Performance of a global network of laser-optical tracking stations for LEO space surveillance

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ABSTRACT

We present preliminary results from a large system study to investigate the performance of a global laser-ranging network. In order to determine when favorable weather and lighting conditions for laser ranging can be expected at any particular site of a network of globally-distributed stations, we compiled daily weather parameters for cloud, wind and visibility from publicly available long-term weather data. For these observing times, synthetic laser ranging measurements are simulated for various types of LEO orbits and subsequently used for precise orbit determination. We derive state vector uncertainties that can be achieved as well as predicted uncertainty when propagating the orbit for a couple of days without any new measurements.

1. INTRODUCTION

With more than 13000 known resident space objects, most of which is space debris, the low-Earth orbit (LEO) space environment is nearing congestion. Several planned mega-constellations with hundreds or even thousands of small satellites, an expected increase in launch activities from spacefaring nations and the private sector, and inevitable fragmentation/collision events will likely lead to a significant growth in the population over the next decades.

A prerequisite of operating in a congested space environment is precise information on the objects' orbits and their associated uncertainties. Many space situational awareness (SSA) use cases (e.g. catalog maintenance, conjunction assessment, collision avoidance, and re-entry analysis) need high precision orbits with small state vector covariances.

Laser ranging has demonstrated high accuracy for determining ranges to space objects to within a meter or better. Time-of-flight measurements from laser-ranging facilities of the International Laser Ranging Service (ILRS) network are regularly being used to determine precision orbits and ephemerides of ~80 satellites, mostly for geodesy, Global Navigation Satellite System (GNSS) validation, and mission support. With better range accuracy and lower operational cost per station, laser ranging is a highly promising sensor technology for LEO space surveillance and can complement existing radar facilities.

However, as an optical ranging method, laser ranging requires clear skies with little cloud cover and good visibility. Furthermore, in most cases the space object needs to be illuminated by the sun and the station in umbra to allow passive-optical tracking in order to compensate for the typically low accuracy of Two-line elements (TLE) tracking predictions. These requirements and constraints drive the design of a laser-ranging network and have an impact on the orbit uncertainties that can be achieved for different LEO orbit types.

Section 2 provides a high-level description of the simulation framework that is being developed for the system study. The compilation of station data and their geographical distribution is described in Section 3. Section 4 discusses how statistical information on weather parameters that impact observability and operation (cloud cover, wind, aerosol concentration) has been derived. Section 5 gives an overview over the methods and software used for orbit determination and propagation, exemplified for a small regional network consisting of only 3 European stations. Finally, we summarize in our main results and discuss next steps.

2. SIMULATION FRAMEWORK

A realistic simulation of networks of laser-optical tracking stations for SSA application of LEO space objects requires the interplay of various software modules. We have development a simulation framework consisting of own tools with commercial software packages, with aim of ensuring reliable results and maximum freedom in defining simulation scenarios and parameters.

The general simulation workflow is shown in Fig. 1 and contains the following major parts:

- ***Selection of orbit or orbital type***
  Interface to publicly available SpaceTrack/NORAD catalog containing TLE of space objects.

- ***Selection of observation time period***
  The time period of the year where laser-ranging observation shall be simulated is a crucial factor for the expected local weather and illumination conditions.

- ***Definition of network layout***
  A network of laser-optical tracking stations can defined based on master list of candidate stations. Different geographical distributions can be selected, e.g. regional, global, clustered, or only those belong to a specific country or organization. A detailed description of the master list and selection options are discussed in Section 3.

- ***Determination of pass times***
  The times when the space object in questions is observable from any one station of the network are basically limited by the object's orbital parameters, the geographical location of the stations, illuminations conditions needed for target acquisition (i.e. target in sunlight, station in Earth shadow), as well as elevation cutoffs due to safety or local terrain. We use the commercial software STK (Systems Tool Kit).

