OBSERVATION OF ORBITAL DEBRIS WITH SPACE-BASED SPACE SURVEILLANCE SENSOR CONSTELLATIONS

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SUMMARY

- INTRODUCTION
- OVERVIEW OF BAS³E SIMULATOR
- GENERAL ASSUMPTIONS AND MODELS
- SURVEILLANCE OF OBJECTS IN LEO
- CONCLUSIONS

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INTRODUCTION (I)

PURPOSE

- Evaluate the feasibility to use space-based sensors for both Low Earth Orbit (LEO) and Geostationary Orbit (GEO) object surveillance.
- Assess the ability of space-based space surveillance constellation to detect and catalogue the space debris population on these both orbital regimes.
- Determine the optimum configuration of space-based space surveillance sensor constellations, in terms of:
  - Percentage of visible space debris population
  - Attitude constraints
  - Orbit determination accuracies

INTRODUCTION (II)

HOW

- Conducted simulations for a 10 day period and for different constellations of spacecraft evenly spaced (in terms of mean anomaly) in a quasi-circular, Sun-synchronous dawn-dusk orbits, for which the constellation altitudes and number of satellites were varied.

- The analysis of these simulations focused on the following points:
  - Attitude constraints *(angular velocity and angular acceleration)*
  - Sensor optical characteristics *(luminosity detectability threshold)*
  - Characterization of the space debris population which can be observed *(nº of observed objects, nº of observations, duration of visibility periods)*
  - Orbit determination accuracies

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INTRODUCTION (III)

Banc d´Analyse et de Simulation d'un Système de Surveillance de l'Espace

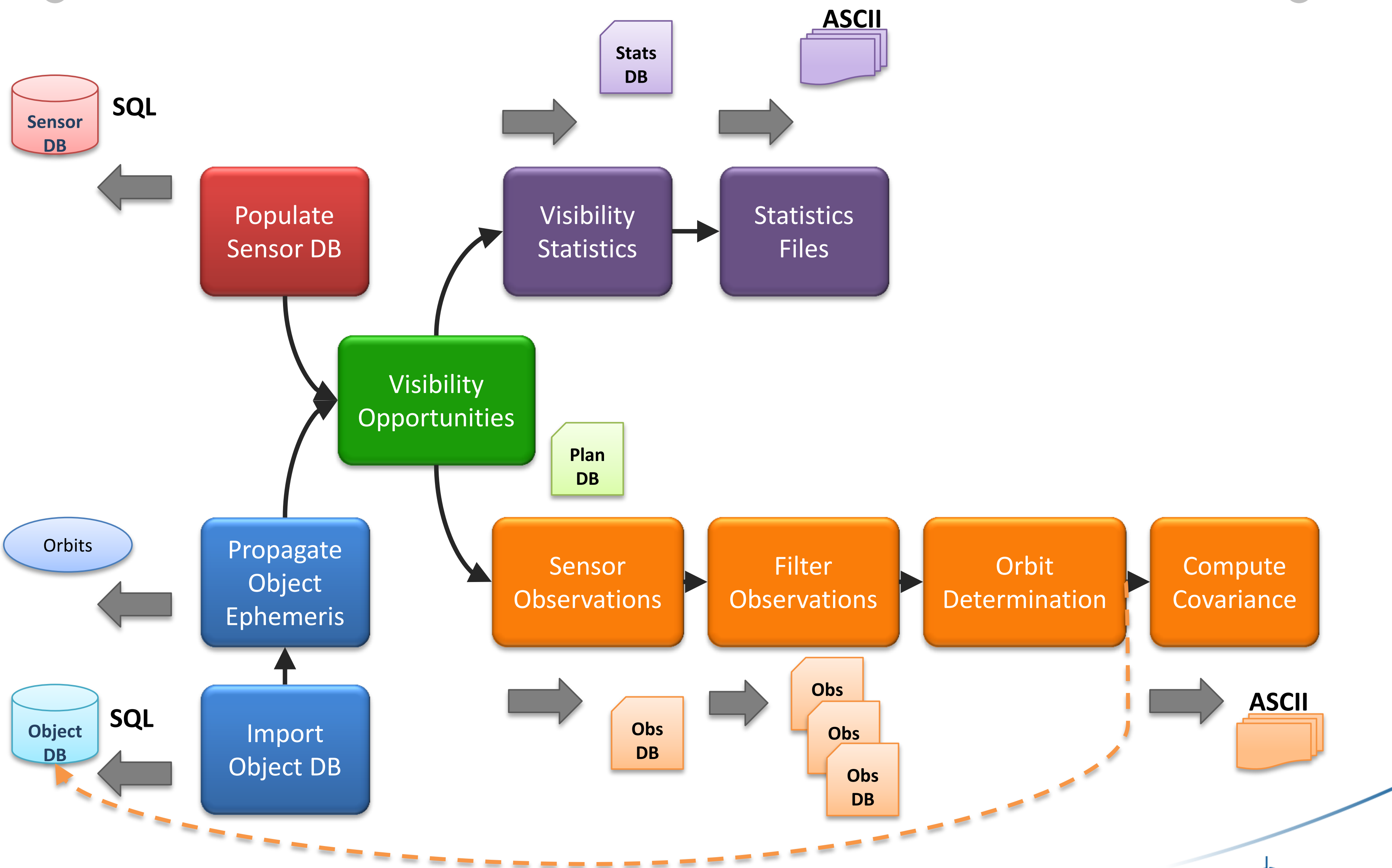
The ***BAS^{3}E*** simulator is a CNES software tool, developed in collaboration with GMV. Some of its capabilities are listed below:

- Orbit determination of space objects
- Orbit propagation
- Computation of statistics during passes
- Sensor modelling
- Sensor load computation
- Simulation of observations of space objects obtained by a given sensor network taking into account sensor visibility constraints.

ENHANCEMENT:

Originally conceived for ground-based observations (telescope and radar), BAS^{3}E has been recently enhanced to enable the definition of **"orbiting" sensor sites**, which allow for the simulation of space-based space surveillance sensors.

