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Analysis of the Orbit Determination Accuracy Using Laser Ranges and Angular Measurements

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Abstract

The increasing amount of space debris requires huge efforts for the tracking networks in order to maintain the orbits of all the objects. The precise knowledge of the positions of space debris objects is fundamental for collision avoidance maneuvers performed by satellite operators and for future active debris removal missions. It is very well known that the accuracy of an orbit determination process depends on the kind of observables used, their accuracy, the length of the observed arc, and the observer-target geometry of the observations. One possible solution to improve orbits and at the same time, reducing the amount of observation time, is the combination of different type of observables.

In this paper an in-depth study is carried out to investigate the benefit of adding laser range measurements to the classical optical astrometric observations in terms of improved accuracy of the determined orbit. In particular, after some validation tests to prove the effectiveness of the algorithm, it will be shown how different kinds of observables influence the accuracies of the estimated orbital parameters. Then, the influence of the observation geometry is analyzed and finally the improvements achieved on the orbit prediction, especially for high altitude objects, will be shown. All the mentioned tests are performed using real ranges from the International Laser Ranging Service (ILRS) stations and real angular/laser measurements provided by sensors of the Swiss Optical Ground Station and Geodynamics Observatory Zimmerwald owned by the Astronomical Institute of the University of Bern (AIUB).

Keywords: (space debris, laser ranging, orbit determination accuracy, real measurements)

Nomenclature

- a semi-major axis,
- e eccentricity,
- i inclination,
- Ω Right Ascension of Ascending Node,
- ω Argument of Perigee,
- A/M Area to Mass Ratio,
- p_i weight of the ith measurement,
- σ_0 a priori errors of parameters to be estimated,
- σ_α standard deviation of angular measurements,
- σ_r standard deviation of range measurements,
- M mean anomaly w.r.t. the osculating epoch.

Acronyms/Abbreviations

International Laser Ranging Service (ILRS)
Astronomical Institute of the University of Bern (AIUB)
With respect to (w.r.t.)
Active Debris Removal (ADR)
Orbit Determination (OD)
Satellite Laser Ranging (SLR)
Least Squares (LSQ)
Orbital Elements (OE)
Low Earth Orbit (LEO)
Medium Earth Orbit (MEO)
Geostationary Earth Orbit (GEO)
Right Ascension (RA)
Declination (DE)
Global Positioning System (GPS)
Area to Mass Ratio (AMR)
Right Ascension of Ascending Node (RAAN)
NASA GSFC SLR Mission Contractor, USA (HTS)
NERC Space Geodesy Facility, United Kingdom (SGF)
Japan Aerospace Exploration Agency, JAPAN (JAX)
Consolidated Laser Ranging Data Format (CRD)
Standard Deviation (STD)
Radial, Along-track and Cross-track (RSW)
Global Navigation Satellite System (GLONASS)
Root Mean Square (RMS)
Modified Julian Date (MJD)
Field of View (FoV)

1. Introduction

The space operations have a side product: orbital debris. Until September 2012 were regularly tracked more than 23000 space debris objects with a size larger than 10 cm [1]. Recent studies [2,3] proved that the space debris populations will continue to grow even if we stop to launch new satellites; this growth will be driven mainly by accidental collisions and breakups.

In order to ensure the long-term sustainability of outer space activities, the various agencies and institutions are facing this problem developing guidelines for the satellite owners, operators and manufacturers and answering questions about the space debris population and its evolution. Studies on the evolution of the space debris population [3,4] showed the need of ADR operations to preserve the environment for the future generations. Although the ADR will be necessary for the long-term sustainability it is of fundamental importance for the satellite operators (and for future ADR missions) to know precisely the position of space debris in order to avoid unnecessary maneuvers that will reduce the satellite lifetime.

The accuracy of an OD depends on: the number of observations, the length of the observed arc [5,6], the observation geometry [7] and the accuracy of the observations. Therefore to improve the OD accuracy one can optimize each just mentioned aspect. It is quite common in the OD process to use range measurements together with the angular ones. Recent studies showed the possibility of successfully track space debris objects with the 1 m level precision [8].

In this paper we investigated the influence of merging the laser range and angular measurements in the OD process. After a general introduction on the SLR measurements, we will show the results of the validation tests performed on our OD tool. We will then report the results obtained by merging real range and angular measurements in different scenarios for different orbital regimes (especially for MEO and GEO). These tests were carried out to identify the influence of the observation geometry, of the length of the observed arc and the effect of different kinds of observables on the estimated OE. For all tests only real data are used: the angular and part of the laser measurements were provided by sensors of the Swiss Optical Ground Station and Geodynamics Observatory Zimmerwald owned by the AIUB; while the other ranges were provided by ILRS stations.

