Orbit propagation and statistical methods to address the Compliance of GTO with the French Space Operations Act

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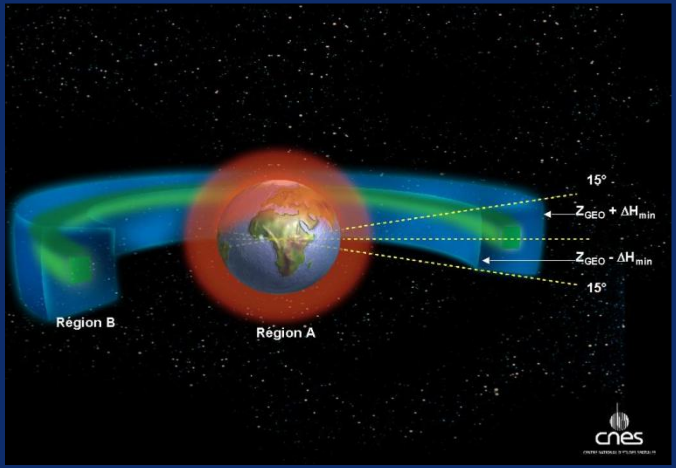
Context

- Space Debris Mitigation is one objective of the French Space Operations Act
- After the end of its mission, a spacecraft should :
  - In LEO region, perform a direct and controlled re-entry

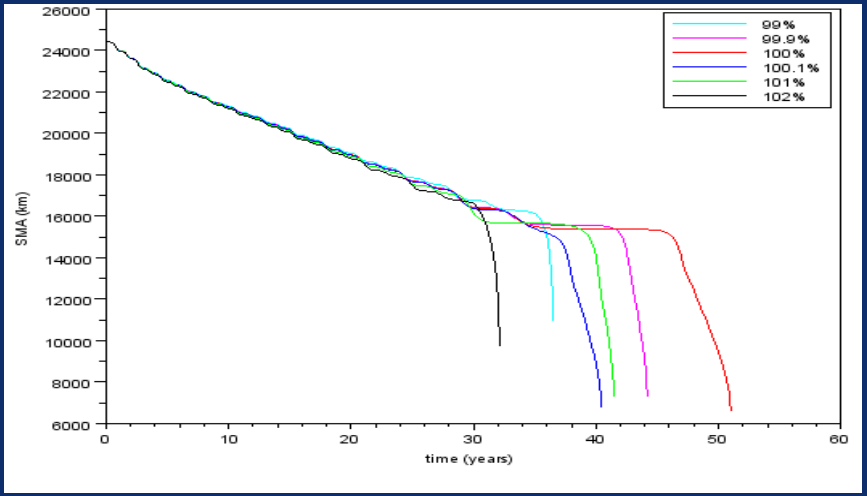
    >> If the impossibility is duly proven, limit the disposal orbit lifetime or reach a stable orbit above LEO region
  - In GEO region, reach a stable orbit outside GEO region
- French Space Agency CNES defines technical methods and Good Practices to address the compliance of disposal orbits with the law technical requirements:
  - Input parameters
  - Minimum dynamical model for orbit propagation
  - Software : STELA
  - Methodology to check the criteria
  - Criteria
- This study deals with GTO.



Protected regions A (LEO) & B (GEO) defined by IADC

The problem of GTO orbital propagation

- Evolution of highly elliptical orbits is very sensitive to initial conditions due to the importance of the 3rd body perturbation
- Resonance effects due to coupling between perturbations (e.g. Earth -J2 term- and Sun gravitational perturbations)
- Uncertainties of the input parameters (area-to-mass ratio, atmospheric density, orbit dispersions) make the entry conditions into resonance highly unpredictable



SMA evolution sensitivity to slight S/m variation

>> Trying to estimate HEO lifetime with a single extrapolation may lead to erroneous conclusions.