OVERVIEW OF EXECUTED STAGES



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GENERAL ASSUMPTIONS AND MODELS

SPACE DEBRIS POPULATIONS AND PROPAGATION MODELS FOR SIMULATION

Low Earth Orbit (LEO)

- Source: ESA's debris catalogue MASTER-2009
- Nº of objects: 20811

Geostationary Orbit (GEO)

- Source: MEDEE software tool from CNES
- Nº of objects: 536

	LEO	GEO
Third body perturbations	Sun and Moon gravity forces	Sun and Moon gravity forces
Atmospheric drag	Numerical MSISE2000 atmosphere model for constant solar activity	Not considered
Solar Radiation Pressure	Not considered	Considered
Earth potential	12x12	12x12
Integrator	Runge-Kutta Dormand Prince method, minimum and maximum step size of 10 s, and 120 s respectively	Runge-Kutta Dormand Prince method, minimum and maximum step size of 10 s, and 120 s respectively
Earth model	WGS84	WGS84

GENERAL ASSUMPTIONS AND MODELS

SPACE-BASED SPACE SURVEILLANCE SENSOR CONSTELLATIONS

- Constellations of spacecraft evenly spaced (in terms of mean anomaly) in a quasi-circular, Sun-synchronous dawn-dusk orbits.
- Spacecraft were considered to be equipped with one sensor.
- Constellations differed in altitude and number of sensors.

CONFIGURATIONS

Altitude [km]	Number of sensors
500	5, 10, 20
750	2, 4, 8
1000	2, 4, 8

OBSERVATION CONSTRAINTS

- Sun exclusion angle *(min angle 90 deg)*
- Moon exclusion angle *(min angle 20 deg)*
- Earth exclusion angle *(min angle 20 deg)*
- Distance to Galactic plane *(min angle 30 deg)*
- South Atlantic Anomaly

GENERAL ASSUMPTIONS AND MODELS

COMPUTED STATISTICS DURING VISIBILITY PERIODS

- Key points for the evaluation of the feasibility to use SBSS sensor constellations for space surveillance:
  - Attitude constraints
  - Sensor optical characteristics
  - Percentage of observable space debris population
- Consequently, in order to characterize the periods of visibility, the statistics listed below were computed.
  - Maximum angular velocity and acceleration
  - Maximum/minimum solar phase angle
  - Maximum/minimum luminosity of observed objects
  - Number of visibility periods during a given period
  - Duration of the visibility periods

GENERAL ASSUMPTIONS AND MODELS

OBSERVATIONS

Observation components

- Azimuth, elevation *(Sigma: 0.001 [deg])*
- luminosity

Magnitude thresholds *(for observation filtering)*

- 12, 14, 16

PROPAGATION MODELS FOR ORBIT DETERMINATION

	LEO	GEO
Third body perturbations	Sun and Moon gravity forces	Sun and Moon gravity forces
Atmospheric drag	Numerical MSISE2000 atmosphere model for constant solar activity	Not considered
Solar Radiation Pressure	Not considered	Considered
Earth potential	8x8	8x8
Integrator	Runge-Kutta Dormand Prince method, minimum and maximum step size of 10 s, and 120 s respectively	Runge-Kutta Dormand Prince method, minimum and maximum step size of 10 s, and 120 s respectively
Earth model	WGS84	WGS84

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GENERAL ASSUMPTIONS AND MODELS

ESTIMATION PARAMETERS

	LEO	GEO
State-vector estimation	True	True
Estimated parameters	Atmospheric drag multiplicative factor	None
Considered observations	Azimuth, elevation	Azimuth, elevation
Estimation method	Least-Squares	Least-Squares
Convergence criteria	Maximum position and velocity corrections of 0.1 [m] and 0.001 [m/s] respectively. Maximum WRMS correction of 1e-3.	Maximum position and velocity corrections of 0.1 [m] and 0.001 [m/s] respectively. Maximum WRMS correction of 1e-3.
Maximum nº of iterations	20	20

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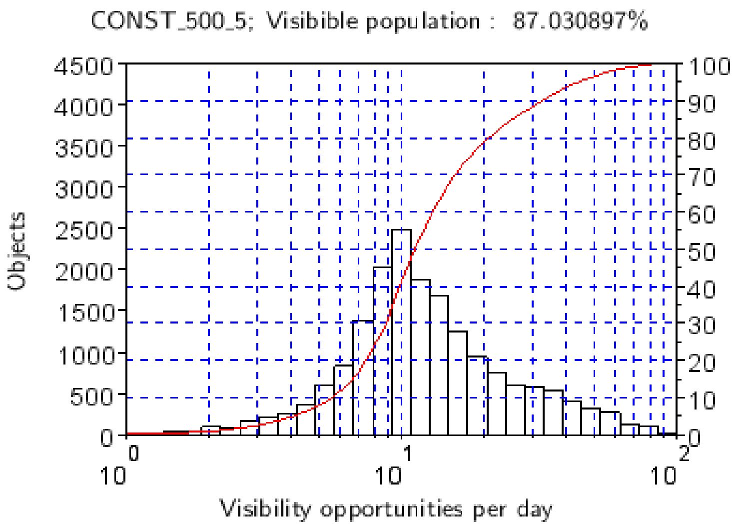
SURVEILLANCE OF OBJECTS IN LEO

