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Dynamical Evolution of Debris Clouds in GEO

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Introduction

- A growing concern developed in 1980s regarding the possible overcrowding of the geostationary orbit (GEO) and the consequent menace to its long-term utilization
- During the 1990s, it became clear that spacecraft and upper stage breakups contributed to the GEO debris environment
- **To date, only two fragmentations near GEO have been identified with high confidence**:
  - A breakup of an Ekran 2 satellite, in 1978
  - An explosion of a Titan 3C Transtage, in 1992

Other fragmentations might be expected to have occurred in proximity of the geosynchronous region, but their identification is made problematic by the

- difficulty to detect and track small objects at a so high altitude
- long time passed since the events
- the orbital perturbations affecting the resulting debris clouds

Observation Campaigns in GEO

Optical observations have recently confirmed the presence of a large population of decimeter-sized particles

To expand the knowledge of the debris population in and near the geostationary ring, various international observation campaigns in GEO have been carried out in the framework of the Inter-Agency Space Debris Coordination Committee (IADC) activities, mainly using

- the ESA 1 m telescope, at the Teide Observatory in Tenerife, Canary Islands
- the NASA Charged Coupled Device (CCD) Debris Telescope (CDT), located near Cloudcroft, in New Mexico
- the University of Michigan's Curtis Schmidt Telescope at the Cerro Tololo Inter-American Observatory in Chile

Some preliminary results confirmed the **presence of a few clusters of small debris at high inclination** in the distributions of inclination versus right ascension of the ascending node.

……… Similar clusters might be expected for fragments of breakup events **…….**

Purpose of this Work

To provide the optical observers with useful information and clues in

- identifying
  and
- characterizing

some clusters of small objects, maybe due to breakup events in proximity of the geosynchronous region

- Three fragmentations in GEO of a typical communications spacecraft have been simulated by assuming a reasonable range of the fragments' ejection velocities
- The resulting debris clouds have been propagated for 72 years, saving the results at intermediate time steps
- The results are presented as snapshots, at given post-explosion times, in the orbital element space

Simulated Fragmentations

A typical 2000 kg spacecraft was supposed to explode in GEO

Breakup Initial Conditions

Breakup Epoch	1 May 1999, $3^h\,32^m$ UTC
Semi-major axis	42164 km
Eccentricity	0.00007
Inclination	0.1°
Ascending Node Right Ascension	75°
Perigee Argument	64°
Mean Anomaly	159°

The fragmentations were modeled using the debris CLouD SIMulator software (CLDSIM) developed at ISTI

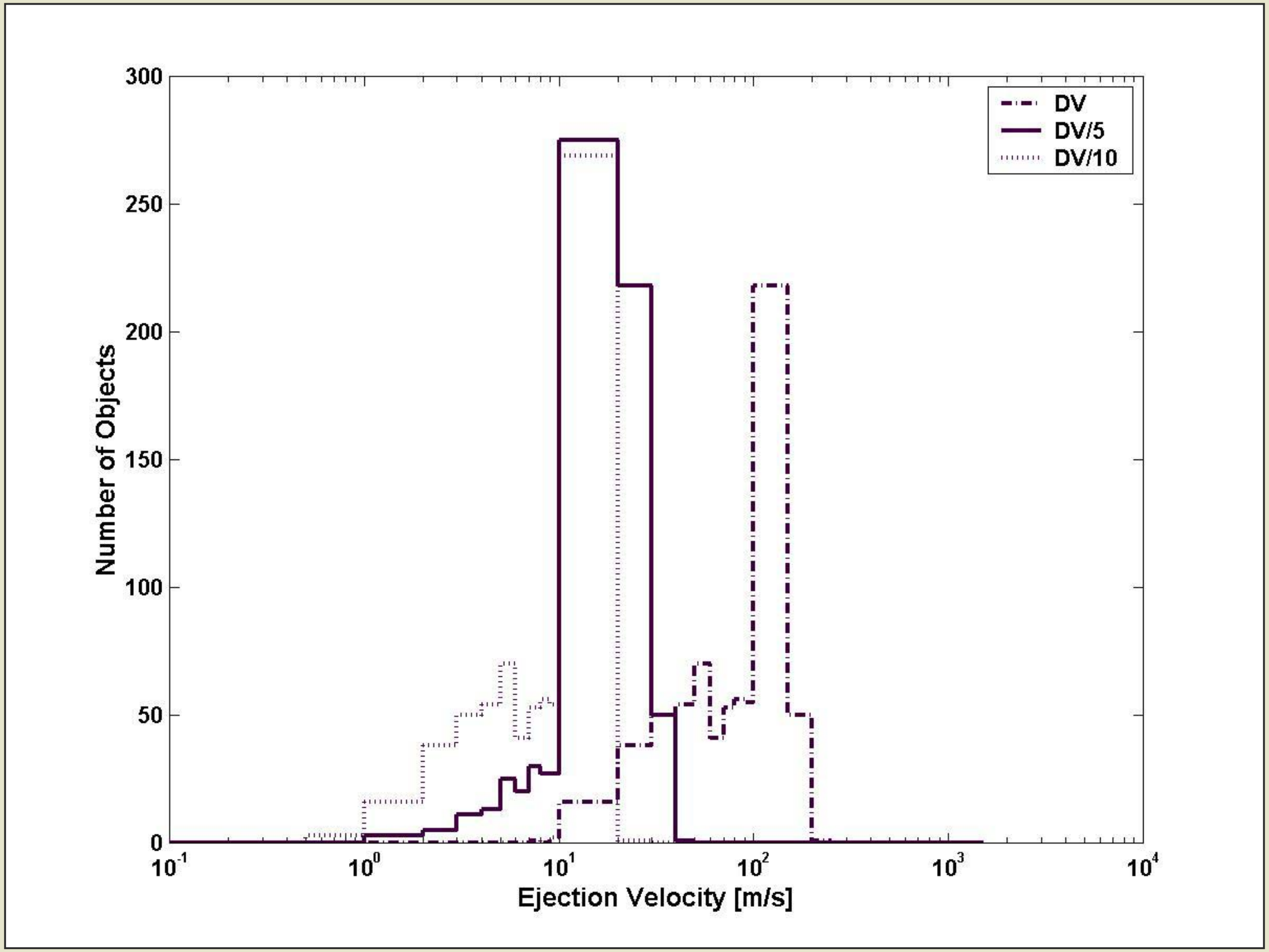
Three different breakups were simulated by varying the fragments' ejection velocities

$$\log(\overline{\Delta V}) = -0.0676\,(\log d)^2 - 0.804\log d - 1.514$$

$$\Delta V = \begin{cases} \overline{\Delta V}\,(0.1 + 0.6\sqrt{3y}) & 0.00 \le y < 0.75 \\ \overline{\Delta V}\,(1.3 - 0.6\sqrt{1-y}) & 0.75 \le y \le 1.00 \end{cases}$$

