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

Cristina SANTANA

Date
16/03/2016
INTRODUCTION
OVERVIEW OF BAS$^3$E SIMULATOR
GENERAL ASSUMPTIONS AND MODELS
SURVEILLANCE OF OBJECTS IN LEO
CONCLUSIONS
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GENERAL ASSUMPTIONS AND MODELS
SURVEILLANCE OF OBJECTS IN LEO
CONCLUSIONS
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
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
SUMMARY

- INTRODUCTION
- OVERVIEW OF BAS$^3$E SIMULATOR
- GENERAL ASSUMPTIONS AND MODELS
- SURVEILLANCE OF OBJECTS IN LEO
- CONCLUSIONS
The \textit{BAS}^3\textit{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.

\textbf{ENHANCEMENT:}
Originally conceived for ground-based observations (telescope and radar), \textit{BAS}^3\textit{E} has been recently enhanced to enable the definition of \textit{"orbiting" sensor sites}, which allow for the simulation of space-based space surveillance sensors.
OVERVIEW OF EXECUTED STAGES

- Populate Sensor DB
- Visibility Opportunities
- Visibility Statistics
- Statistics Files
- ASCII
- SQL
- Sensor DB
- Propagate Object Ephemeris
- Import Object DB
- Sensor Observations
- Filter Observations
- Orbit Determination
- Compute Covariance
- Observations
- Obs DB
- Obs DB
- ASCII
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GENERAL ASSUMPTIONS AND MODELS
SURVEILLANCE OF OBJECTS IN LEO
CONCLUSIONS
### General Assumptions and Models

#### Space Debris Populations and Propagation Models for Simulation

<table>
<thead>
<tr>
<th>Low Earth Orbit (LEO)</th>
<th>Geostationary Orbit (GEO)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Source:</strong> ESA's debris catalogue MASTER-2009</td>
<td><strong>Source:</strong> MEDEE software tool from CNES</td>
</tr>
<tr>
<td><strong>Nº of objects:</strong> 20811</td>
<td><strong>Nº of objects:</strong> 536</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Altitude [km]</th>
<th>Number of sensors</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>5, 10, 20</td>
</tr>
<tr>
<td>750</td>
<td>2, 4, 8</td>
</tr>
<tr>
<td>1000</td>
<td>2, 4, 8</td>
</tr>
</tbody>
</table>

OBSERVATION CONSTRAINTS

- Sun exclusion angle \((\text{min angle } 90 \text{ deg})\)
- Moon exclusion angle \((\text{min angle } 20 \text{ deg})\)
- Earth exclusion angle \((\text{min angle } 20 \text{ deg})\)
- Distance to Galactic plane \((\text{min angle } 30 \text{ deg})\)
- South Atlantic Anomaly
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
### Observation components
- Azimuth, elevation (*Sigma: 0.001 [deg]*)
- Luminosity

### Magnitude thresholds (for observation filtering)
- 12, 14, 16

### Propagation Models for Orbit Determination

<table>
<thead>
<tr>
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<th>GEO</th>
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### GENERAL ASSUMPTIONS AND MODELS

#### ESTIMATION PARAMETERS

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

MEAN VISIBILITY OPPORTUNITIES PER DAY

PERCENTAGE OF VISIBLE POPULATION

<table>
<thead>
<tr>
<th>Altitude [km]</th>
<th>Number of sensors</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>5</td>
</tr>
<tr>
<td>750</td>
<td>2</td>
</tr>
<tr>
<td>1000</td>
<td>8</td>
</tr>
</tbody>
</table>

- 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

Mean visibility opportunities per day: Altitude: 500[km]; Number of sensors: 5
SURVEILLANCE OF OBJECTS IN LEO

RELATION BETWEEN ANGULAR VELOCITY & ACCELERATION

DURATION OF VISIBILITY PERIODS

<table>
<thead>
<tr>
<th>Altitude [km]</th>
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<tbody>
<tr>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>500</td>
<td>Percentile 50%: 199</td>
</tr>
<tr>
<td></td>
<td>Percentile 50%: 199</td>
</tr>
<tr>
<td></td>
<td>Percentile 50%: 199</td>
</tr>
<tr>
<td>750</td>
<td>Percentile 50%: 245</td>
</tr>
<tr>
<td></td>
<td>Percentile 50%: 245</td>
</tr>
<tr>
<td></td>
<td>Percentile 50%: 245</td>
</tr>
<tr>
<td>1000</td>
<td>Percentile 50%: 321</td>
</tr>
<tr>
<td></td>
<td>Percentile 50%: 321</td>
</tr>
<tr>
<td></td>
<td>Percentile 50%: 321</td>
</tr>
</tbody>
</table>
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.
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**
- **Solar Phase Angle**
- **Distance object – sensor**

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<td>Object Diameter</td>
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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
SURVEILLANCE OF OBJECTS IN LEO

ORBIT DETERMINATION COVARIANCE

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.

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

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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.
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.
SURVEILLANCE OF OBJECTS IN GEO
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MEAN VISIBILITY OPPORTUNITIES PER DAY

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<td>10</td>
</tr>
<tr>
<td>1000</td>
<td>20</td>
</tr>
</tbody>
</table>

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

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<tr>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>500</td>
<td>Percentile 50%: 513</td>
</tr>
<tr>
<td>750</td>
<td>Percentile 50%: 736</td>
</tr>
<tr>
<td>1000</td>
<td>Percentile 50%: 926</td>
</tr>
</tbody>
</table>
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

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