- ***Expected visibility intervals due to weather***
  Typical local weather for a given time of year can have a huge impact on the chances of performing successful laser-ranging observations or not. As an optical method, laser-ranging requires that at least parts of the local sky are free of clouds. Overcast sky or any precipitation (e.g. rain, snow, hail) lead to a loss of observability. High average wind speeds or strong gusts may not allow opening the telescope dome or negatively affect the tracking.

- ***Folding in operational constraints***
  In order to render the simulation more realistic, we can set station duty cycles and random downtimes. This leads to a further reduction in actually available measurement times.

- ***Generation of synthetic data***
  The AGI software Orbit Determination Tool Kit (ODTK) is used to generate synthetic laser-ranging data with user-defined measurement noise and bias levels.

- ***Orbit determination and propagation***
  The synthetic data can then to fed to an orbital determination filter process yielding state vector uncertainties. Subsequent orbit propagation can be used to look at the temporal evolution of state vector uncertainties for time periods without any new measurements. This provides information when, at the latest, an object should be scheduled for re-observation give a maximum allowed covariance size limit.

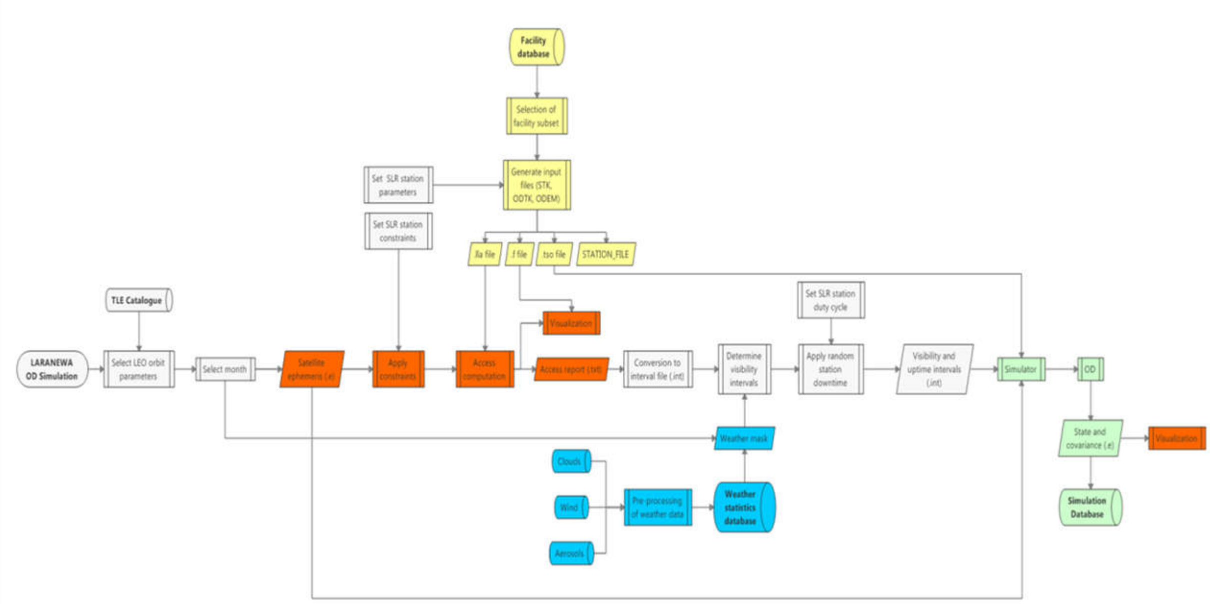

Fig. 1. General workflow of the simulation environment, starting on the left-hand side with selecting one or more resident space object (RSO) orbits and the observation time period. Software modules related to station data and weather statistics are shown in yellow and blue, respectively. Computation of visibility time based on orbit, lighting conditions permitting passive-optical observations, and outages due to bad weather are depicted in orange. In green, simulation of laser-ranging measurement and orbit determination.

3. STATION MASTER LIST

We aim to inject some realism into the simulation by only considering those sites where conditions for optical observations are favorable and with existing basic infrastructure for access, security, accommodation, etc. The layout laser-optical networks are all based on an extensive compilation of operational, engineering or inactive ILRS stations [1,2,3], sites of astronomical observatories [4,5], and known installations for space surveillance, e.g. radars, optical telescopes [6].