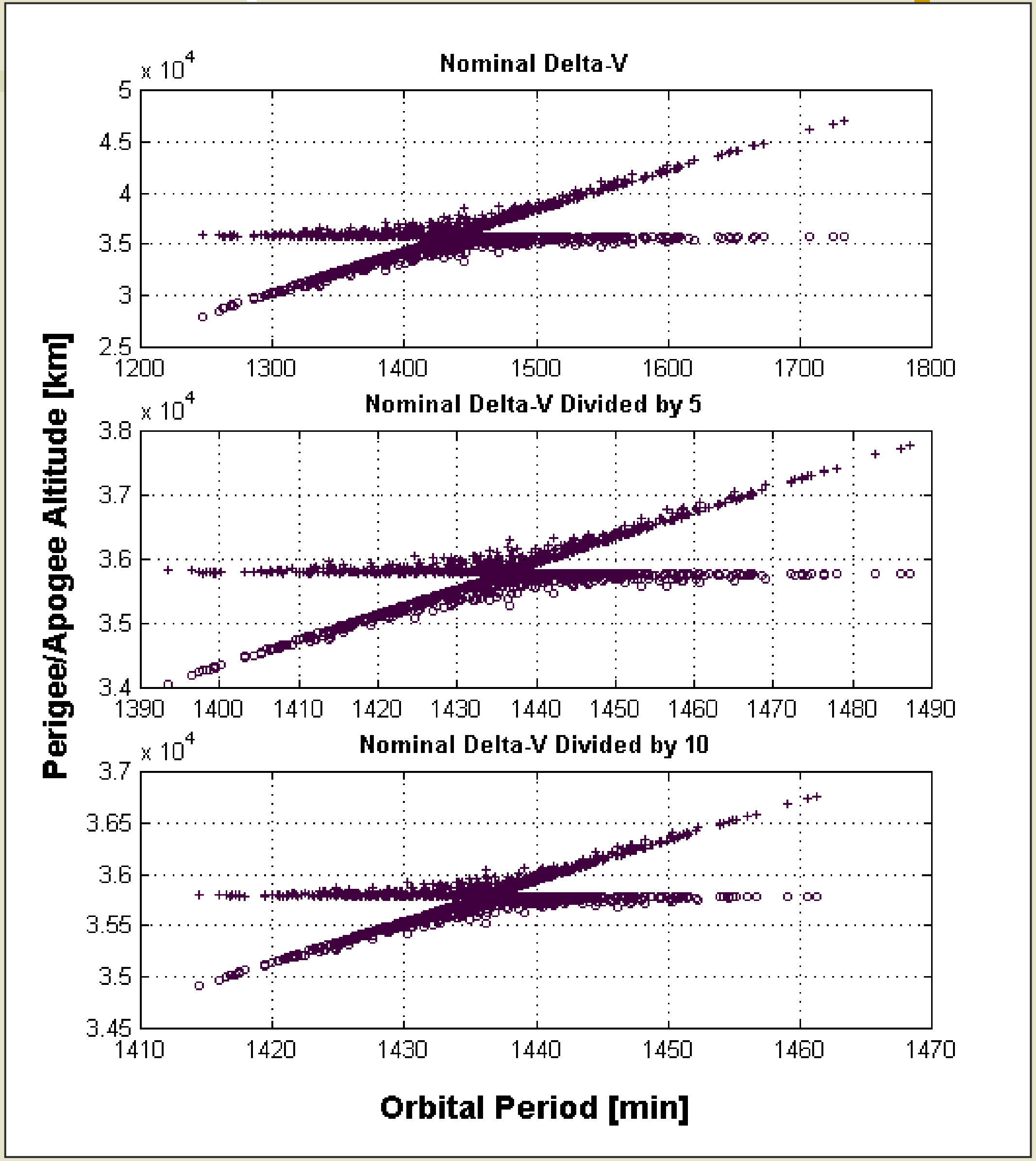
1. ΔV
2. $\Delta V / 5$
3. $\Delta V / 10$

