ASSESSING ORBIT DETERMINATION THROUGH ONE WAY DOPPLER SIGNALS

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ABSTRACT *– In a search for cheap, easy, and still fairly reliable system for satellite control, an economical way of yielding orbit information is to measure the Doppler shift suffered by the signal transmitted by the satellite, commonly named one-way Doppler measurements. This paper gives an analysis of such Doppler based orbit determination which will be used in the French Brazilian Micro-satellite (FBM) satellite under development. The ground segment consists basically of a control center and a single tracking station located at Natal, Northeast of Brazil. Requeriments for orbit accuracy coming from the scientific community is rather loose, so that the main requirements are due to operations of tracking and scheduling of the control center. Initially a covariance analysis is shown, which depicts the accuracy achievable by the orbit determination based solely on one-way Doppler measurements from a single tracking station. Afterwards, we use one-way Doppler measurements taken from the SCD1 Brazilian satellite, a live flying satellite with similar orbit pattern. These measurements presented problems typical of the ones expected during the FBM mission. Orbit determinations are performed using such set of data to show the errors with respect to the reference orbit. At the end some conclusions and recommendations are drawn.*

KEYWORDS: Orbit Determination, Doppler measurement, satellite control.

INTRODUCTION

As far as satellite control is concerned the knowledge of its orbit is paramount. It gives to the ground station antenna the means to track the satellite and as a consequence to implement other tasks related to reception of telemetry and scientific data as well as to release telecommands to control the satellite. To enlarge the degree of autonomy, the station should have its own orbit determination (OD) system without overloading the budget of the mission. An OD based on measuring the Doppler shift of the signal transmitted by the satellite (one-way Doppler) may be accurate enough and an economically appealling implementation.

In a quest for low cost yet fairly reliable system for satellite control there is a search for small and dedicated ground stations for tracking, telemetry and telecommand tasks. In such systems an economical way of yielding orbit information is to measure the Doppler shift suffered by the signal downlinked by the satellite to the ground station, commonly named one-way Doppler measurements.

Although no new ground equipment is required the satelite on-board oscillator should have some minimal stability requirements.

This paper gives an analysis of such Doppler based orbit determination and tries to assess the approach motivated by the French Brazilian Micro-satellite (FBM) mission under development [1]. The French Brazilian Micro-satellite is a joint project between Brazil and France, and aims at developing a low cost scientific micro-satellite to carry on-board 4 French and 5 Brazilian experiments as payloads. The satellite is to be 3-axis stabilized, class of 100-200kg mass at circular low (775 km) Earth orbit with nearly equatorial inclination. The ground segment consists basically of a control center and a single tracking station located at Natal, Northeast of Brazil. Requeriments for orbit accuracy coming from the scientific community is rather loose, so that the main requirements are due to operations of tracking and scheduling of the control center. The Orbit Determination (OD) must be performed once a day to update the on-board orbit ephemeris. In case of shortage of Doppler data, the OD must be good enough to endure ten days of tracking without update.

Initially a covariance analysis, accounting for on-board oscillator stability, dynamical model error, measurement error, and station errors, is performed [2]. This depicts the accuracy achievable by the orbit determination based solely on one-way Doppler measurements from a single tracking station. Afterwards, we use actual one-way Doppler measurements taken from the SCD1 Brazilian satellite, a live flying satellite with similar orbit pattern and measurement accuracy. These measurements presented problems which would be typical of the ones expected during the FBM mission. Orbit determinations are performed using such set of data, showing the errors with respect to the reference orbit generated by the control center using more precise 2-way range measurements. At the end some conclusions and recommendations are drawn.

COVARIANCE ANALYSIS

Covariance analysis were performed using the package MODEAS [2], for a single tracking station taking Doppler measurements, for the FBM mission [1]. Sources of measurement errors steamed from the ground segment, geometry between the orbit and the tracking station, the on-board oscillator stability, and miscellaneous additional sources such as troposphere, transit time error, time tag error, and resolution error. The overall budget error was such that the random noise and bias ranged between 0.9 and 9 m/s.

The dynamical errors were accounted for by simulating imperfect dynamical modelling of the orbit, in order to provoke errors in the orbit determination process. Errors were assumed in the Earth gravitational coefficient GM, J_2, coefficients C, S, drag coefficient C_d, radiation pressure coefficient C_r, and Sun gravitational coefficient.