2. Why SLR measurements?

One way to improve the accuracy of predicted orbits to avoid unnecessary collision avoidance maneuvers is to use high precision measurements like the laser ranges.

The satellite laser tracking started to be used intensively for OD purposes in the last 40 years. This success is mainly due to the fact that the used measurements do not need an active payload on board of the satellite and the accuracy of the produced ranges is very high (~1 mm) [9]. These are the two main reasons why the laser technique is also suitable for the OD of space debris. Although the only requirement needed for the tracking is the target capability to reflect the light, not all space debris can be tracked by laser facilities. In fact, to be trackable, the object should be either quite big and rather low in altitudes or it should carry retroreflectors on board. The LEO upper-stages are suitable targets for this kind of experiments. On the other hand, if an object carries retroreflectors (which, recently, is a common habit among satellite manufacturers), the limitation of the size is reduced and this technique can be applied even to smaller objects at higher altitudes.

To exploit the high precision of the SLR measurements we needed to adapt the tool daily used at the AIUB for OD. Three main aspects of the tool were improved: the satellite orbit modelling, the corrections to be applied to the measurements and the modifications at the normal equations level in terms of partial derivatives and measurements weights.

3. Validation of the orbit determination performed using SLR measurements

To check the correctness of our implementation we divided the validation tests in two parts: the first concerning the application of the range-corrections and the second concerning the OD results.

The validation of the range corrections was performed comparing the ranges before and after their application with those provided by the Bernese GNSS Software Version 5.2 [10]. This comparison was performed excluding all the other possible sources of error like those given by: the propagation, the dynamical model and the orbit estimation part.

The solution of our OD process was validated comparing the ephemerides obtained by the propagation of the orbit determined with only real laser measurements (publicly available on the ILRS [11]) with the satellite positions provided by the ILRS. This comparison was repeated for different satellites belonging to different orbital regimes.

The accuracy of the OD results depends on: the arc-length covered by the observations, the number of observations, their accuracy and the relative object-observer/s position. The latter factor is influenced by the station positions and the satellite orbit. Furthermore the satellite orbit, more precisely its altitude and inclination, determines its visibility window which is, especially for LEO objects, the main factor that limits the amount of observations collectable [12]. On the other hand, having high-altitude satellites as in the upper MEO and GEO regions (from 20000 to 40000 km of altitude), which have very broad visibility windows, does not mean more observations since, in this case, the station laser power is the main limit for collecting observations.

The altitude of the satellite is determining the dynamical model of the forces used in the OD. LEO satellites are, in fact, more sensitive to the higher terms of the gravity field, to the atmospheric drag and the radiations of the Earth in terms of Albedo and thermal radiation. Higher satellites are more sensitive to the correct modelling of the solar radiation pressure. There are several methods to counteract the effect of the miss-modelling like the set-up of empirical accelerations or scaling parameters for the estimation of the AMR and the ballistic coefficient. In all the OD performed in this study no empirical accelerations are used and no scaling parameters are estimated. Only in the case of Glonass 123 and Irnss1a the AMR is estimated and the obtained value is used in the following tests; while the AMR of Lageos 1 is provided by Sosnica et al. [11].

The above mentioned factors drove the choice of the observation arc-length, in particular we needed to select an amount of observations not too much spread over time in order to not accumulate miss-modelling effects but, at the same time, not too short in order to guarantee a good coverage of the orbit. Since there are not specific guidelines about the selection of the arc-length we needed to determine it. First of all, we took the epoch of the positions given by the ILRS, this was used as our central time interval for the OD. Then, we selected the laser measurements used for the OD, keeping the position interval in the middle of our arc of observations; the length of the latter was increased from 1 day up to 23 days (for the presented case of Lageos 1). An OD process was then performed, and the determined orbit was propagated. The positions obtained at the same epoch of those provided by ILRS were stored and then compared. During these tests, no screening of the observations is performed, all the available stations in the CRD-file are used and only the outliers were excluded.

Here, we will report the validation test performed on Lageos 1. This satellite was chosen because its altitude, about 6000 km, is a sort of compromise since is not too high to be reachable from almost all SLR stations and it has a nice visibility window which allows a pass length over a single station of more than 30 minutes. At the same time, its orbit is less sensitive to the higher terms of the gravity field (the gravity field used for the OD is up to degree 40x40) and is not influenced by the atmospheric drag. Table 1 reports the results obtained from the validation tests using Lageos 1 observations. In the first column, the observations arc-length is shown. In the second, the number of observations (normal points) used in the OD is reported. In the latter three we reported the mean position differences w.r.t. three centers (namely SGF, JAX and HTS), obtained from the comparison of 4 days of propagation within the fit-span. For completeness, in the bottom part of the table we reported the mean position difference among the centers.