Distribution of Ejection Velocities for Debris ≥ 10 cm

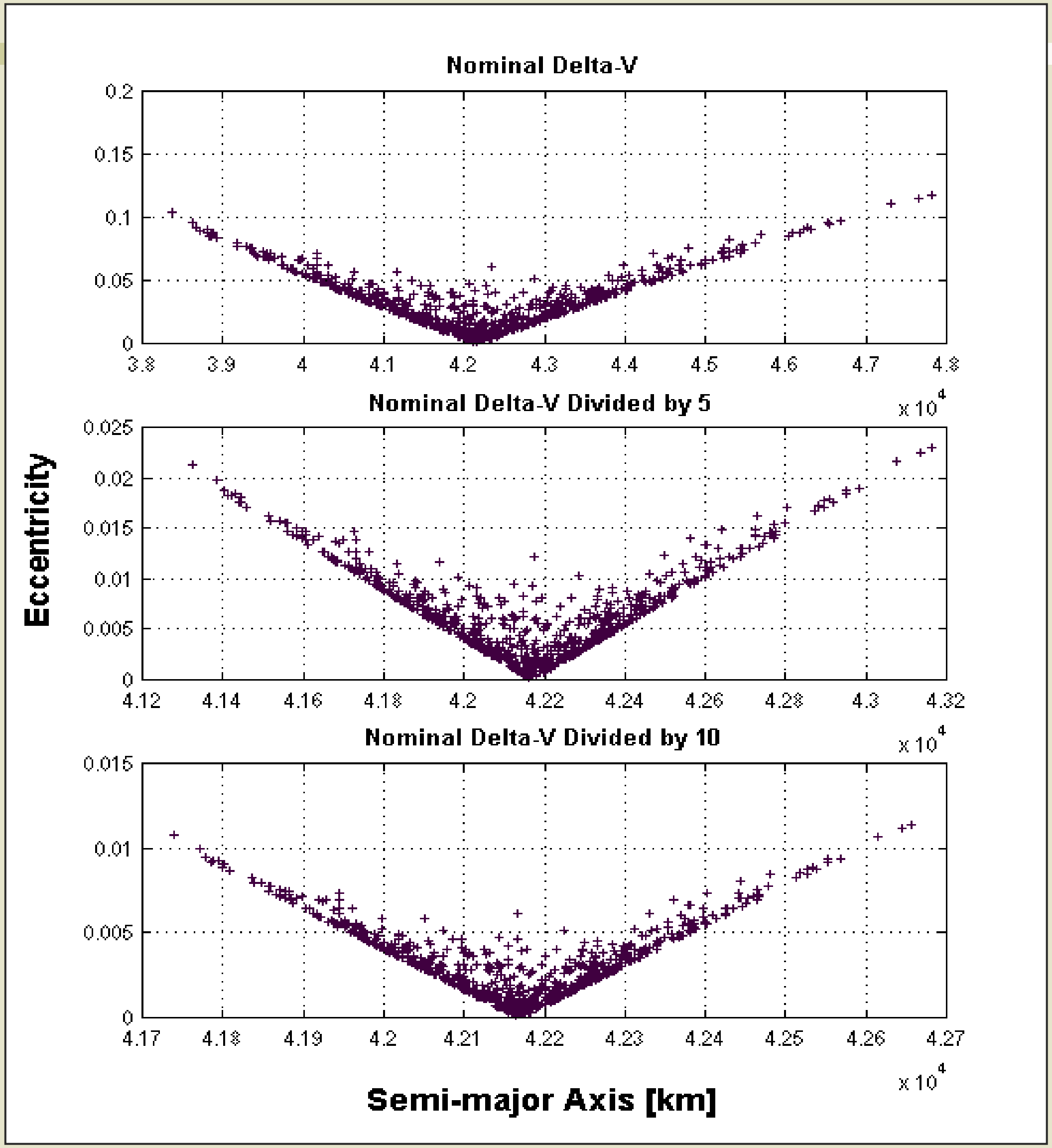


Gabbard Diagram for Debris ≥ 10 cm at the Breakup Time

As the aim of this work is to support the observation campaigns in GEO and since only particles larger than 10 cm are at present within the reach of dedicated optical sensors, only the space distribution and long-term evolution of these largest fragments are presented



Distribution of Eccentricity vs. Semi-major Axis for Debris ≥ 10 cm at the Breakup Time



Debris Clouds Propagation

In each case, the resulting debris cloud consisted of

- 1733 fragments larger than 1 mm
- 1630 fragments larger than 1 cm
- 705 fragments exceeding 10 cm in diameter

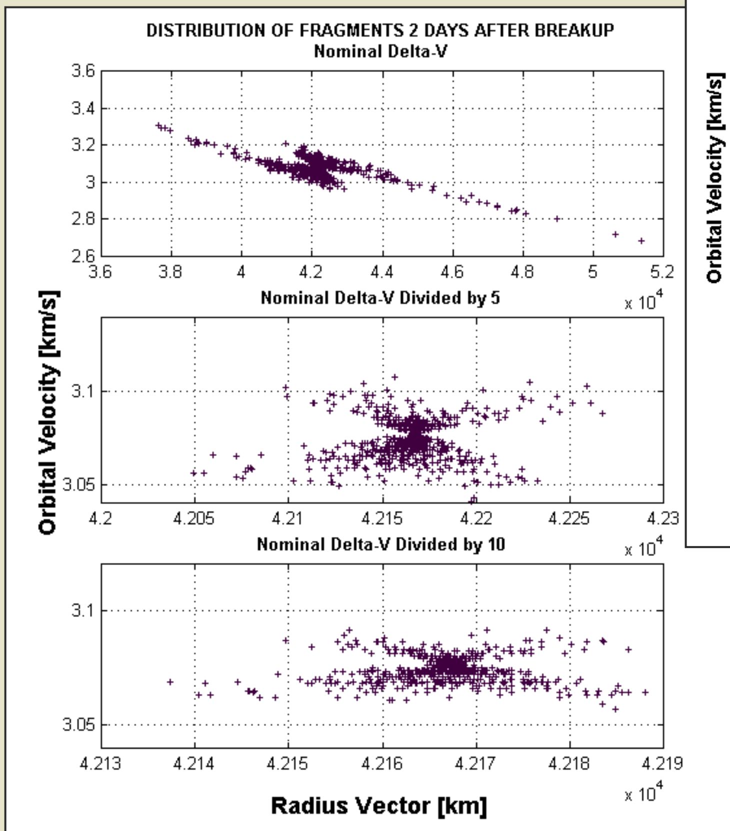
The maximum debris ΔV for the nominal explosion was 1.9430 km/s, dropping to 0.3885 km/s and 0.1943 km/s for simulations 2 and 3, respectively

Each fragment was individually propagated using a modified version of the ASAP/JPL program for 72 years, saving the results at intermediate time steps: 2 days, 1 year, 6, 12, 18, 24, 30, 36, 42, 48, 54, 60, 66, 72 years from the breakup.

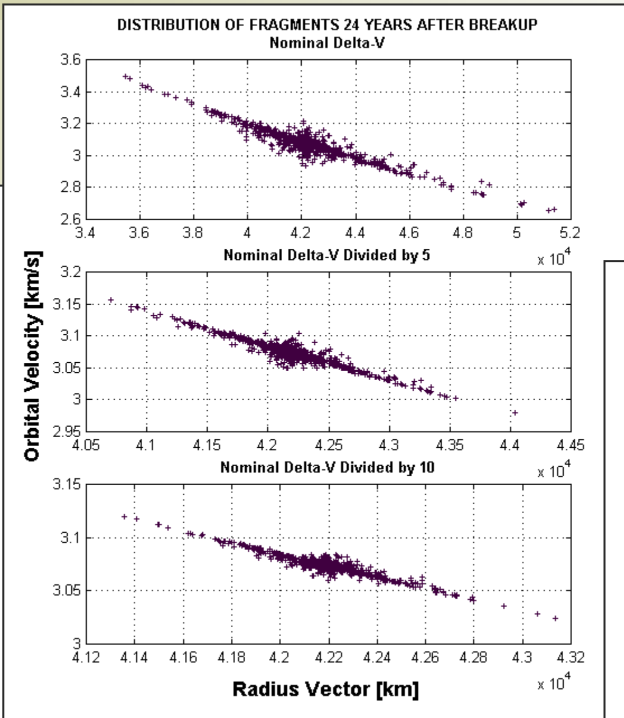
All the relevant orbit perturbations were included:

- Geopotential (8 x 8)
- Luni-solar attraction
- Solar radiation pressure

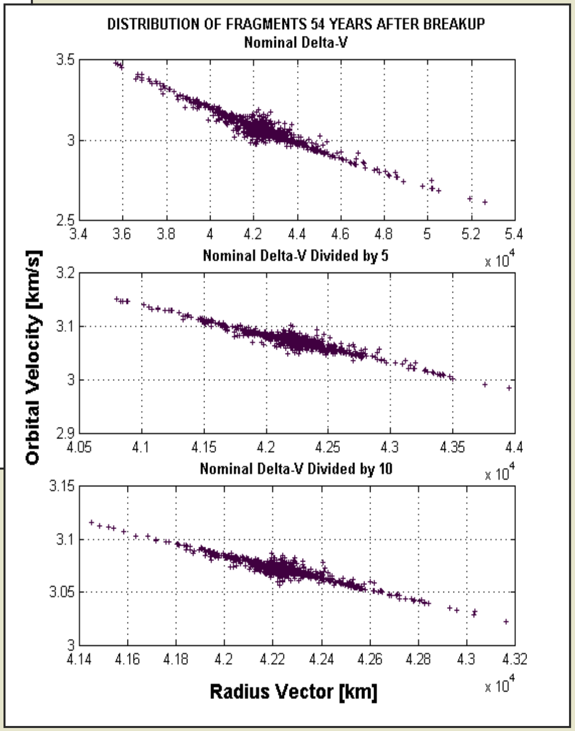
Distribution of Orbital Velocity vs. Radius Vector for Debris ≥ 10 cm