MEAN VISIBILITY OPPORTUNITIES PER DAY



Mean visibility opportunities per day: Altitude: 500[km]; Number of sensors: 5

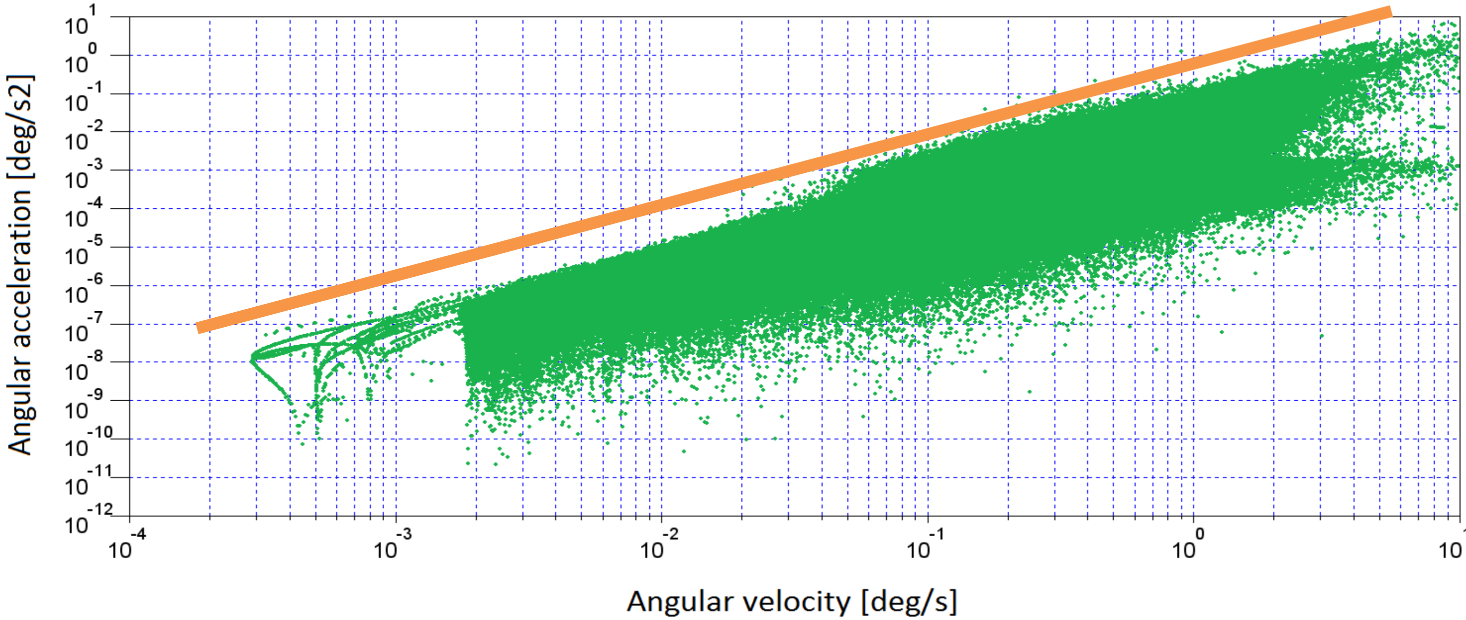
PERCENTAGE OF VISIBLE POPULATION

Altitude [km]	Number of sensors		
	5	10	20
500	87.03%	87.05%	87.05%
	2	4	8
750	83.39%	83.66%	83.79%
1000	57.86%	58.14%	58.19%

- Disperse distribution of the visibility opportunities per day reveals the diversity of eccentricity and semi-major axis values
- Percentage of visible population decreases with increasing altitudes
- Number of visibility opportunities per day increases with increasing number of sensors

SURVEILLANCE OF OBJECTS IN LEO

RELATION BETWEEN ANGULAR VELOCITY & ACCELERATION

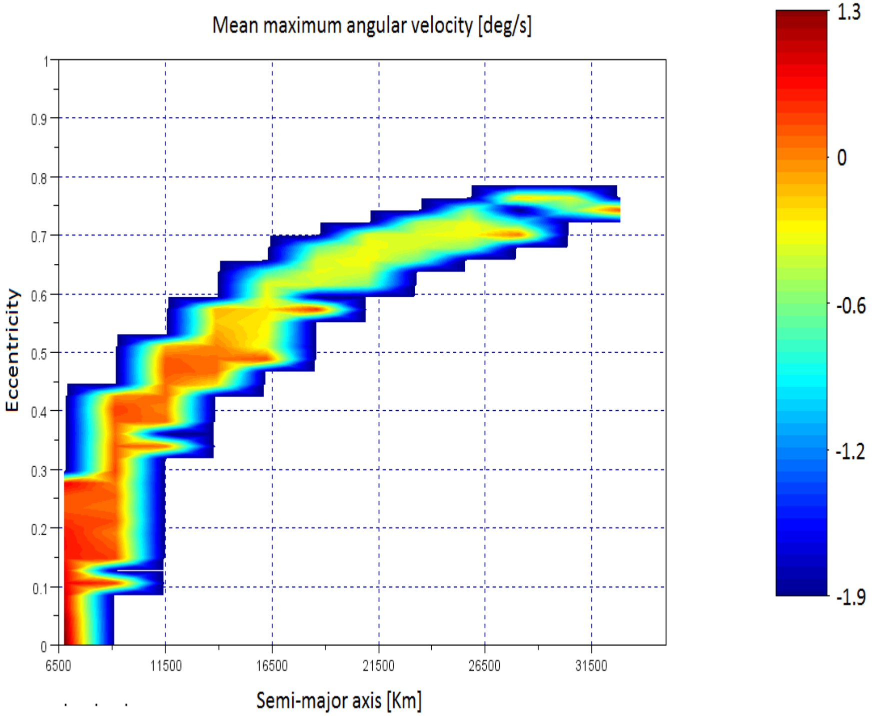


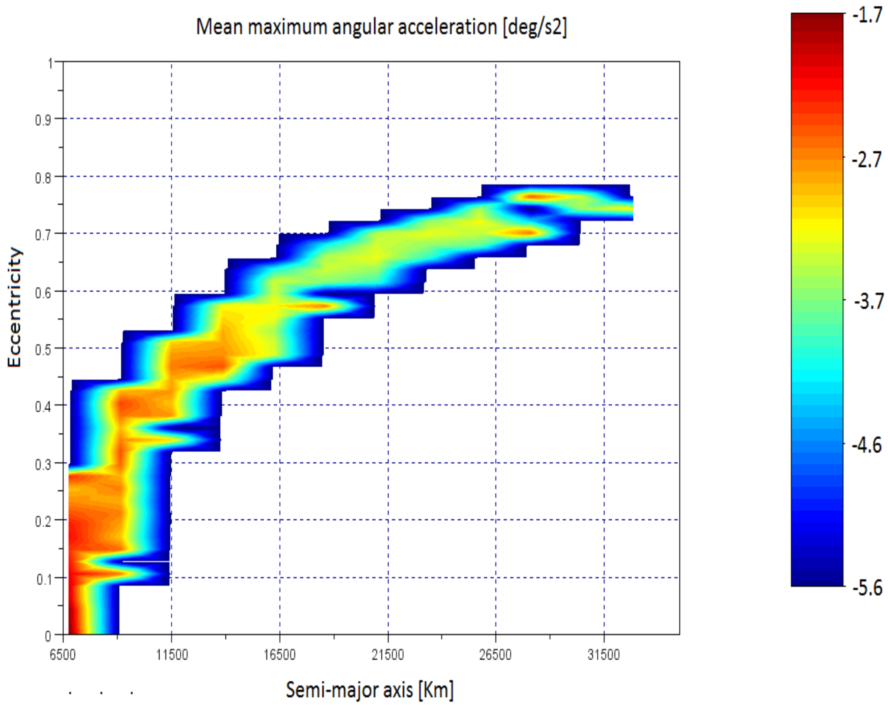
Altitude [km]	Number of sensors		
	5	10	20
500	*Percentile 50%: 199*	*Percentile 50%: 199*	*Percentile 50%: 199*
	2	4	8
750	*Percentile 50%: 245*	*Percentile 50%: 245*	*Percentile 50%: 245*
1000	*Percentile 50%: 321*	*Percentile 50%: 321*	*Percentile 50%: 321*