>> Orbit propagations shall be performed and analysed statistically

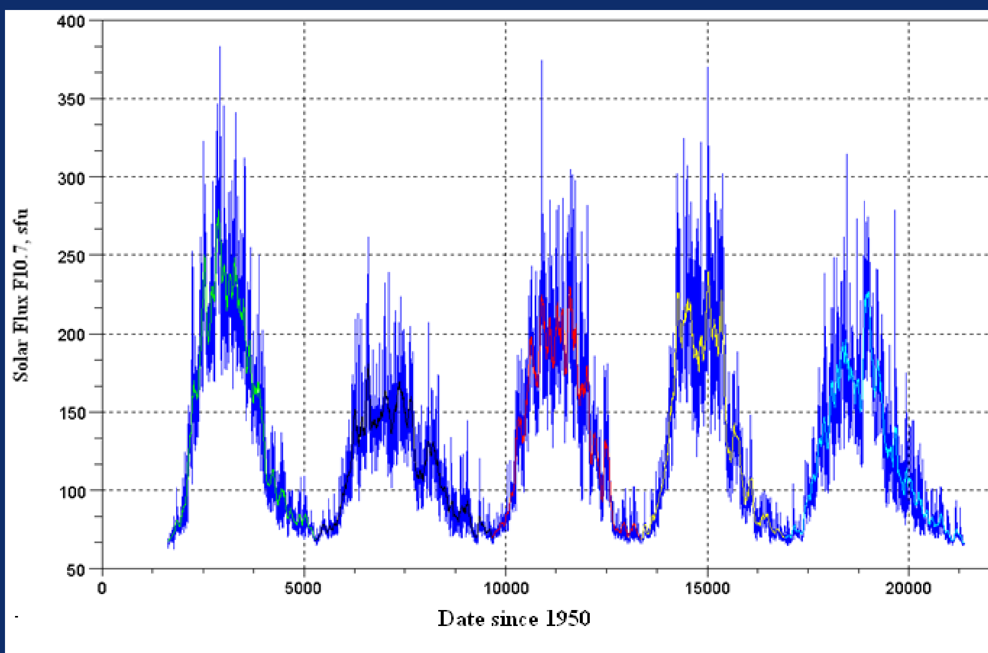
Input parameters scattering

Input parameter	Source of uncertainty
Orbital elements	Injection or manoeuver accuracy, orbit determination accuracy
Initial Date	Mission delay or prolongation, postponed launch…
Object Mass	Remaining propellant
Object Area	Unknown attitude (Random tumbling, gradient stabilization..?)
Drag coefficient	Physics
Reflectivity coefficient	Physics
Solar activity	Very high dispersion for long term prediction

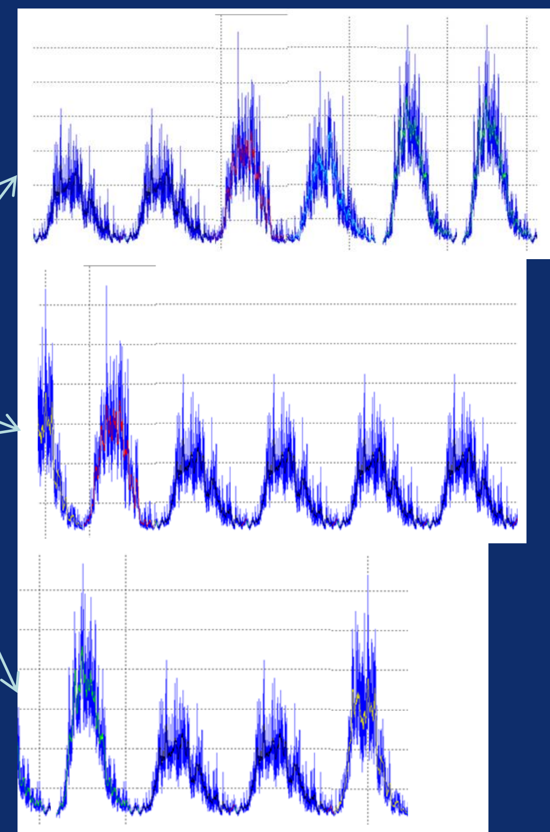
Solar Activity

- Good Practices recommend a randomly chosen solar activity using data from the past
  - Random set of solar cycle
  - Random initial day within the first cycle

>> Similar approach as ISO27852 Annex B



Measured solar activity (1957 – 2012)