2 Days after Breakup



24 Years after Breakup



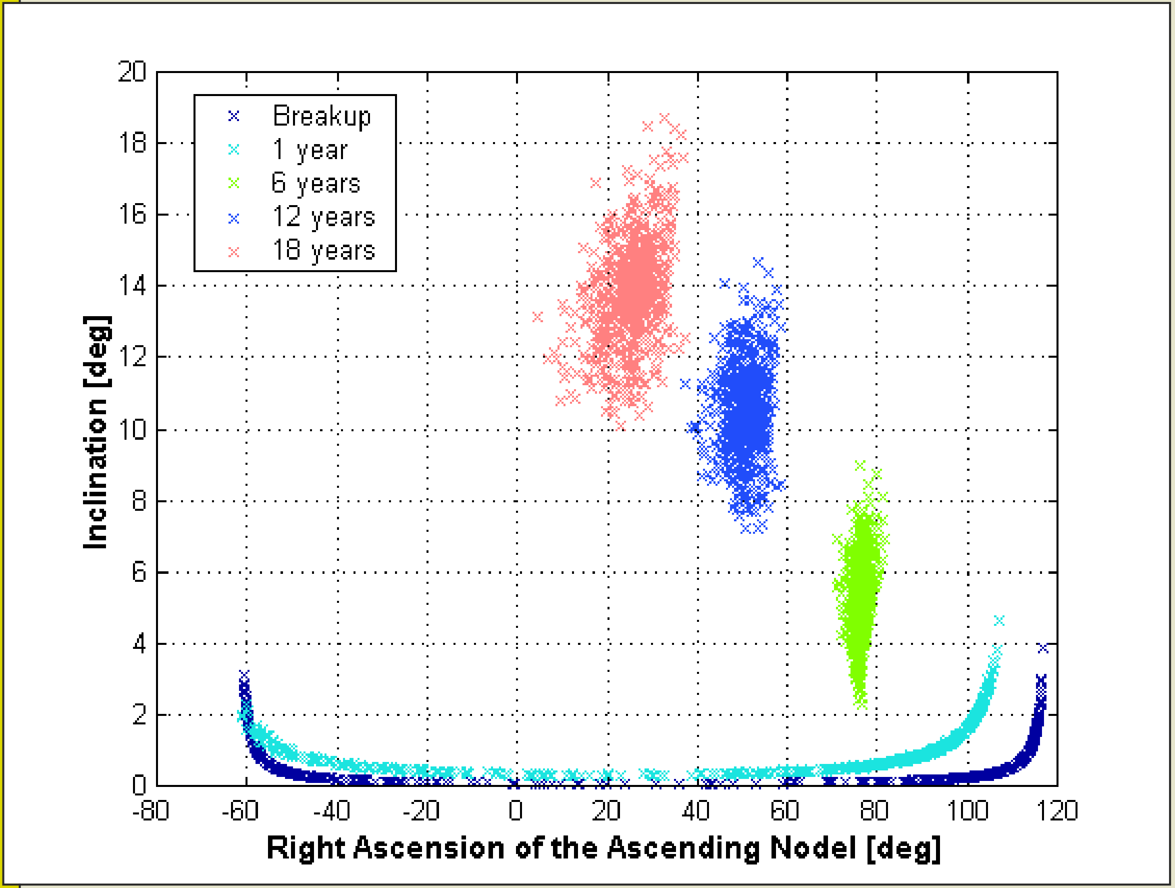
54 Years after Breakup

Distribution of Inclination vs. Right Ascension of Ascending Node for Debris ≥ 10 cm [Nominal ΔV]

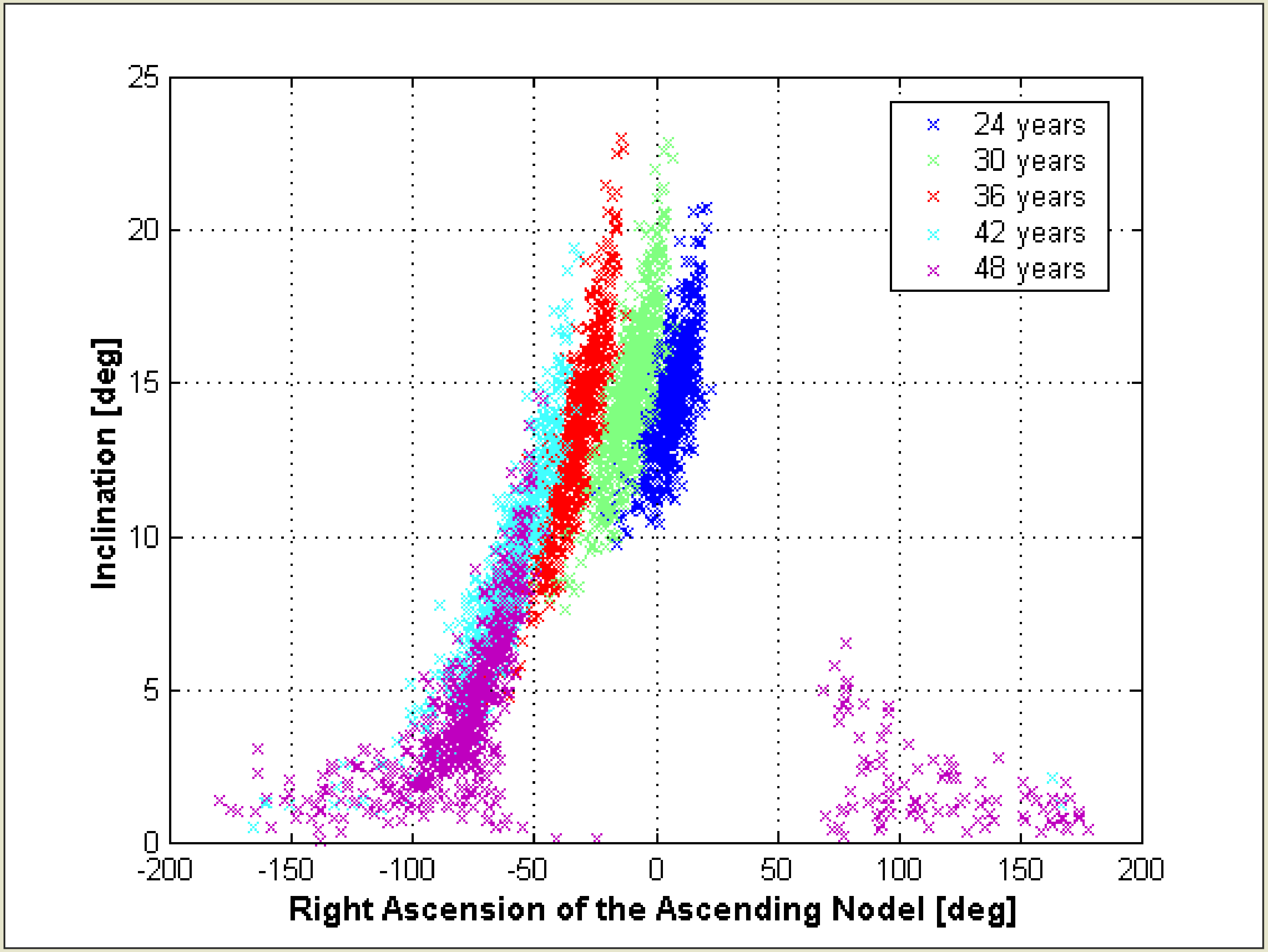
A broad flattened U-shaped distribution of the fragments' inclination vs. RAN can be observed up until 1 year from the event