DURATION OF VISIBILITY PERIODS

SURVEILLANCE OF OBJECTS IN LEO

MAXIMUM ANGULAR VELOCITY AND ACCELERATION AS A FUNCTION OF ECCENTRICITY AND SEMI-MAJOR AXIS

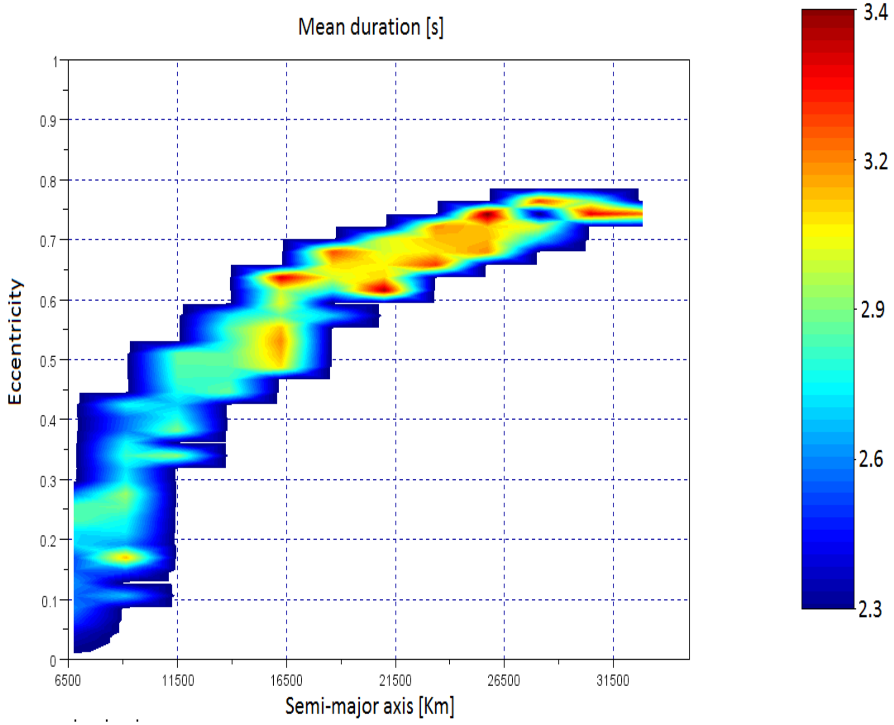




Angular velocity and acceleration increase with a decrease in eccentricity and semi-major axis.

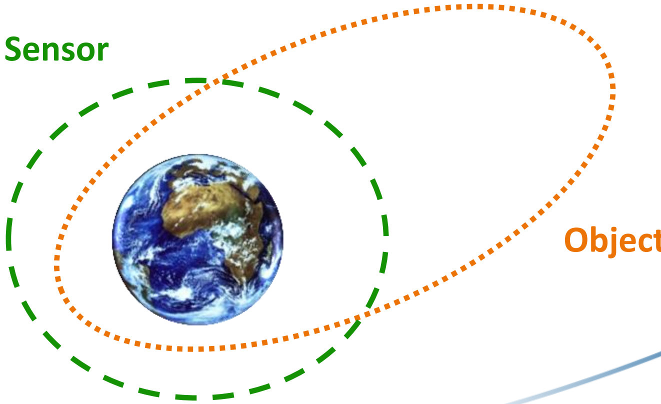
SURVEILLANCE OF OBJECTS IN LEO

MEAN DURATION AS A FUNCTION OF ECCENTRICITY AND SEMI-MAJOR AXIS



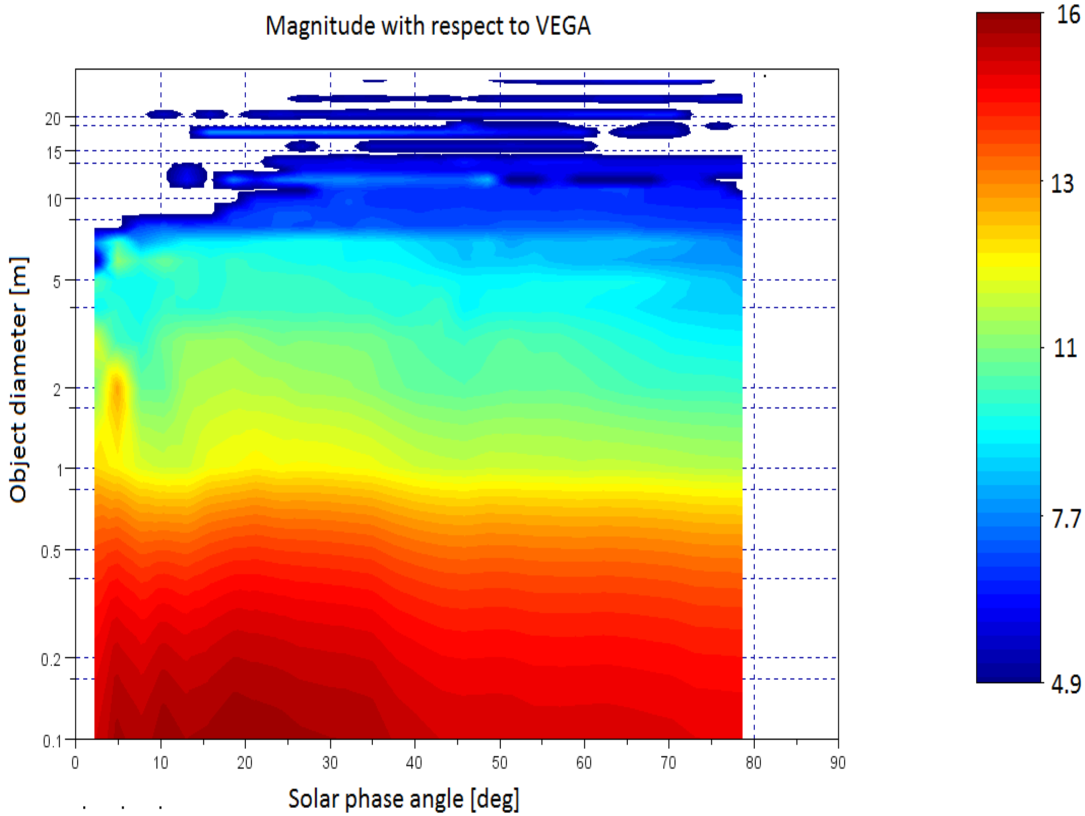
Decrease with a decrease in eccentricity and semi-major axis.