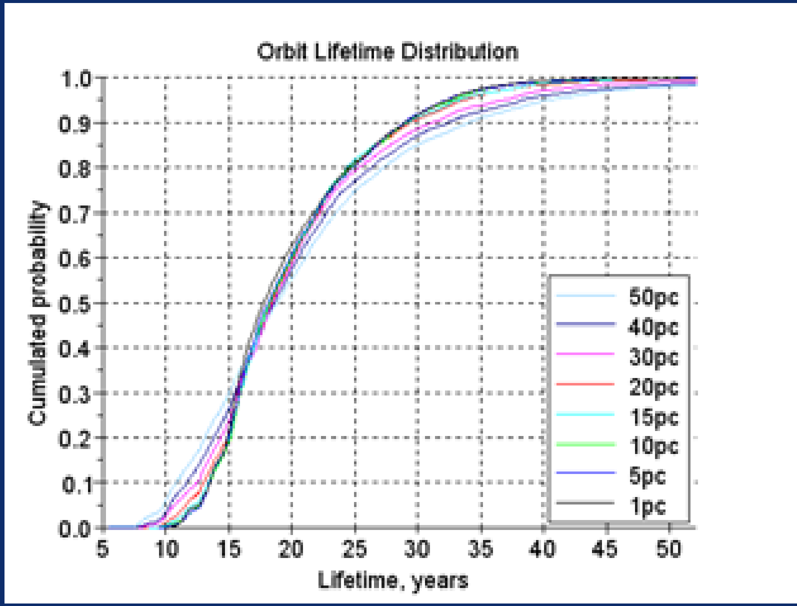
Random solar activities

Ballistic coefficient

- Good Practices recommend that global uncertainty on ballistic coefficient (and its equivalent for SRP) should be at least +/- 20% (uniform dispersion)
  - Uncorrelated dispersions of each parameter
  - Results not much sensitive to these uncertainties in the range [0%; 20%]
  - Lower impact of solar radiation pressure compared to others perturbations

Input parameter	Order of magnitude of uncertainty
Object Mass	<5% uniform
Object Area	15-20% uniform
Drag coefficient	10-15% uniform
Reflectivity coefficient	10% uniform

>> Further consolidation expected based on observation of space debris



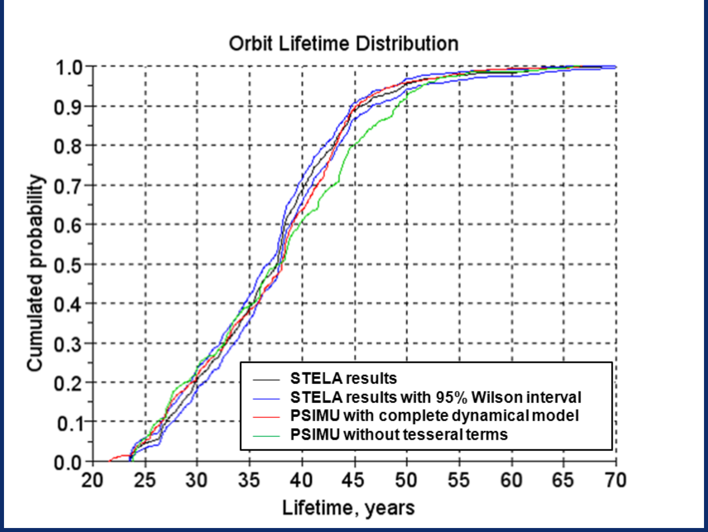
Statistics of GTO orbital lifetimes depending on ballistic coefficient scattering

Minimum dynamical model

- Good Practices recommend minimum dynamical model for GTO propagation

Earth's gravity field	Complete 7x7 model *NB : additional zonal terms needed close to the critical inclination (63.4deg for prograde orbits).*
Solar and Lunar gravity	Yes
Atmospheric drag	Yes (MSIS00 atmospheric model recommended)
Solar radiation pressure (SRP)	Yes (taking into account Earth shadow)