Six years afterwards, the dispersion in RAN dramatically reduces and the debris cloud evolves towards a quite compact patch

This trend is substantially confirmed in the following 36 years, even though the dispersion in inclination progressively increases



Distribution of Inclination vs. Right Ascension of Ascending Node for Debris ≥ 10 cm [Nominal ΔV]

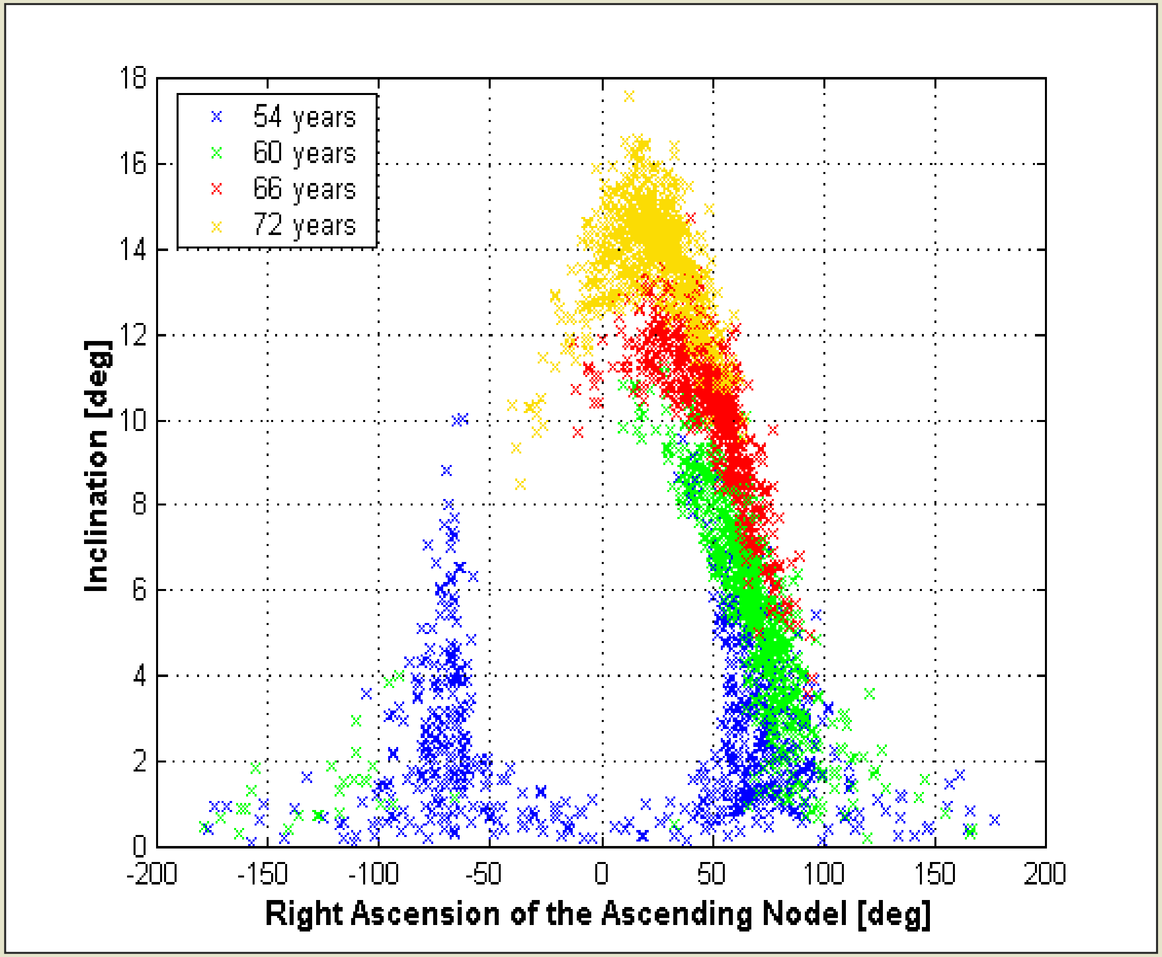


Distribution of Inclination vs. Right Ascension of Ascending Node for Debris ≥ 10 cm [Nominal ΔV]

Between 48 and 60 years after the breakup, *corresponding to the interval of time needed for a full precession of the orbit pole caused by the luni-solar perturbations*, the dispersion of the ascending nodes increases again