Explanation:
The "visibility opportunities" for eccentric orbits would occur more frequently closer to their apogee where objects speed is slower.



SURVEILLANCE OF OBJECTS IN LEO

OBJECT MAGNITUDE WITH RESPECT TO VEGA AS A FUNCTION OF SOLAR PHASE ANGLE AND OBJECT DIAMETER



A clear decrease in the observed object magnitude is appreciated with an increase of the object diameter, however the solar phase angle values do not seem to have a remarkable impact on the magnitude.

WHY NOT ??? !!!

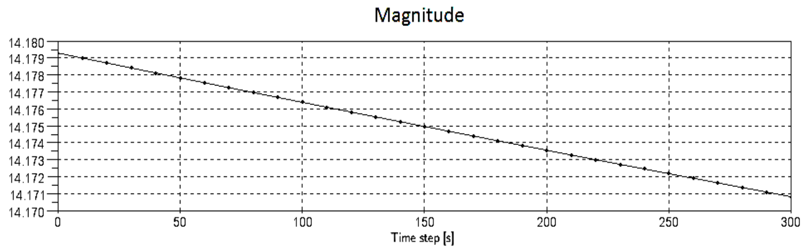
SURVEILLANCE OF OBJECTS IN LEO

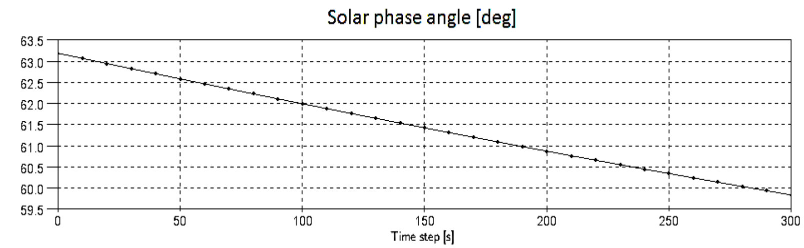
PARAMETERS INFLUENCING MAGNITUDE VALUE

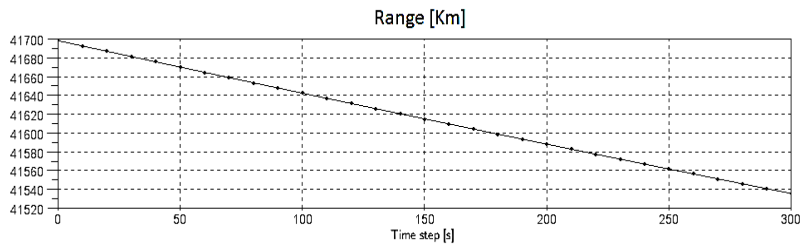
- Object Diameter ↑ → Magnitude ↓
- Solar Phase Angle ↑ → Magnitude ↑
- Distance object – sensor ↑ → Magnitude ↑