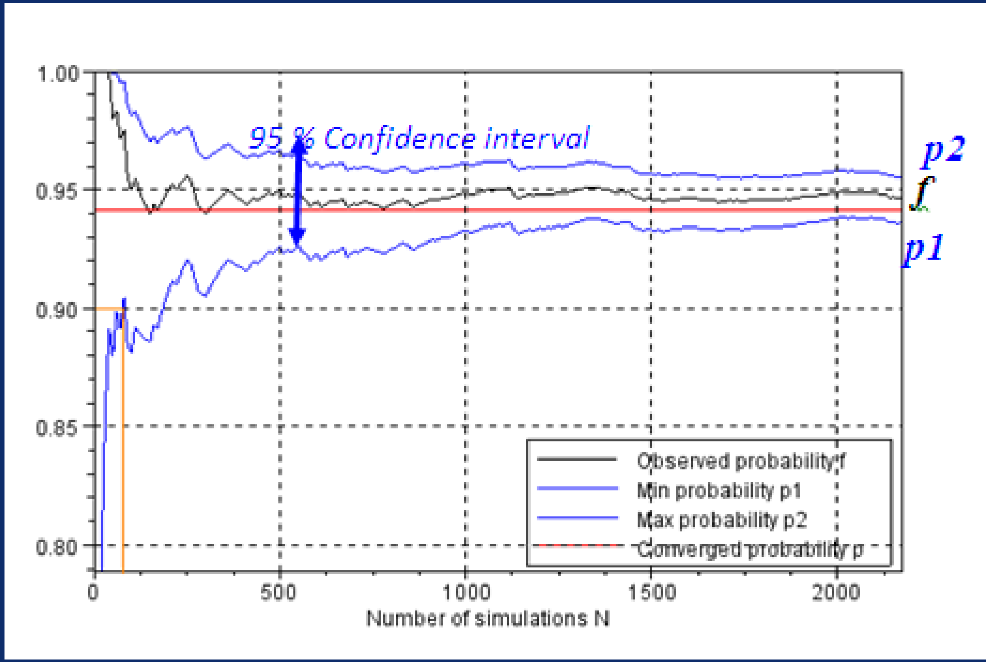
- STELA is the reference tool to check the compliance against French Space Operations Act :
  - Semi-analytical model: 100 years of propagation in ~1 min
  - Validated by comparison with numerical integration of the full dynamical model
  - Freeware : http://logiciels.cnes.fr/STELA



Validation of GTO statistical lifetimes

Monte-Carlo methodology

- Good Practices recommend to address the question of statistical convergence by computing a confidence interval for the results of the Monte Carlo, associated to a confidence level.
- CNES uses :
  - A Wilson 95% confidence interval with correction of continuity
  - The limit (upper or lower) of the confidence interval to check the criteria



Probability to obtain lifetime < 25 years as a function of simulations number

p2 : upper limit of the confidence interval

f : observed probability

p1 : lower limit of the confidence interval

Definition of statistical criteria

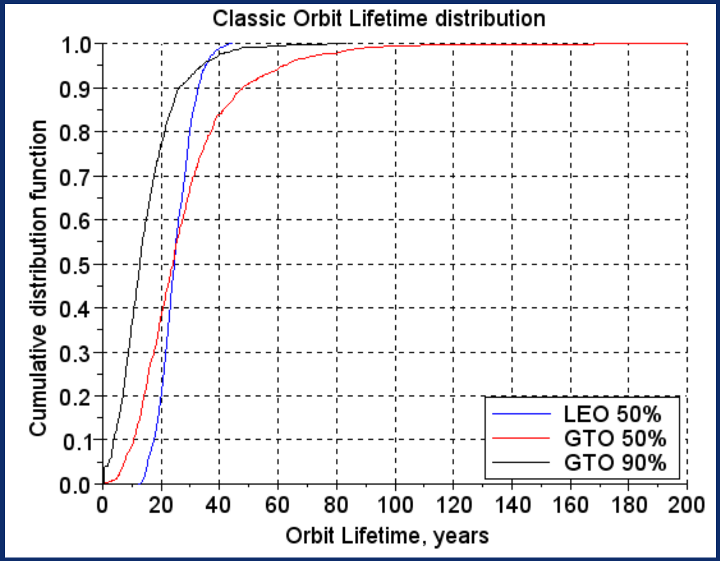
- CNES uses the following statistical criteria :
  - SC1: Lifetime < 25 years with a 0.9 probability
  - SC2: No LEO crossing for 100 years with a 0.9 probability
  - SC3: No GEO crossing between 1 and 100 years with a 0.9 probability
  - SC4: No GEO crossing for 100 years with a 0.9 probability