Table 1 Lageos 1 results of validation tests.

Arc-Length	Num. of obs.	Mean Position Difference w.r.t.		
		SGF [m]	JAX [m]	HTS [m]
1 Day	297	0.94	1.90	1.50
3 Days	870	0.84	1.47	1.22
5 Days	1427	0.81	1.36	1.14
7 Days	2044	0.81	1.41	1.15
9 Days	2553	0.83	1.17	1.05
11 Days	3023	0.72	1.25	0.99
13 Days	3595	0.71	0.91	0.82
15 Days	4095	0.68	0.94	0.80
19 Days	5034	0.78	1.03	0.93
23 Days	5992	0.74	1.23	0.97
Mean Pos. Diff. between centers [m]		SGF Vs HTS	SGF Vs JAX	HTS Vs JAX
		0.47	0.95	0.79

As one can see from Table 2, the best OD results were obtained with the 15 days observation arc; in this case we have the minimum distance w.r.t. the different centers and more important, the distance of our results is of the same order of magnitude as the distance between the centers themselves. It is easy to see also the "parabolic" behavior of the mean error that shows higher values for short arcs in which the observations are not enough and the geometry is not very good. At the same time, the error increases as the arc is getting longer; this is probably due to the deficiencies of the dynamical model and to the fact that these were not compensated using empirical accelerations.

Before merging angular and SLR measurements, it was necessary to tune the weighting of the observables. This procedure was needed because the two observables have very different accuracies, so we needed to make the system able to take the advantages of both kinds of measurements without ignoring one or the other. In a LSQ adjustment the weight of a generic observable is $p_i = \sigma_0^2/\sigma_i^2$ where $\sigma_i = \sigma_\alpha, \sigma_r$ with σ_α and σ_r respectively the STD on the angular and range measurements. If we put $\sigma_0 = \sigma_\alpha$, we weight relatively the two observables. In particular the assigned weight to the angular measurements $p_\alpha = 1$ and the weight on the ranges is proportional to the ratio of the two STDs ($p_r = \sigma_\alpha^2/\sigma_r^2$). Both STDs are determined experimentally. For the angles, the mean residuals obtained from the system time offset calibration [13] is used. For the ranges, the a posteriori RMS for unit weight obtained from an OD over an optimal observation arc using only SLR measurements is used. While the resulting σ_α is constant to 0.5arcsec for all the following tests, for the ranges a particular value has to be determined for each orbital regime.

4. Orbit determination results

At this point, we are ready to analyze the influence of the SLR measurements on an OD process based on angular measurements. With these tests we tried to understand the influence of the length of the observation arc, the number of observations, the relative observer-object geometry and the number of follow-ups. These tests were repeated for different orbital regimes to investigate what is the influence of the different observables on each orbital parameter. Finally, we will show the achievable improvements of an OD with 3D measurements (RA + DE + ranges) w.r.t. the angles-only solution and how the use of 3D measurements will allow us to save time for future catalogue maintenance application. The just mentioned topics will be addressed separately in the following sections.

4.1. Influence of the Arc-length

The first test was performed to evaluate the influence of the length of the observed arc. Only the observations (both SLR and angular) acquired by the Zimmerwald observatory for a total of 5 days of observations spread over 18 days will be used. For this experiment, only the SLR observations acquired during the night-time after the first angular measurements are taken into account. This choice was made to simulate an active tracking of space debris. The considered object is the Lageos 1 satellite, so the STD used to determine the weight of SLR measurements is 55 cm (together with 0.5 arcsec for the angles). As mentioned before, this RMS is obtained from an OD performed using only normal points spread over an observation arc of optimal length. The OD is carried out without using any empirical acceleration to compensate the deficiencies of the dynamical model. This test was carried out performing an OD covering an increasing observation arc from one pass up to 5 observation nights. For each observation arc an OD is performed first, using only angular measurements (2D), then merging angles and ranges, and finally for completeness with ranges-only (1D). For each OD the ephemerides were generated and compared with those obtained from the reference orbit. The comparison period is coincident with the reference orbit which starts 8 days after the last observation night and lasts 5 days. This time distance was chosen on purpose to evaluate what was the committed error for the target object after roughly one month from the first observation. The reference orbit was generated performing an OD using all possible laser observations over 5 days from all available stations to get rid, as much as possible, of geometry dependencies. These observations were provided by the ILRS.

The mean error of the ephemerides generated by the OD results w.r.t. the reference ones are summarized in Table 2. In the table, it is possible to see: the number of observations used in the OD separated by type (1D for SLR and 2D for RA and DE), the errors separated by components (RSW) and the total position error in meters obtained for different arc-lengths. In the 2D observations counting we counted the number of epochs for which a couple of RA, DE measurements is available. We did not report the number of observations used in the OD with 3D measurements as it is given by the sum of the number of 1D and 2D observations.

