeks of follow-up, the accuracy from the improved orbits is compliant with the collision avoidance requirements (99.5% and 99.9% of resident LEOs for Pop. 1 and 2).

$$\downarrow$$

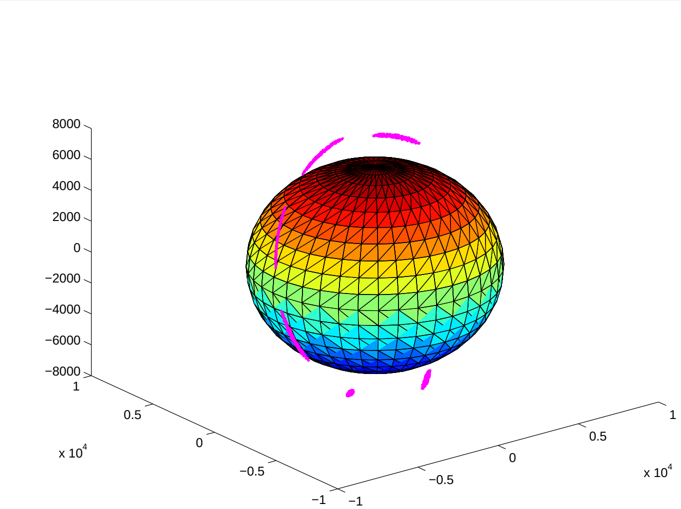
Fixed an **object-centred reference frame (OCRF)**, with origin in the centre of mass of the object (radial, tangent, binormal direction) the reached accuracy is inside the envelope

- **for position:** $4 \times 30 \times 20$ m
- **for velocity:** $20 \times 4 \times 20$ mm/s

Fragmentation detection simulations

- 1 catastrophic collision and 1 explosion @ 1400 km were simulated (NASA Model)
- Fragments with $L_c \geq 10$ cm and $\Delta V \leq 100$ m/s were propagated for 21 days and observations generated
- Simulated correlation and orbit determination process, to check how soon after the event it is possible to have robust information on the fragmentation, e.g., by a Gabbard diagram.

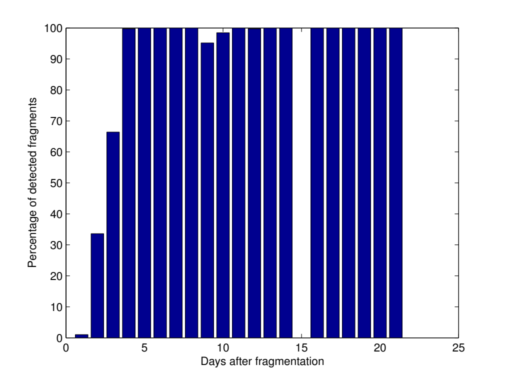
Collision cloud: T0 + 7776 sec



Detection statistics: collision

Percentages of objects observed each day after collision.

- 1 day: 1.02 %
- 2 days: 33.59 %
- 3 days: 66.41 %
- 4 days: 99.74 %
- 5 days: 100 %
- 6 days: 100 %
- 7 days: 100 %
- ....



Catalog build up of fragments

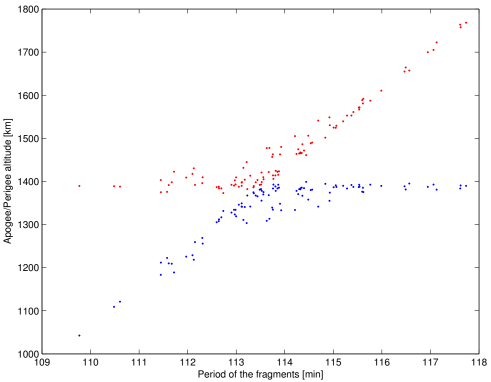
- If 2 days are enough to be able to observe a quite high percentage of fragments, say between 25 % and 30 %, they cannot be enough also to compute reliable orbits for the observed fragments.
- There are too few observations and in fact no orbits are available after only two days for both the simulations.
- After 4 days the situation improves and we have 90 orbits for the collision fragments, 46 orbits for the explosion fragments, if we consider as acceptable correlations of at least 3 tracklets and discard the ones between only 2 tracklets.
- By comparison with the ground truth we find that some of the correlations are false, that is they put together observations of different objects. Anyway, all the false correlations have only 3 tracklets and this is true for both the simulations in the entire period examined.

Catalog build up of fragments

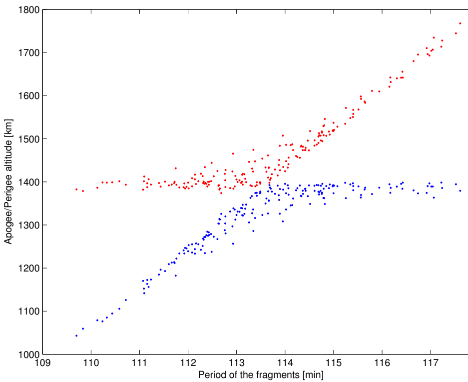
- It is quite natural to have false correlations even among 3 tracklets, because all the fragments have similar orbits.
- To exclude false correlations we must consider only orbits which fit at least 4 tracklets.
- In the following diagrams we will consider as reliable the orbits which fit at least 5 tracklets and we will consider as cataloged the orbits with at least 10 tracklets.
- We find that after only 2 weeks all the objects are cataloged.

6 days after event

Explosion



Collision



Fragm. Det. - Conclusions

- The detection of a stream of fragments, with low ejection velocity, within 24 hours is like detecting a single object, because the fragments are not spread along the entire orbit.
- After a few days, the core of the fragments cloud with $\Delta V < 100$ m/s is fully detected.
- The reason why it is not possible to detect a large fraction in 1 day is meteo, that is cloud cover on the critical stations (see day 15).
- The Gabbard diagram, built with the output of the orbit determination simulation after 6 days, shows that the orbital information is more than enough to assess the fragmentation event (parent body, energy, etc.).

Fragm. Det. - Conclusions

- Thus collision detection can be easily achieved.
- From the results of our simulation, for a large and catastrophic impact/collision, the time span to detect a number of fragments with close orbits, enough to decide there has been some fragmentation, is 2 days.
- As for the time span needed to assess the fragmentation event, finding the parent body and evaluating the impact energy, 6 days are certainly enough (some less precise indication in 4 days).
- Finding all (or at least 98 %) of the fragments may require about 2 weeks.

LEO study conclusions

- more than 98% of the LEO objects with perigee height above 1100 km and diameter greater than 8 cm can be catalogued in 2 months
- a central area around 1100 km of orbital perigee altitude has been identified where the radar and the optical network should operate in a cooperative way
- all the numbered orbits are accurate enough to allow follow-up observations with no trailing loss
- the orbit accuracy of the improved orbits is compliant with the collision avoidance requirements
- the network is able to detect and catalogue the fragments generated by a catastrophic event just a few days after the event

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