>> SC1 to limit the probability of very long lifetimes

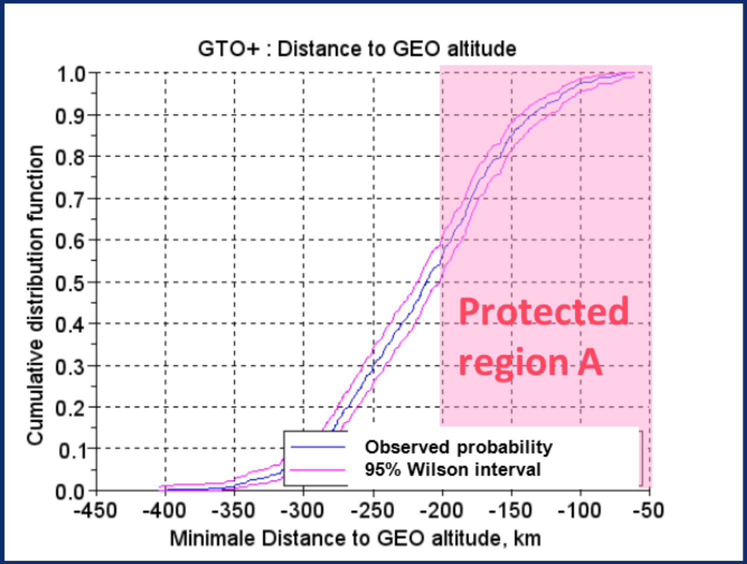
Ex : for typical GTO, lifetimes < 50years with probability 0.99 (0.91 if p=0.5)

>> SC3 / SC4 to protect the GEO operational control box (ISO 26872)

Ex : for typical GTO+, no intrusion with probability 0.9995 (0.977 if p=0.5)



Comparison of statistics of orbital lifetimes for typical GTO and LEO



Statistics of minimum distance to GEO altitude for GTO+ (6650 km / GEO - 500km)

Conclusions

- A Statistical approach is required to assess the compliance of GTO disposal orbits with the French Space Operations Act

- CNES proposes statistical criteria (0.9 probability) to protect LEO and GEO regions :
  - To cope with the complex dynamical properties of GTO orbital evolution
  - To mitigate the risk of extreme values of orbital lifetimes and interference with the GEO operational control box

- Good Practices recommend a Monte-Carlo methodology including :
  - The assessment of a confidence level for the results
  - The standardization of input parameters and their scattering

- The STELA tool implements these Good Practices ; the new version (2.3) enables to perform Monte-Carlo simulations and associated post-treatments with an efficient computing time