Table 2 Results of the influence of the arc-length test for Lageos 1.

Days of obs.		1P*	1	2	3	4	5
Num. of obs.	1D	14	50	57	100	134	169
	2D	18	59	63	83	97	101
R [m]	1D	60.5	0.61	0.50	0.74	0.83	0.80
	2D	19.7	16.4	13.1	17.0	21.9	22.0
	3D	4.10	0.43	0.54	0.89	1.06	1.06
S [m]	1D	2.0e4	15.8	13.9	3.92	3.41	1.65
	2D	1.9e3	2.5e3	53.2	34.5	44.5	44.7
	3D	3.0e3	55.6	12.2	2.9	2.56	2.32
W [m]	1D	47.9	11.6	11.5	9.67	9.39	8.52
	2D	23.1	11.8	8.14	7.73	6.99	6.80
	3D	10.7	11.3	11.4	9.59	9.27	8.42
Total [m]	1D	2.0e4	20.2	18.7	10.9	10.4	8.88
	2D	1.9e3	2.5e3	56.4	42.6	54.3	54.6
	3D	3.0e3	57.0	17.3	10.5	10.1	9.11

1D = SLR, 2D = RA&DE, 3D = SLR + RA&DE,
* 1 Pass

We would like to focus the attention on the comparison between the results obtained with the classical angular-only case and the one with 3D measurements. The ranges-only case was added for completeness and to have a general overview that allowed us to understand better the other results. It must be said that the sometimes more precise orbit obtained in the 1D case was possible because, for convenience, we used the SLR measurements to improve an already good a priori orbit. This is the only reason why it was possible to obtain the convergence of LSQ especially in the 1-pass case. The ranges being one dimensional measurements do not allow the estimation of the orbital plane. This problem can be avoided if data from a second station, or the angular measurements are available.

Looking now at the error components, there are two main remarks that can be done: first, the error component on the along-track direction is the biggest among the three (especially for the 1-pass case); second, the smallest cross-track error is obtained for the 2D case. The main reason of the first can be easily explained if we look at the 1-pass case: here, the radial component is constrained by the measurements themselves but at the same time the observed arc is too short to estimate correctly the semi-major axis, the eccentricity and the perigee passing time. These parameters are so correlated in this case that they can be adjusted to fit perfectly the measurements but, at the same time, these are not enough to ensure the correctness of the estimation. The second effect can be explained by the nature of the used observables. In fact, the astrometric positions are just directions in the inertial frame, so even a series of them allows a relatively easy identification of the orbital plane orientation (namely i and Ω). The nature of this observable, as everybody knows, has another consequence: being only a direction, a single couple of RA and DE does not give any information about the distance of the object; this quantity can be in any case estimated combining series of astrometric positions with the corresponding epoch. This phenomenon is reflected directly in the higher error obtained in the radial direction.

From these tests it is already possible to notice the huge impact of the SLR measurements on the orbit accuracy especially for the shortest arcs. Looking at the 1-night arc, for a total of two satellite passes, we have an improvement of two orders of magnitude from roughly 2.5 km of error to just 57 m. Then, always comparing the 2D case with the 3D one, increasing the arc the error is dropping down from roughly 2arcsec (at the Lageos 1 altitude, 1 arcsec ≃29m) to less than 0.5arcsec. The only exception to this trend is for the 1-pass case where the error of the merged solution, still remaining of the same order of magnitude, is bigger than the angles only case. This is probably due to the fact that the number of observations for the 1D and 2D cases is almost the same, but the first ones are much more precise than the others and the solution obtained from these is much worse than the other. This produces, in our opinion, a drift of the solution. Finally, one can see that due to the high number of SLR measurements, to the geometry changes obtained in the 18 days of observation arc, and the ≃6.4 revolutions per day of the satellite, the 1D solution is of the same order of magnitude than the 3D one and, for the case of 5 nights, it is even slightly better. Observing the value of the errors for the 1D and 3D case, we can make one last consideration. Starting from 3 nights there are not substantial changes in the error values, it seems that the errors are converging on a “plateau” level; in our opinion, this is the precision limit with that geometry configuration before the error starts to increase again due to miss modelling effects.

4.2. Influence of the number of observations

To simulate a more realistic environment of debris tracking the test presented in the previous paragraph (4.1), were repeated using just a small fraction of the observations available. This because, due to the shape of the object and its attitude, it is not possible to have the same amount of observations as for a regular geodetic satellite, even if the target carries a retroreflector on board. The results obtained can be seen in Table 3. As in the previous case, the observations used were acquired only from the Zimmerwald observatory.