SURVEILLANCE OF OBJECTS IN LEO

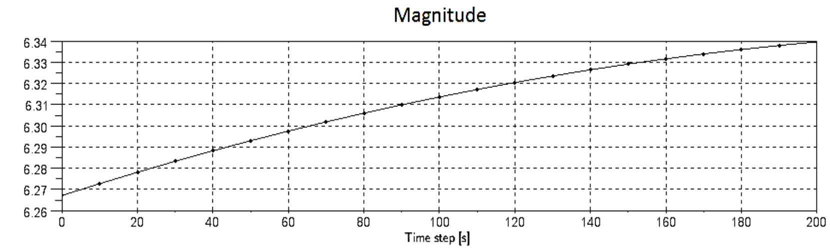
EVOLUTION OF SOLAR PHASE ANGLE AND RANGE DURING A PERIOD OF VISIBILITY

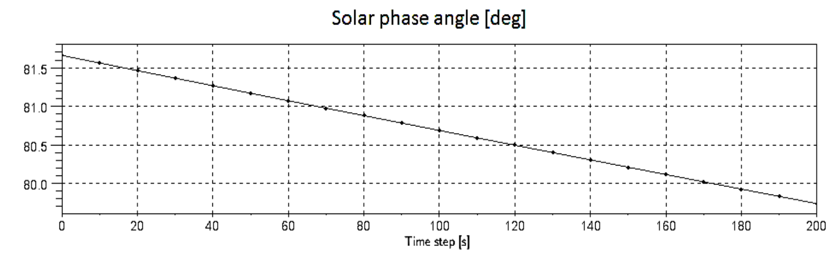


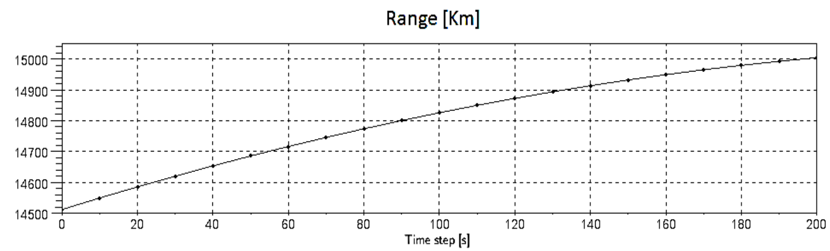




Magnitude follows trend of solar phase angle evolution







Magnitude does NOT follow trend of solar phase angle evolution

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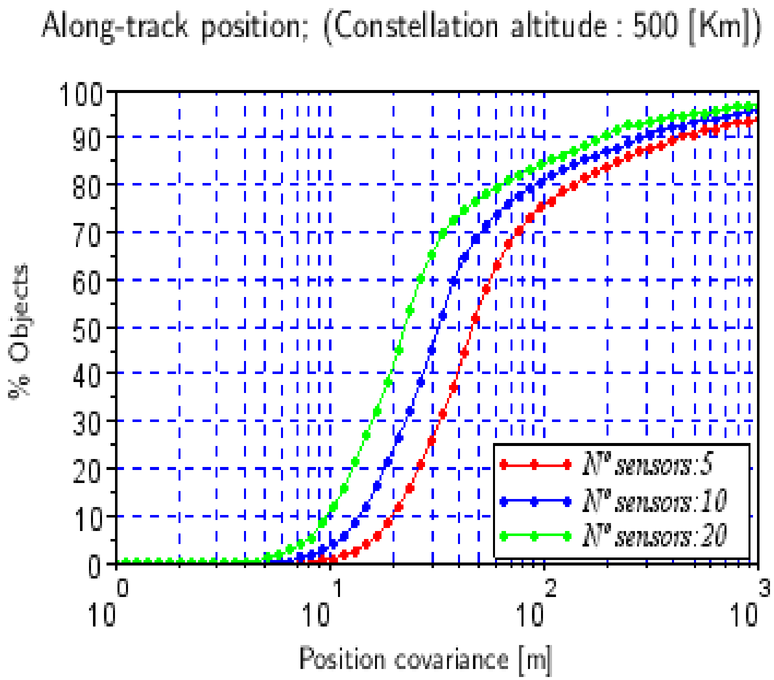
SURVEILLANCE OF OBJECTS IN LEO

ORBIT DETERMINATION COVARIANCE



Covariance for along-track component:
Altitude: 500[km]; Magnitude threshold: 12

- Covariance decreases with increasing number of sensors
- Radial and cross-track component behave similarly
- Slight decrease in the covariance for decreasing altitudes and increasing magnitude thresholds
- Covariance was in the order of tens of meters for 50% of the observed objects.

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CONCLUSIONS (I)

Surveillance of LEO population

- ***Altitude*** of SBSS constellations, delimits the percentage of visible population
- ***Number of sensors*** establishes the number of visibility opportunities per day
- Statistics are more restrictive than those computed for the surveillance of the GEO population. The ***duration*** of the visibility opportunities are shorter and the required ***angular velocities and accelerations*** higher.
- Angular velocity values for percentile 50% were around 5.0e-1 deg/s and angular acceleration for percentile 50% were around 3.0e-4 deg/s2.

Surveillance of GEO population

- ***Altitude*** of SBSS constellations, has no effect on the percentage of the visible population *(97%, 99%, 98% approx. for 500[Km], 750[Km], 1000[Km] respectively).*
- ***Number of sensors*** establishes the number of visibility opportunities per day
- Angular velocity values for percentile 50% were around 4.0e- 3 deg/s and angular acceleration for percentile 50% were around 3.0.e-7 deg/s2.

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CONCLUSIONS (II)

Surveillance of LEO population

- ***Access the largest % of the space debris population:*** discard constellations in 1000[Km] altitude orbits. *(58% of visible population for 1000[km] versus 87% and 83% for 500[km] and 750[km] respectively)*
- ***Attitude constraints:*** no optimum configuration stands out.
- ***Orbit Determination accuracy:*** constellations at 500[km] present the best accuracy which also improve with an increase in number of sensors and magnitude threshold.

Surveillance of GEO population

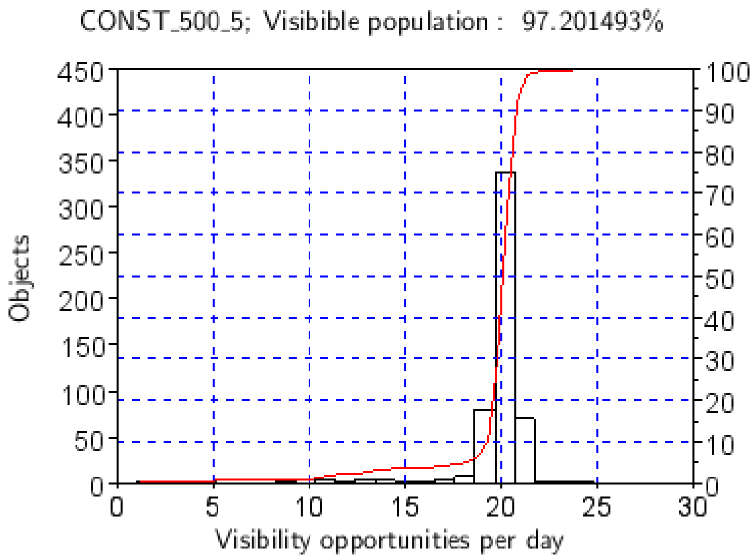
- ***Access the largest % of the space population:*** do not reveal an optimum configuration. *(The percentages of visible population are 97%, 99% and 98% for constellations at 500[km], 750[km] and 1000[km] respectively)*
- ***Attitude constraints:*** no optimum configuration stands out.
- ***Orbit Determination accuracy:*** constellations at 500[km] present the best accuracy which also improve with an increase in number of sensors and magnitude threshold.