In total, 425 sites/locations constitute the master list of stations from which networks of various sizes and geographical distribution can be defined. We have compiled geographical coordinates (latitude, longitude, altitude), associated country and continent, as well as membership with international organization or supranational unions like NATO or the EU. The global distribution of sites in the station master list is shown in Fig. 2.

To facilitate the network definition, a graphical user interface (GUI) has been developed in Python that enables the user to select:

- All stations of a continent (Europe, North America, South America, Asia, Africa, Oceania, Antarctica)
- All stations within the European Union, including overseas territories
- All stations within NATO countries
- All stations belonging to Germany
- ILRS stations, either operational, engineering, or closed/inactive
- Random number of stations for any of the selections above. For the geographical distribution of random station networks Fibonacci spherical grids/lattices are generated and the stations closest to the grid point is being selected

Fig. 2. Distribution of 425 sites in the master list. The high number of sites in Europe and North America is clearly seen, as is the small number of locations in Africa. 7 sites are located in Antarctica, including one at the South Pole.

4. GLOBAL WEATHER DATA

The local weather conditions with their seasonal and/or daily variability are of paramount importance for a realistic analysis of the performance of a network consisting of laser-ranging stations. Unsuitable weather plays are decisive role in whether a predicted pass of a space object over the station can actually be used to perform the observation and get range information. In the following we will discuss the relevant weather parameters, describe available data sources and their limitations, and explain the functioning of the "weather filter" that is used to prune object visibility times and come up with probable observability periods. We have identified three main weather conditions that have a bearing on optical observations:

4.1 Cloud cover

Water droplets in clouds absorb and scatter visible or near-infrared laser light significantly. The amount of cloud cover over a station can be measured from space or the ground, and it typically described as cloud fraction (CF) or sky cover [7]. Based on past success rate for laser-ranging observation under varying cloud conditions, we define maximum permissible cloud cover of 0.5 (or 50%). Stations/visibility times where the expected cloud cover is above this threshold are discarded and lost for observations.

4.2 Aerosol concentration

Attenuation of a laser beam travelling from the laser transmitter through the atmosphere to the space object and back to the receiver telescope/detector can also happen due to aerosols or haze.

4.3 Wind

We have considered further constraints on the operability of a laser-optical tracking station due to wind. Too strong wind loads and/or intermittent gusts may prevent the dome from to be opened. We apply cutoff values of 40 km/h or 65 km/h for maximum average wind speed and gust speed, respectively.

Databases containing collections of past weather for the above quantities must fulfill the following requirements:

- Global coverage
- Spatial consistency of data product
- High temporal resolution

Although many geostationary weather satellites provide high-cadence observations, they are not available for all longitudes. Furthermore, the resolution of GEO imagery depends on latitude, with the highest resolution at the equator. Weather data from sun-synchronous LEO orbit have excellent global coverages and spatial consistency. However, very often prolonged gaps appear in the data at specific local times (dawn, dusks). We therefore decided to use weather data of the European Centre for Medium-Range Weather Forecasts (ECMWF), consisting of re-analysis of weather data coupled with numerical weather prediction models [8].

The spatial resolution of ECMWF weather data is 0.75 degrees on a latitude/longitude grid. The average distance of the stations in the master list to the nearest ECMWF grid point is about 28 km. We consider this distance sufficiently small to capture seasonal and daily variations at all stations of the master list. However, the local microclimate is most likely not properly represented (e.g. mountain tops vs. at sea level). The temporal resolution of the ECMWF weather data is 3 hours. At 0000, 0600, 1200, and 1800 UTC re-analysis data is used; in between (at 0300, 0900, 1500, and 2100 UTC) data coming from assimilated weather predictions.