but after a few years, the spreading of the nodes shrinks once again and

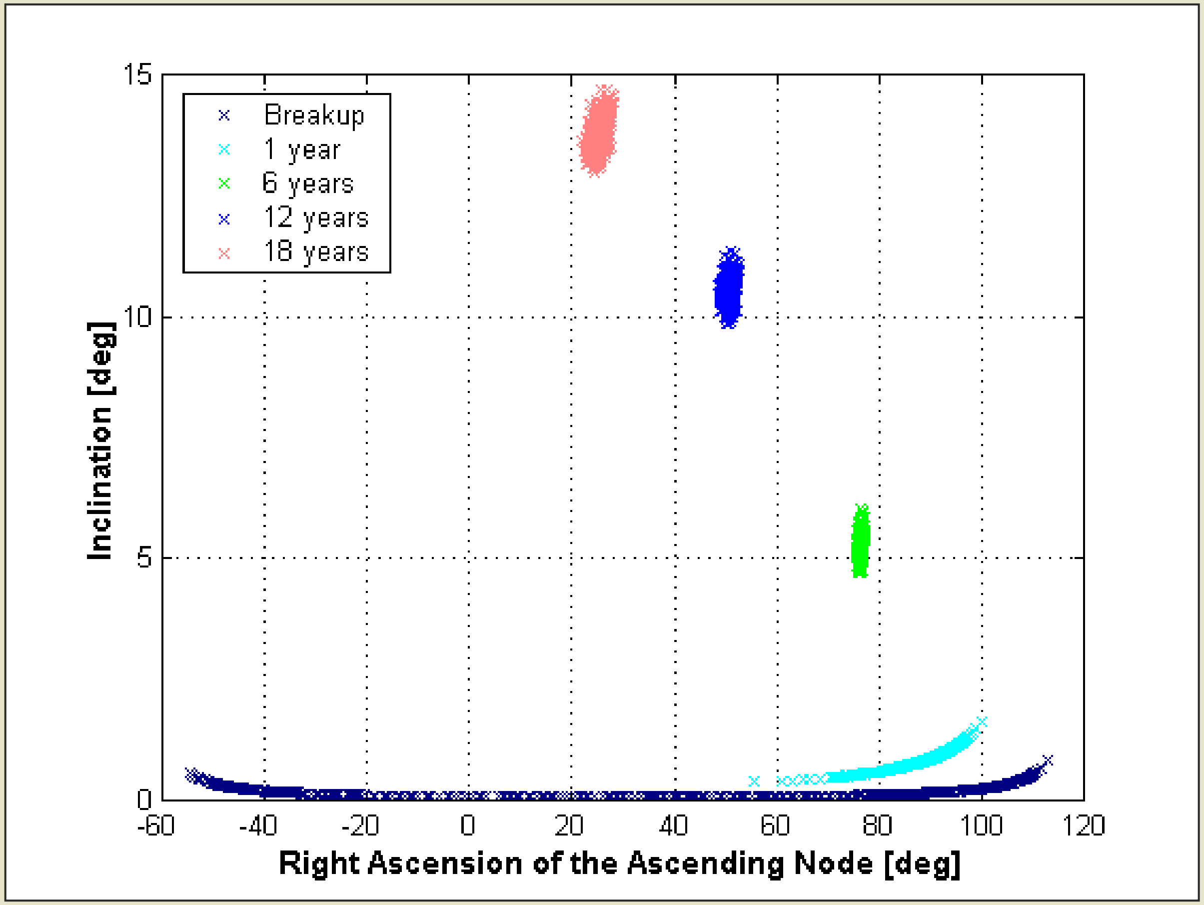
even 72 years after the explosion, the debris cloud remains clearly circumscribed and recognizable in the *i*-Ω plot



Distribution of Inclination vs. Right Ascension of Ascending Node for Debris ≥ 10 cm [Nominal $\Delta V / 5$]

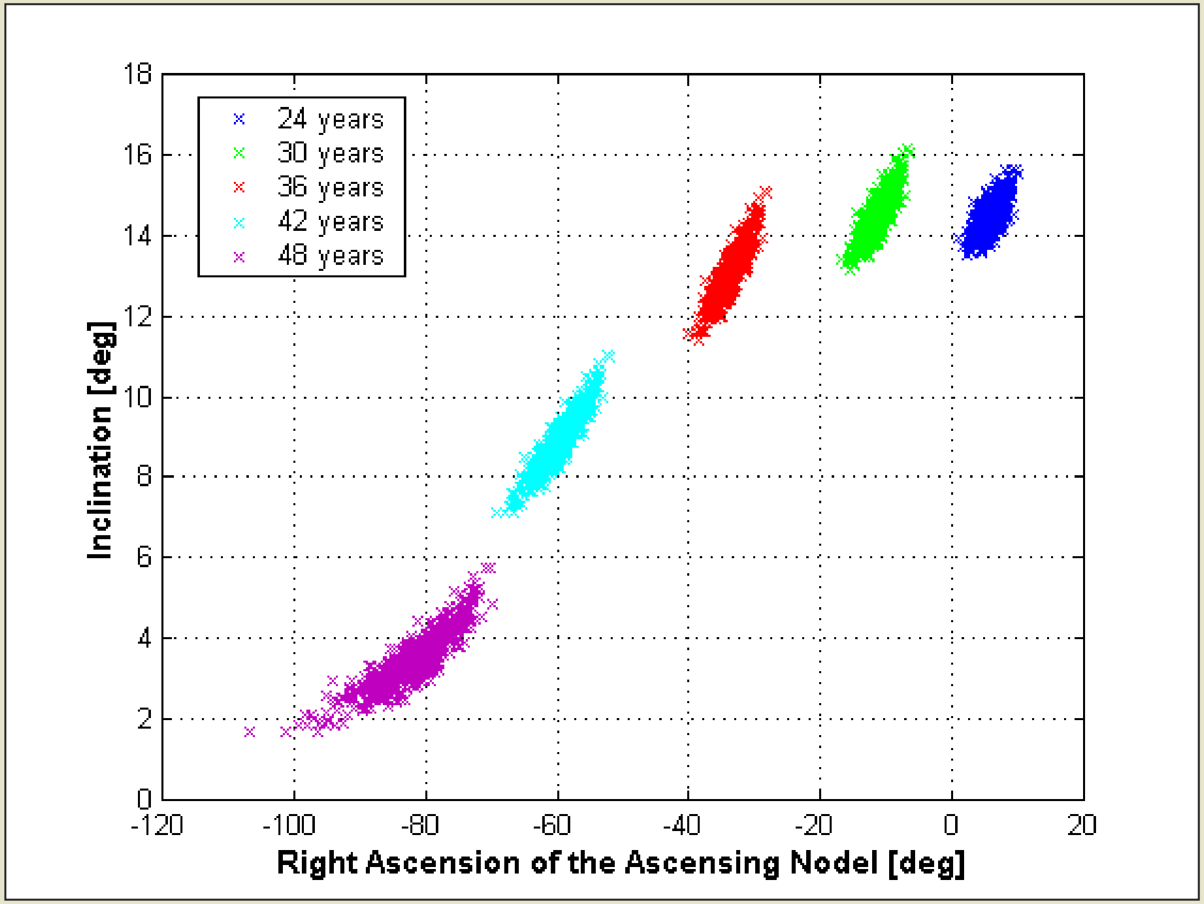
With a ΔV reduced by a factor 5, the dispersion of the points in the i-Ω plot is, of course, appreciably smaller, but the general trend of the evolution is similar to that of the previous case.

Soon after the explosion, the fragments display ascending nodes in a wide range of right ascensions, but just 1 year later the nodal scattering is reduced to less than 50°



Distribution of Inclination vs. Right Ascension of Ascending Node for Debris ≥ 10 cm [Nominal $\Delta V / 5$]