Table 3 OD results for Lageos 1 varying the arc-length using sparse range measurements.

Days	Num. of obs.		Mean Error w.r.t. the reference orbit			
of obs.	1D	2D	R [m]	S [m]	W [m]	Total [m]
1P*	3/14	18	30.62	4614	25.03	4614
1	6/50	59	3.11	1144	9.64	1144
2	7/57	63	0.693	3.48	12.95	13.76
3	11/100	83	2.40	27.10	13.08	30.85
4	12/134	97	4.39	25.02	8.72	27.44
5	13/169	101	4.88	30.02	9.09	32.27

* 1 Pass

The second column of Table 3 shows the number of SLR measurements used over those available. Comparing the obtained results with those shown in the last line of Table 2, we can see, as expected, that exception made for the 2 observation nights case, the error w.r.t. the reference orbit increases due to the reduction of the number of observations. At the same time it is important to notice that this is not so crucial. In fact, again with the exception of the 1-night case, the error remains of the same order of magnitude. This experiment confirmed the benefits given by SLR data. Although we used just a tenth or even less of the observations available we were able to obtain results at least two times better than in the angle-only case; this factor is of crucial importance if one wants to optimize the observation time.

From the previous example we have seen that a higher number of observations produces better results. Is it always like this? In principle yes but, at the same time, the distribution of the observations and the relative object-observer geometry are also very important. In the following Figure 1 and Table 4 are shown the distance of the ephemerides w.r.t. the reference orbit. These were obtained from a Lageos 1 OD using only the observations acquired during one pass of the satellite from Zimmerwald observatory. The total length of the pass is about 40 minutes, while the ranges are homogeneously distributed over the entire pass, the angular ones are concentrated in roughly 5 minutes in the middle of it. The difference between each runs relies in the number of range measurements considered and their distribution. In the figure each color is associated with a different number of ranges taken into account in the OD process: from 0 (only angles) to 19 that was the maximum number available for the selected pass. Two lines refer to the same number of ranges used, namely “Mer. 3 s, m, e” and “Mer. 3 rng”. In these runs only three ranges are used with a different distribution over the pass. In the first, the ranges are one at the beginning, one in the middle and one at the end of the angular measurements; in the second, are just the first three ranges available after the first epoch of the angular measurements. In all the other cases, the considered ranges are selected in chronological order since the first angular measurement. The only exception is constituted by the "Mer. all obs." case, where all the observations available in the pass are considered, even those before the angular ones.

Figure 1 shows the effects of the distribution of the observations. The best solution, in this case, is given adding three ranges, one at the beginning, one in the middle and one at the end of the series of angular measurements. The solution obtained using all ranges available, which coincides with the longest observed arc in this case, is more or less comparable with that obtained using only the first two ranges. The obtained errors, in these cases, are respectively ≃4 and ≃5 time bigger w.r.t. those obtained for the best solution. As obvious, the angle-only solution due to the very short arc gives the biggest error while the others, increasing the number of used ranges, produce better results getting close to the best solution (curve labeled with "Mer. 3 s, m, e") but then they tend toward the solution obtained using all observations available. This behavior is probably due to the distribution of the ranges and the length of the observed arc. The same trend is visible in Table 4 comparing the radial component of the errors (third column) obtained for the angle-only and the 1-range solution (third and fourth row of the table). Only one range produces an improvement of two orders of magnitude. The same jump in the error is visible comparing the one- with the two-ranges solution. Afterward, the improvements are less pronounced.

Concluding this section, we can say that the number of ranges used in the OD process is of fundamental importance together with their distribution and the object-observer relative geometry which we suppose is the main cause of the obtained plateau in the position error w.r.t. the reference orbit.

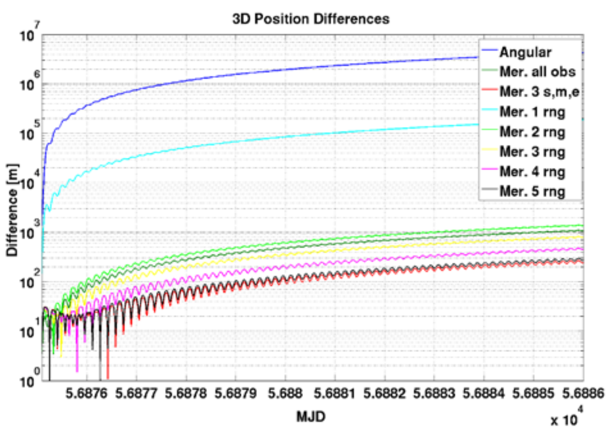

Figure 1 Ephemerides difference obtained for 1 pass of Lageos 1 varying the number of the ranges used.