END

SURVEILLANCE OF OBJECTS IN GEO

SURVEILLANCE OF OBJECTS IN GEO

MEAN VISIBILITY OPPORTUNITIES PER DAY



Mean visibility opportunities per day:
Altitude: 500[km]; Number of sensors: 5

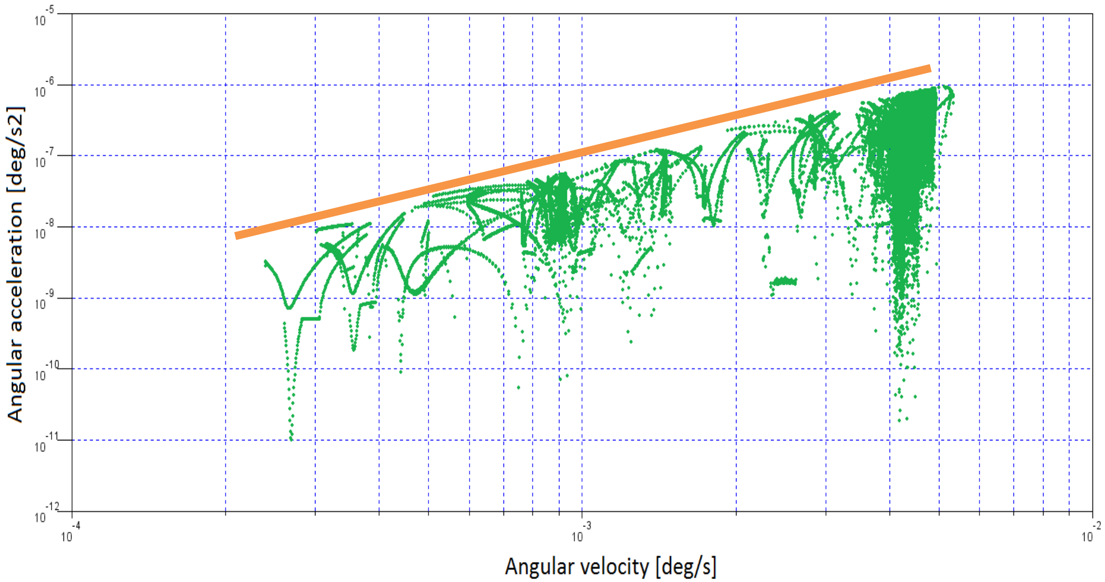
PERCENTAGE OF VISIBLE POPULATION

Altitude [km]	Number of sensors		
	5	10	20
500	97.20%	97.20%	97.20%
	2	4	8
750	99.44%	99.44%	99.44%
1000	98.32%	98.32%	98.32%

- Marginal variation in the percentage visible population (maximum difference of 2%) with altitude
- Distribution of the visibility opportunities per day is not as dispersed as for LEO (average values around 10 to 25)
- Number of visibility opportunities per day increases with increasing number of sensors

SURVEILLANCE OF OBJECTS IN GEO

RELATION BETWEEN ANGULAR VELOCITY & ACCELERATION



Similar trend as for LEO for both cases besides:

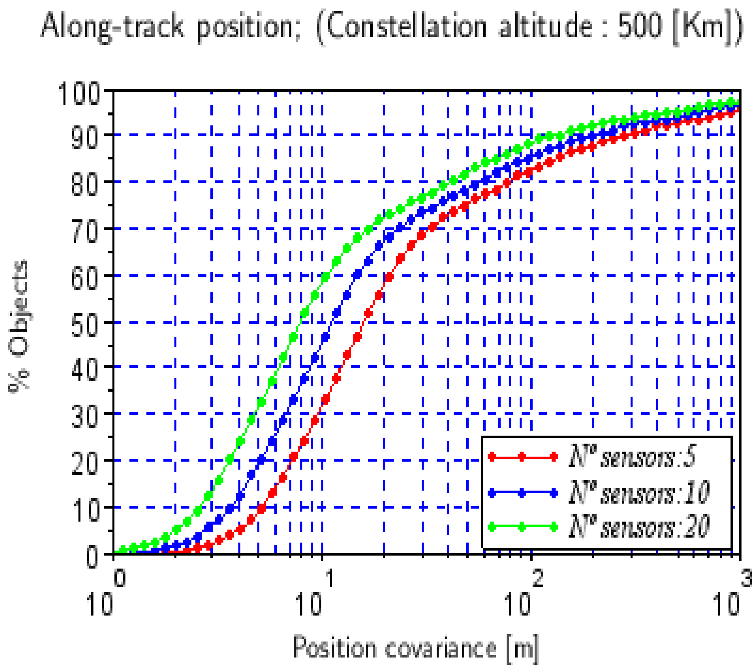
- Smaller angular velocity and acceleration values
- Longer visibility period durations

Altitude [km]	Number of sensors		
	5	10	20
500	Percentile 50%: 513	Percentile 50%: 513	Percentile 50%: 513
	2	4	8
750	Percentile 50%: 736	Percentile 50%: 736	Percentile 50%: 736
1000	Percentile 50%: 926	Percentile 50%: 926	Percentile 50%: 926

DURATION OF VISIBILITY PERIODS

SURVEILLANCE OF OBJECTS IN GEO

ORBIT DETERMINATION COVARIANCE



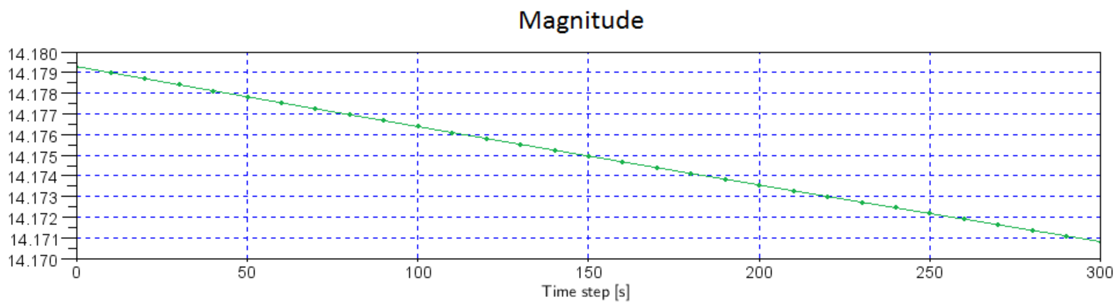
Covariance for along-track component:
Altitude: 500[km]; Magnitude threshold: 12