The ECMWF weather data has been pre-processed to provide suitable daily, monthly, or annual averages. A uniformly distributed random number generator has been used to determine whether an observation is expected to be possible or not, given the statistics of all relevant weather parameters. This filter is applied to all pass times of the space objects over the particular station.

5. EXAMPLE SIMULATION

To illustrate the effect of weather on the achievable orbit uncertainty, we show here results for a rather small network, consisting only of three laser-ranging stations in Europe well spread in latitude:

- Andøya (ASC), Norway
- Stuttgart (DWD), Germany
- Tenerife (TNRF), Canary Islands, Spain

The space object simulated is on a sun-synchronous orbit with 800 km altitude; its right ascension of the ascending node (RAAN) is 90 degrees. For each site, a minimum elevation of 30 degrees above the local horizon has been assumed. Similarly, the maximum elevation of the Sun has been set to -6 degrees (begin of nautical twilight); the space object shall be in direct sunlight. The observation time period is 7 days in the beginning of October 2017. Of 49 passes over the stations that meet the observing constraints, only 15 remain due to weather, see Fig. 3. These intervals have been used to generate synthetic range data (~1 m RMS uncertainty) and perform an orbit determination (filter and smoother). The resulting position vector uncertainty is shown in Fig. 4.

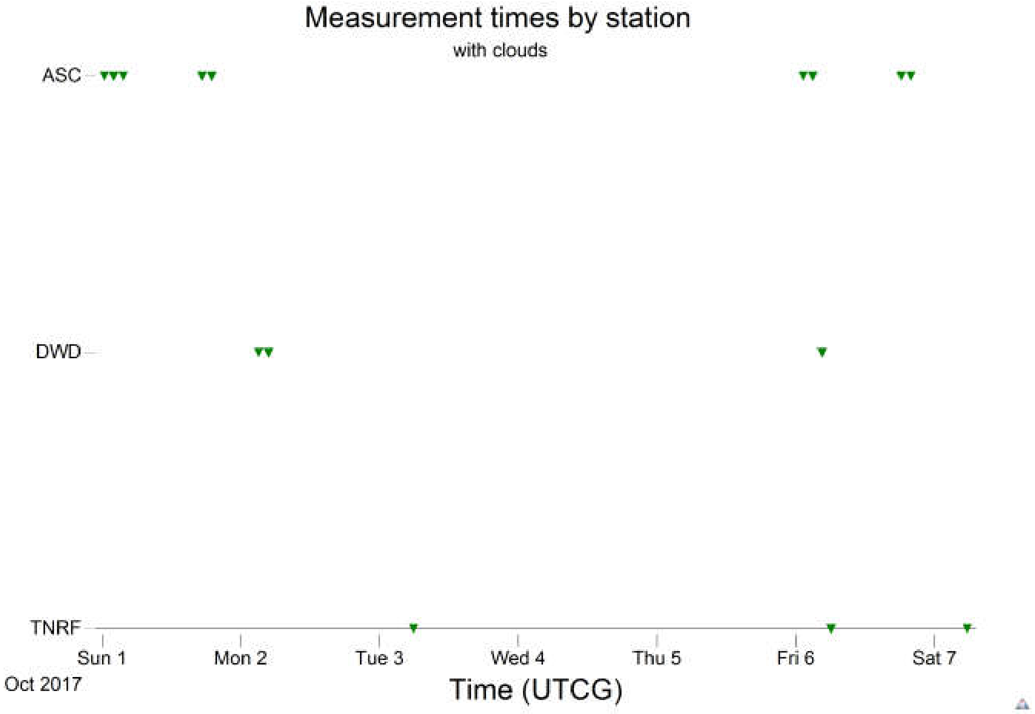

Fig. 3. Measurement times remaining after filtering times with "bad" weather. Note the data gap of ~2 days.