- These methods are also proposed and currently discussed within IADC & ISO

Thank you for your attention

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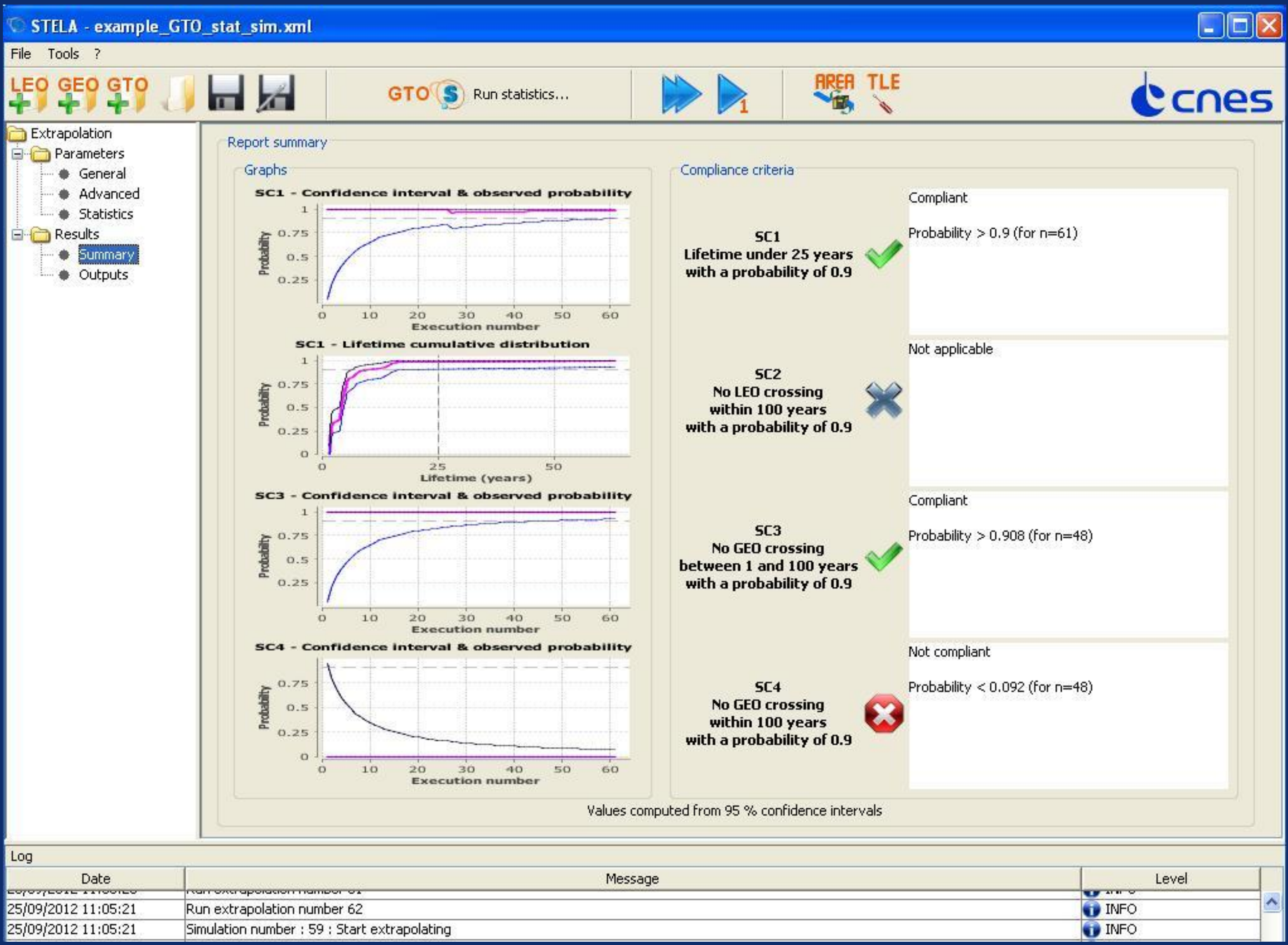
STELA - example_GTO_stat_sim.xml
File Tools ?
LEO GEO GTO
GTO Run statistics...
AREA TLE
cnes
Extrapolation
Parameters
General
Advanced
Statistics
Results
Summary
Outputs
Report summary
Graphs
SC1 - Confidence interval & observed probability
Execution number
SC1 - Lifetime cumulative distribution
Lifetime (years)
SC3 - Confidence interval & observed probability
Execution number
SC4 - Confidence interval & observed probability
Execution number
Probability
Compliance criteria
SC1
Lifetime under 25 years
with a probability of 0.9
Compliant
Probability > 0.9 (for n=61)
SC2
No LEO crossing
within 100 years
with a probability of 0.9
Not applicable
SC3
No GEO crossing
between 1 and 100 years
with a probability of 0.9
Compliant
Probability > 0.908 (for n=48)
SC4
No GEO crossing
within 100 years
with a probability of 0.9
Not compliant
Probability < 0.092 (for n=48)
Values computed from 95 % confidence intervals
Log
Date
Message
Level
25/09/2012 11:05:21
Run extrapolation number 62
INFO
25/09/2012 11:05:21
Simulation number : 59 : Start extrapolating
INFO