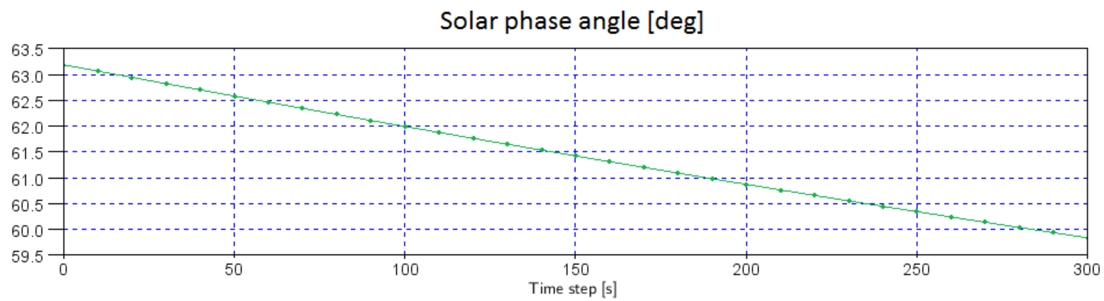
- Covariance decreases with increasing number of sensors
- Radial and cross-track component behave similarly
- Slight decrease in the covariance for decreasing altitudes and increasing magnitude thresholds
- Covariance was smaller than 20[m] for 50% of the observed objects. This represents a better accuracy than for the LEO case

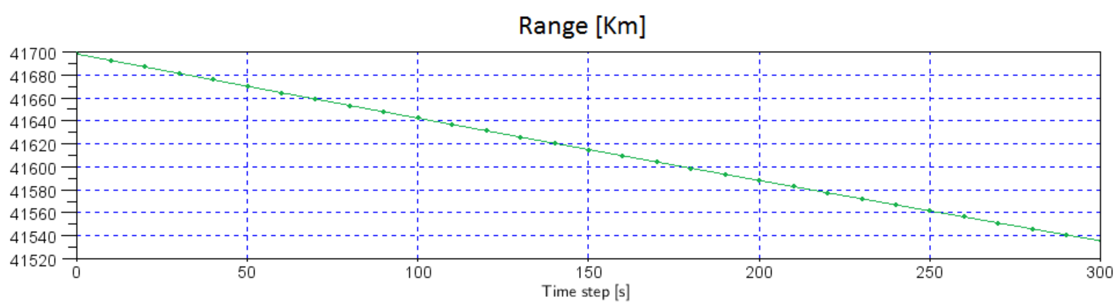
EVOLUTION DURING VISIBILITY PERIOD

SURVEILLANCE OF OBJECTS IN LEO

EVOLUTION OF SOLAR PHASE ANGLE AND RANGE DURING A PERIOD OF VISIBILITY





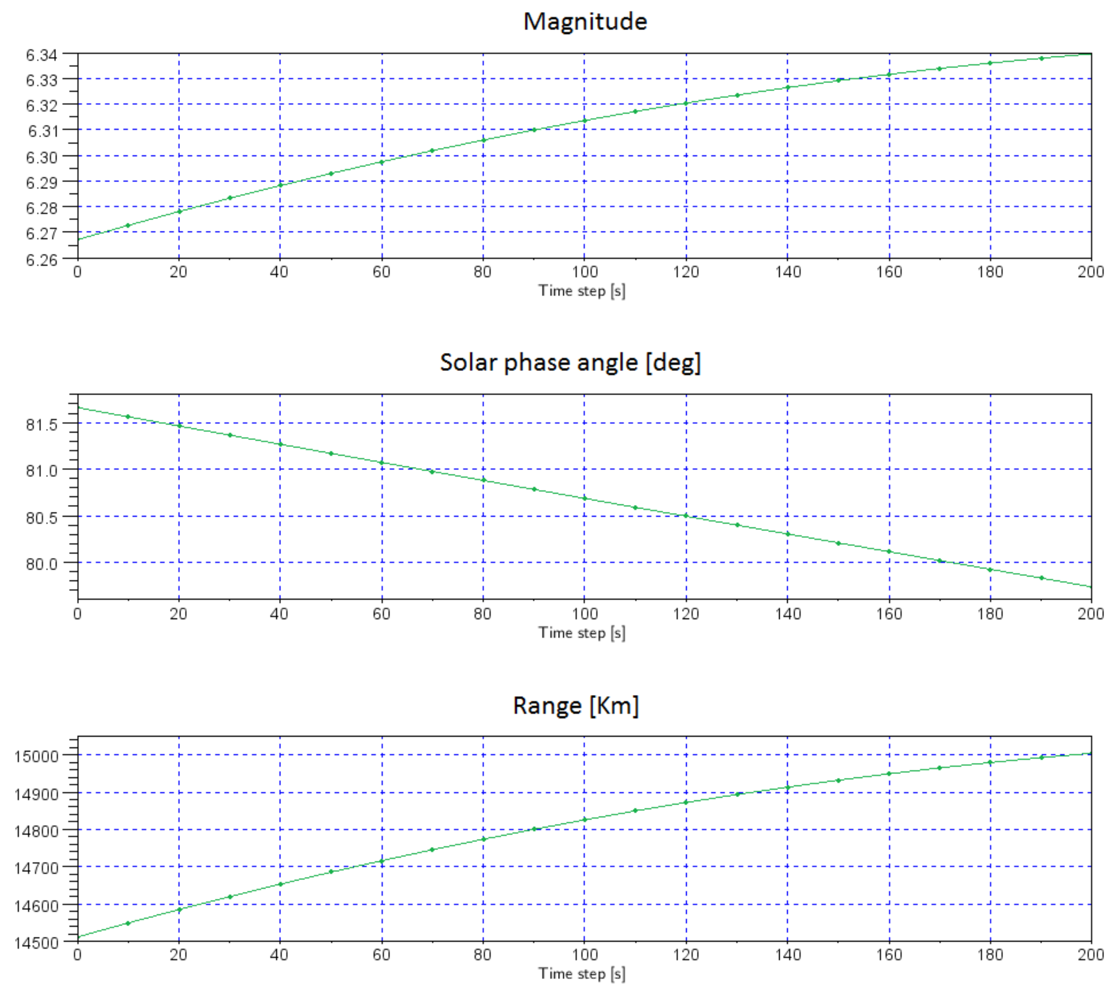


Random period of visibility for an object from the GEO population and a sensor from the constellation at an altitude of 750 [km].

Magnitude follows trend of solar phase angle evolution

SURVEILLANCE OF OBJECTS IN LEO

EVOLUTION OF SOLAR PHASE ANGLE AND RANGE DURING A PERIOD OF VISIBILITY



Random period of visibility for an object from the LEO population and a sensor from the constellation at an altitude of 750 [km].

Magnitude does NOT follow trend of solar phase angle evolution

In this particular case, the other parameter at play, the distance object-sensor, eclipses the effect of the solar phase angle

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