Table 4 OD results from 1 pass of Lageos 1 from Zimmerwald observatory varying the number of used SLR measurements.

Num. of obs.		Mean Error w.r.t. the reference orbit			
1D	2D	R [m]	S [m]	W [m]	Total [m]
-	41	5.925e5	3.263e6	604.1	3.324e6
1	41	995.7	1.461e5	83.55	1.461e5
2	41	7.42	1068	12.23	1068
3	41	6.33	620.2	12.14	620.8
3*	41	5.20	194.9	12.07	193.3
4	41	5.63	356.9	12.10	357.9
5	41	5.26	217.6	12.07	218.9
19*[1]	41	6.02	838.5	6.17	838.7

* 1 at the beginning, 1 in the middle and 1 at the end of the pass (s, m, e in the Figure 1)
*[1] All available ranges

4.3. Influence of the object-observer relative geometry

In this paragraph, we want to highlight the consequences of the relative object-observer geometry in the accuracy of OD results. Since we did not want to feed the system with synthetic observations, the angular measurements used in the following tests were provided by the Zimmerwald observatory while, to introduce the geometry changes, the ranges were provided by three SLR stations (namely Graz, Matera and Mt. Stromlo whose coordinates are visible in Table 5).

Table 5 Coordinates of the stations used in the tests.

Station	Geodetic Coordinates		
	Latitude [°]	Longitude [°]	Elevation [m]
Zimmerwald	46.8772 N	7.4652 E	951.2
Graz	47.0678 N	15.4942 E	495.0
Matera	40.6486 N	16.7046 E	536.9
Mt. Stromlo	35.3161 S	149.0099 E	805.0

These stations were chosen because they are among the most productive station of the ILRS network, consequently there were more data available for the geometry tests and they are able to track even high altitude satellites. With these tests we wanted to show the influence of a displacement of the station which provides ranges. Comparing the coordinates of the Zimmerwald observatory w.r.t. those of the other stations (see Table 5), one can see that Graz was chosen as representative of the effect of a shift in longitude and Matera as a generic shift both in latitude and in longitude. Both stations share with Zimmerwald almost the same visibility window for the considered satellite (Glonass 123) and then, we can have angular and SLR measurements which are collected almost at the same time. The third station, Mt. Stromlo, was chosen since it does not share the visibility window with Zimmerwald and then will provide a completely different observation geometry. For the following tests, as just anticipated, the Glonass 123 satellite is used. For the reasons explained in paragraph 3, for this object, being in the

MEO region, the STD used to determine the weight on the ranges is σ_r =1.3m. This object was chosen especially for the reduced number of measurements available w.r.t. the Lageos 1 satellite. As usual, the tests were performed comparing the ephemerides obtained by an OD using a subset of measurements with those generated by a reference OD. For the reference solution we used 16 days of observations from all available stations both angular and SLR. For the OD tests we used combinations of data coming from the above mentioned stations without any time restrictions. The time interval used for the comparison of the ephemerides coincides with the one used in the various ODs.

The obtained results are reported in Table 6. The mean position error and the mean error of the osculating orbital elements w.r.t. those obtained from the reference ephemerides are shown in the table. The mean errors in RSW directions are obtained, as usual, averaging the difference of the propagated positions w.r.t. the reference ones. The mean errors of the osculating orbital elements are determined averaging the difference of the osculating elements obtained from the conversion of the propagated and of the reference positions at each available epoch. For completeness, the results obtained with an angle-only OD and the number of measurements used in the various OD process are also reported. The best solution is obtained, in this case, merging the angular measurements coming from Zimmerwald with the SLR ones coming from Graz whose average total position error is less than 7m.

Table 6 OD results for one station angular measurements and one SLR with different geometries.

10041B		Ang. Only	Zimmer. & Matera	Zimmer. & Graz	Zimmer. & Mt.Stromlo
obs.	1D	-	31	33	61
	2D	63	63	63	63
Position Error [m]	R	43.2	0.382	0.403	1.271
	S	90.3	13.60	2.165	12.58
	W	7.10	7.762	6.239	1.294
	Tot.	108.5	16.79	6.909	12.90
Orbital Elements Mean Error	a[m]	0.389	9.404e-2	1.559e-2	7.990e-2
	e	1.83e-6	1.200e-8	1.500e-8	3.400e-8
	i [°]	2.38e-5	1.520e-5	1.270e-5	4.300e-6
	Ω [°]	8.30e-6	2.530e-5	1.990e-5	1.600e-6
	ω [°]	3.22e-2	3.484e-4	3.414e-4	1.144e-3
	M [°]	3.22e-2	3.294e-4	3.286e-4	1.171e-3