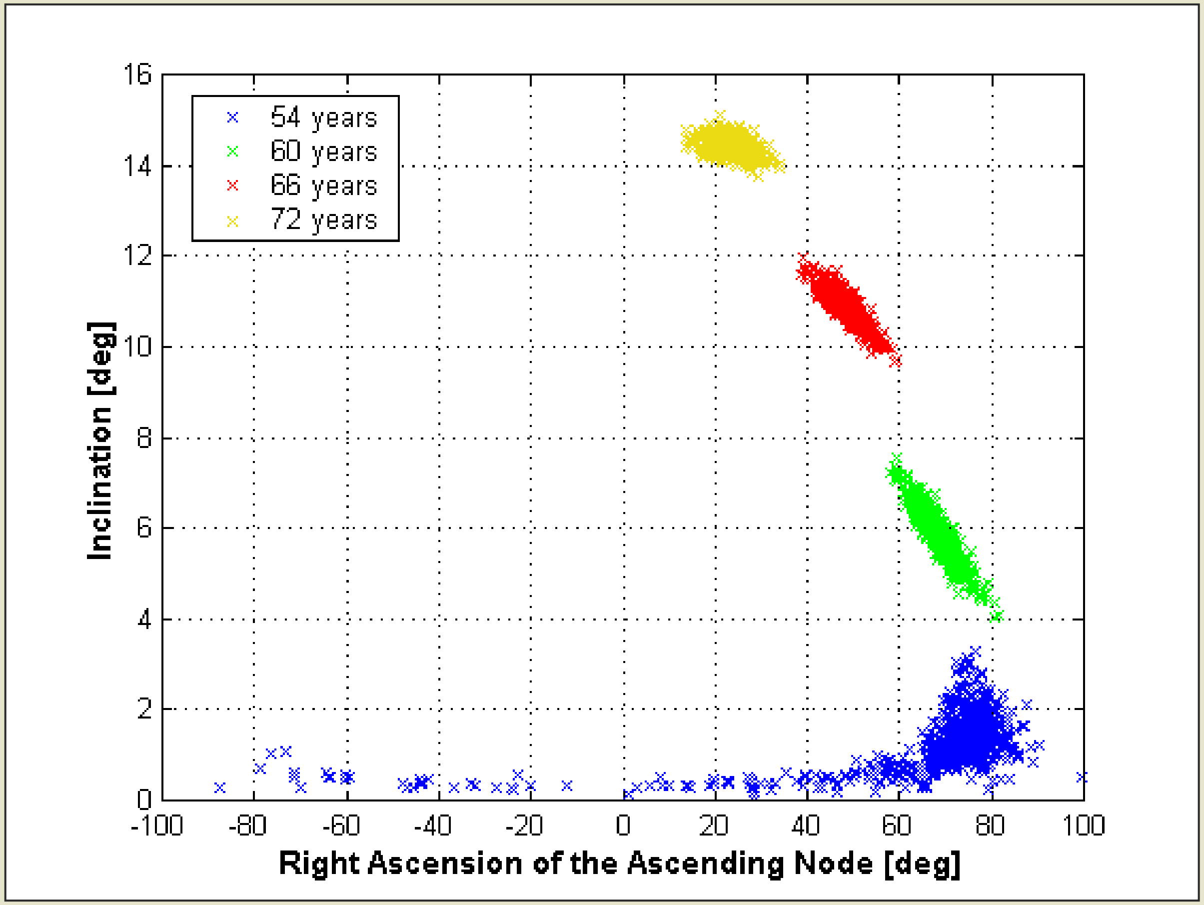
Six years after the breakup the cloud appears concentrated in a small area and this pattern remains practically unchanged for more than 40 years with a progressive limited increase of the spreading in inclination and RAN, as the cloud moves in the *i*-*Ω* plane



Distribution of Inclination vs. Right Ascension of Ascending Node for Debris ≥ 10 cm [Nominal $\Delta V / 5$]

Only around 54 years, *when the orbit plane has completed one full precession cycle due to luni-solar perturbations,* the ascending nodes are broadly scattered again in the *i*-*Ω* plot.

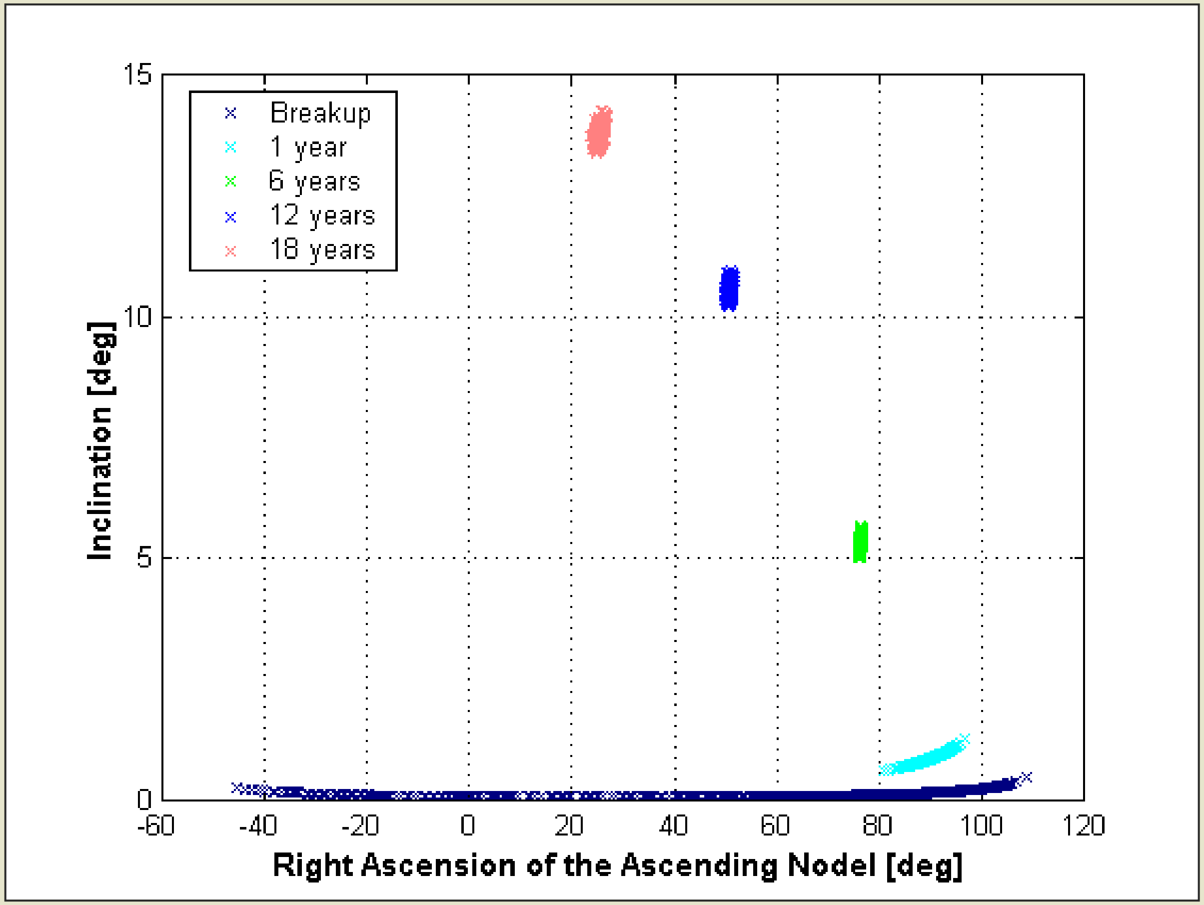
Afterwards, the cloud returns a quite compact spot and even after 72 years the dispersion is about 1.5° in inclination and 21.8° in RAN