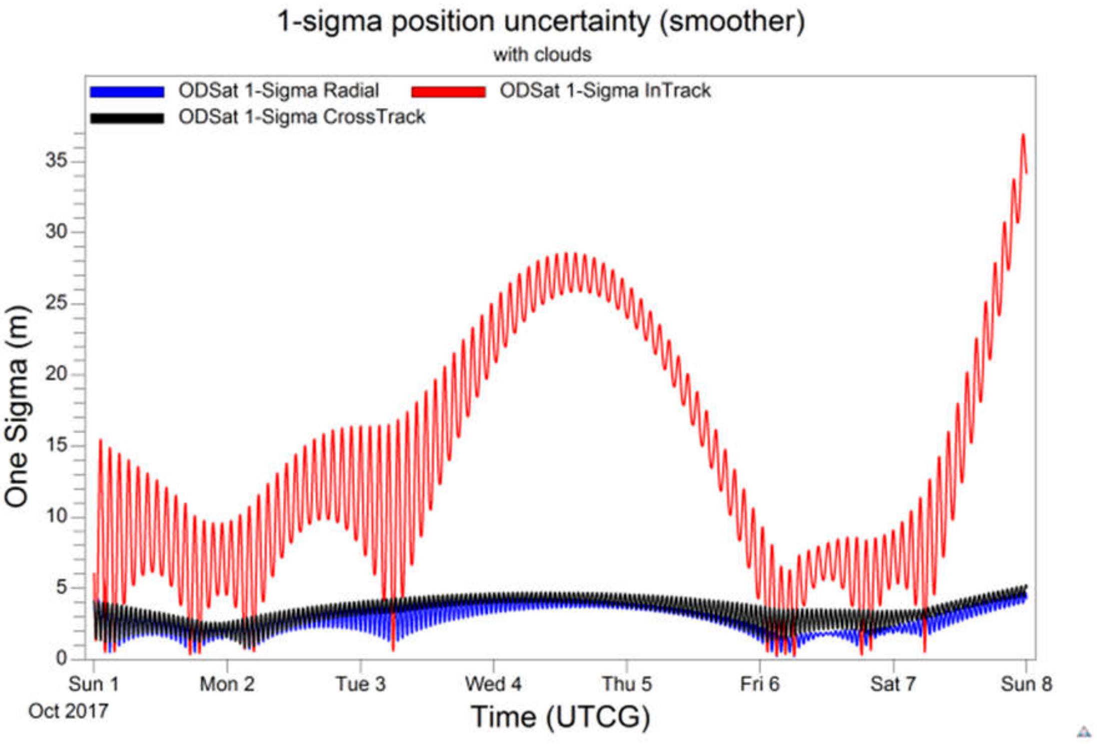

Fig. 4. Smoothed 1-sigma position uncertainties in the radial, in-track and cross-track directions derived from the synthetic laser-ranging measurements, assuming 1-meter range measurement uncertainty.

6. SUMMARY AND OUTLOOK

We have developed a simulation framework to model the performance of networks of laser-ranging stations for SSA applications. Particular emphasis has been put on adding "realisms" into the simulation environment, e.g. by taking into account expected weather conditions as they seriously affect the observability of given pass from a particular station. We conducted an extensive literature search to compile a global list of sites where conditions for optical observations are assumed to be favorable and/or where laser-optical stations could potentially be built and operated.

Below is a list of dedicated simulation scenarios or analysis runs that we consider worthwhile and which will be of interest to space surveillance and laser-ranging communities:

- Simulation of global networks of various size and geographical distribution
- Determination of the optimal network geometry given prevalent weather patterns
- Derivation of the minimum number of stations needed to maintain a predefined covariance size (e.g. for catalog maintenance
- Derivation of the minimum number of station needed to support on-demand measurements (e.g. for refined conjunction analysis or re-entry events)
- Analysis of network throughput: number of LEO space objects whose orbit uncertainty can simultaneously be maintained
- Investigating the benefit of adding blind (i.e. without constraints on object illumination) and/or daylight tracking (i.e. without constraints on station illumination)
- Performance of an ILRS-only network, assuming a small fraction of the observing time is dedicated to SSA
- Adding known SSA sensor network to fuse radar, electro-optical, and laser-optical tracking data

7. ACKNOWLEDGMENTS

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