Looking at each single error component, we can notice that the errors in the radial direction obtained for the Matera and Graz case are comparable while the one obtained in the Mt. Stromlo case is 3 times bigger. On the other hand, the Mt. Stromlo case has the smallest cross-track error. Similar assessments can be done observing the mean error on the osculating elements. Analyzing separately the parameters which describe the orientation of the orbital plane (namely i and Ω) and those which describe the orbit shape and the object position along the orbit (namely a, e, ω and M), the Mt. Stromlo case presents the lowest error for i and Ω and the biggest one for ω and M. The latter two parameters are, together with a and e, the main responsible for the error in the along-track direction. The big error in the along-track component shown in the Matera case w.r.t. the Graz one is probably due to the higher error in the semi-major axis. We think that the smaller error in the orientation of the orbital plane and the higher one in the along-track directions are probably due to the different geometry. Comparing the distribution of the observation in the Graz case with the Mt. Stromlo one, it is possible to see how in the first case, being all the observations concentrated in one part of the orbit, the estimation of the semi-major axis is more accurate. In the second, the bigger spatial distribution of the observations allows a better estimation of the inclination and of the RAAN. Finally, the interpretation of the difference between the Matera and the Graz case is more difficult. Comparing the error components we can see a larger error in the along-track direction of the Matera case w.r.t. the Graz one. Despite almost the same number of observations, probably, the higher error is due to the worse distributions of them over the considered arc. In the Matera case, just in the middle of the observation arc there are 5 days of gap where no measurements are available; while in the Graz case, the SLR measurements are more homogeneously distributed.

4.4. Simulation of discovery and follow-up scenario

To further illustrate the benefits of the SLR measurements in terms of achievable orbit accuracy, and then, what are the improvements, as example, for catalogue maintenance applications, we will compare the OD results obtained using one or two nights of angular observations with those adding a very few number of ranges. As usual, the ephemerides generated after an OD are then compared with those obtained from a reference orbit. Only a very small number of observations are taken into account in these tests so that we could simulate the classical scenario of object discovery and first follow-ups (acquired in the same and in the following night). This choice was made as this way of operating is usually adopted at the AIUB and then, to compare the obtained results with those obtained by Musci in [5].

These tests were performed using data acquired for a GEO satellite, namely IRNSS1a (13034A). We chose the GEO orbital regime because, being this region one of the most exploited, it presents also a higher density of space debris. The maximum observation arc considered in the simulation is roughly 24 hours. The angular data are provided by the Zimmerwald observatory, while the ranges by Herstmonceux (United Kingdom). Also in this case the weights on the SLR measurements are determined using σ_r=1.3m. We would like to highlight that the SLR measurements were available only for the first night of observation. Regarding the angular measurements, a total of 3 tracklets (even if not complete) spread over 3 hours were available for the first night and other 2 consecutive ones for the second night.

Looking at Table 7 we can see how the addition of 2 ranges produces a jump of 3 orders of magnitude in the mean error. As one can see from the last row of the table, this jump brings the recovery time from less than 4 hours up to almost 1 month. The recovery time is the minimum time interval needed to the object to go outside the FoV of the telescope. For these tests, the FoV of one of the Zimmerwald telescope is used (≃26arcmin). An object is considered as lost when the sum of the in the along- and cross-track errors is greater than the half of the FoV. Comparing the obtained results with those shown by Musci in [5] for the same orbital regimes, we can say that 1 night of observations made by 3 tracklets and 2 ranges provides the same accuracy achievable with 4 (angular-only) follow-ups spread over 72 hours or equivalently 3 observation nights.

Table 7 Results of the discovery + follow-up test for GEO.

13034A		1 Night Angles only	1 Night Merged	2 Nights Angles only	2 Nights Merged
obs.	1D	-	2	-	2
	2D	19	19	33	33
Pos. Error [m]	R	7.193e5	486.8	5.436e3	86.07
	S	5.219e6	9.017e3	1.698e4	199.6
	W	8.992e3	50.99	703.9	20.87
	Tot.	5.282e6	9.056e3	1.850e4	234.3
Orbital Elements Error	a[m]	2.793e5	497.2	61.71	6.729
	e	4.997e-3	1.822e-6	8.270e-5	3.089e-6
	i [°]	4.921e-3	3.190e-5	1.387e-3	4.5e-5
	Ω [°]	3.997e-2	2.207e-4	1.407e-3	9.8e-6
	ω [°]	22.93	2.995e-1	5.032	1.760e-2
	M [°]	16.75	2.865e-1	5.055	1.771e-2
Recovery Time [day]		<0.1667	29.83	314.7	2920