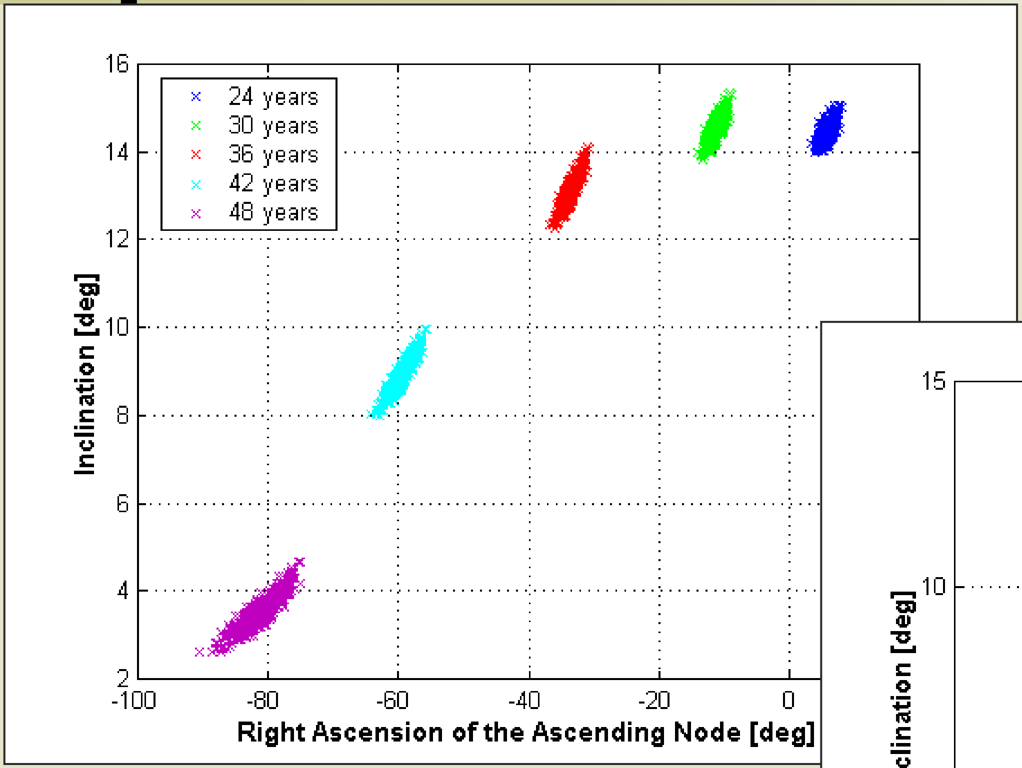
Distribution of Inclination vs. Right Ascension of Ascending Node for Debris ≥ 10 cm [Nominal $\Delta V / 10$]

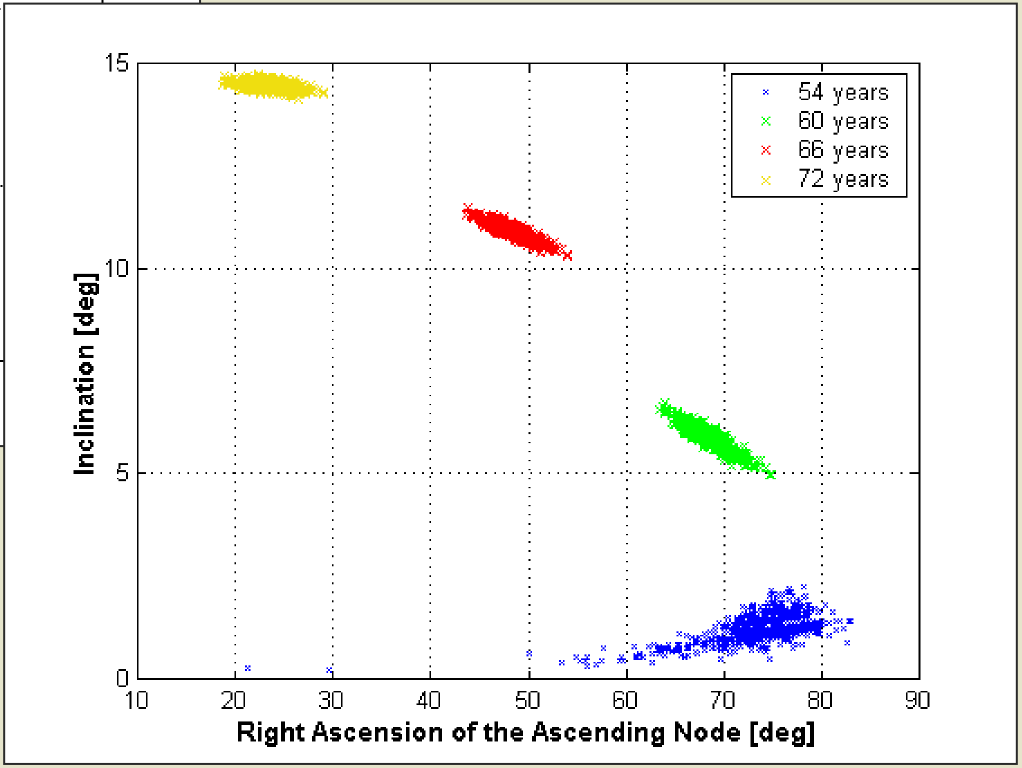
The third simulation assumed a reduction by a factor 10 of the fragments' ejection velocity.

The previous conclusions apply with an even more concentrated character of the cloud, as it evolves in the *i*-*Ω* plane during the 72 years spanned by the simulation



Distribution of Inclination vs. Right Ascension of Ascending Node for Debris ≥ 10 cm [Nominal $\Delta V / 10$]





Conclusions [1]

- An explosion of a satellite in geostationary orbit was simulated by assuming three different distributions of the fragments
- Each resulting debris cloud was propagated for 72 years and its evolution was analyzed only considering the fragments ≥ 10 cm, nearly corresponding to the limiting size accessible to the dedicated optical observation campaigns in GEO

- In each case the clouds maintain their specific identity all along the time span considered and they occupy a relatively small and compact area of the i-Ω plot for most of the time
- As expected, lower ejection velocities of the fragments correspond to smaller debris dispersions in the i-Ω plane at any given time
- Due to the characteristic pattern and long-term stability of the evolving clouds, a plot in the i-Ω plane of the observed un-catalogued objects in the GEO region should clearly identify possible debris clusters resulting from undetected breakup events, irrespective of the elapsed time

Conclusions [2]

The detailed analysis of those clusters, in terms of debris dispersion and position in the i-Ω plot, should provide useful insights on the date and intensity of the events, even decades after the breakups, and this probably applies not only to fragmentations in geostationary orbit, as those simulated in this study, but to breakups at higher inclinations as well

The results presented are only a first step of a comprehensive program to study the evolution of debris clouds resulting from breakup events in the geosynchronous region