Looking now at the bottom graph of Figure 2, we can see how the behavior of the errors is completely different from those shown in the upper graph of the same figure. In this case, the error sinusoidal component is more pronounced than the drifting one. Furthermore, from the vertical green and red lines, it is easy to see how the smallest error occurs close to the observed part of the orbit. This effect is due by the distribution of the angular measurements which are precisely one day apart and the orbital period of the object, being a GEO satellite, is coincident with the sidereal day. The main consequence of this observation distribution is a strong improvement of the estimation of the semi-major axis. At the same time, as shown in [7], this distribution does not give enough information to estimate correctly the eccentricity of the orbit. The same effect even if less pronounced is also visible for the 2-nights case with merged measurements. In this case, the ranges provide not only information about the distance but also increase the length of the observed arc. Being acquired a bit more than two hours after the last angular observation, the ranges help constrain both the semi-major axis and the eccentricity reducing the amplitude of the error oscillations (look at the elements error in Table 7). Consequently, improving the estimation of a and e, the ranges have a strong effects even in the estimation of the argument of perigee and the mean anomaly, (look at the error for ω and M). Another consequence of the distribution of the observations can be seen in the errors of i and Ω. As shown in [7], having series of angular observations in the same part of the orbit, since the arc covered by the tracklet is relatively small, they do not provide enough information to determine correctly the orientation of the orbital plane. The errors for i and Ω are relatively high and stay on the same order of magnitude (especially i) for the angle-only cases. This last test shows the strength of SLR measurements; looking at the last column of Table 7, even a small number of ranges (only 2) produces an improvement of the average error from roughly 2arcmin to 2arcsec. This improvement is even more impressive if one looks at the increase of the recovery time (from 314.7 to 2920 days).

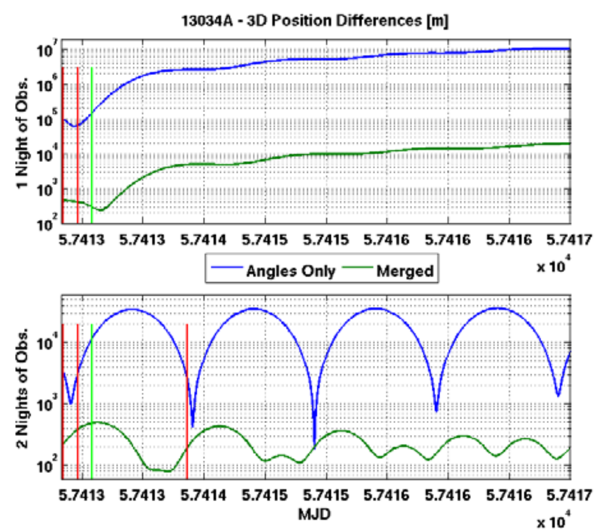

Figure 2 Behavior of the 3D position errors and distribution of used observations for the GEO OD tests.

5. Conclusion

In this study we investigated the benefits, that the high precision ranges provided from an SLR station, could be given to the OD process based on the classical angular measurements. After the validation of the proper application of the corrections to the SLR measurements, of the tool used for the OD and after the weights definition, some studies were performed to highlight the consequences of the use of the laser ranges in the OD process. First, we studied the influence of the length of the observed arc and the influence of the number of SLR observations used in the OD. Then we evaluated the influence of the relative object-observer geometry. Finally, we simulated a classical discovery and follow-up scenario and we highlighted the improvements given by a very small number of ranges. All these tests were performed using exclusively real data provided by the Zimmerwald observatory and the ILRS network.

The tests showed the huge improvements achievable using a relatively small number of ranges over an even smaller observation arc. Furthermore, they showed that, since the SLR measurements are much more precise than the angular ones, a fine tuning of the measurements weights is needed so that the system will not ignore the angles. The tests on the influence of the arc-length seemed to show a plateau in the achievable accuracy highlighting the influence of the relative observer-object geometry. Furthermore, as expected, the improvements given by the SLR data on long observation arcs are less pronounced w.r.t. those obtained for short arcs. The tests made to investigate the geometry influence and those which simulated the discovery + follow-up scenario showed how each single observable is acting on the estimated parameters. Furthermore the last test showed the benefits that the OD, using merged SLR and angular measurements, could bring to the catalogue building and maintenance activities and to the planning of collision avoidance maneuvers.

Nevertheless, this study needs further investigations, but it already proved the benefits that SLR data can bring in the OD for space debris. To have more general outcomes the results coming from the application to a wider set of observations concerning different orbital regimes should be analyzed. Further improvement can be obtained by the investigation of the geometry influence in a more theoretical way. Studies can be carried out using simulation and/or synthetic data in order to not be constrained by the availability of the real data. Otherwise, one can follow an approach similar to that proposed by Cordelli in [7], maybe taking into account also the influences of Gaussian mixtures in the OD process.

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