Table 1 shows the best and the worst case of errors in the radial, normal, and along track position and velocity components [1]. Thus for the FBM mission position errors are expected to range between hundreds of meters up to 3 km in the OD system using one-way Doppler measurements and a single tracking station.

Table 1. Orbit determination position and velocity errors

	Position Error (m)				Velocity Error (m/s)			
Case	Radial	Normal	Along	RMS	Radial	Normal	Along	RMS
Best	27	53	123	137	0.13	0.22	0.03	0.25
Worst	293	1636	2434	2947	2.53	1.52	0.30	2.97

A long term orbit error was also computed to see the error growing pattern of the on-board orbit predictor, which would use the uploaded orbit ephemeris determined on ground. For a period of ten days, the covariance matrix of orbit errors was computed. The figure which follows shows the time-growing characteristics of the error. A critical case was selected: a circular 775km orbit with the worst range-rate measurement noise level. Figure 1 shows the error growing in radial, normal, and along-track components of position. Along track error is predominant in long term runs, reaching an error of 15km in 10 days.

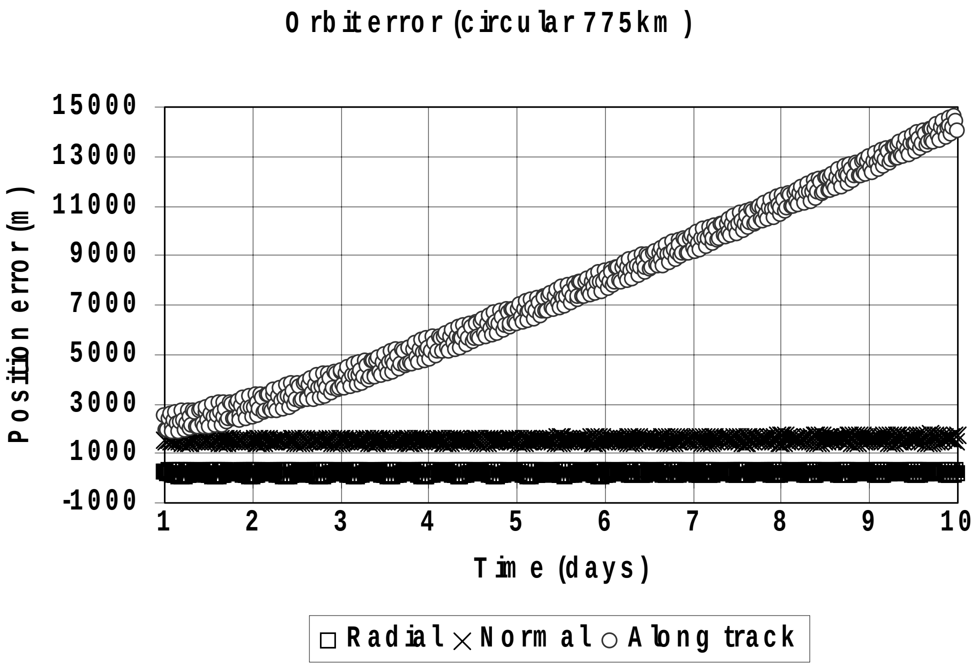

Fig. 1. Position error propagation

ONE-WAY DOPPLER SHIFT MEASUREMENTS

The one-way Doppler shift measurements were collected during a dedicated 3-days campaign, back to August 1996, for testing ground equipment of upcoming missions. The measurements were collected by the Cuiaba ground station (56°W, 16°S) which tracked the SCD1 Brazilian satellite. A total of 8 passes of the SCD1 satellite over Cuiaba were recorded producing on average 600 measurements per pass at 1 Hz sampling rate. Two ground receivers were used: the receiver for the on-board service transponder used for 2-way ranging measurements, and the receiver of the on-board payload transponder, both operating in the non-coherent mode. Such data were considered to represent typical behaviour that one-way Doppler measurements could present and therefore were selected for the analysis.

Accuracy of one-way Doppler shift measurements are highly dependent on the short term stability of the on-board oscillator mainly. Such instabilities cause fluctuations on the transmitted base band. In the SCD1 satellite, the on-board transponders use both the S-band frequency around 2.2GHz. A 7Hz of such a random error will translate to an error of 1m/s in the relative velocity between satellite and observer (Cuiab• ground station), for a typical satellite pass. The accuracy of the Doppler measurements, or equivalently the range-rate measurements, used in ODs, impacts directly in the final accuracy. The service ranging transponder uses a nominal frequency of 2.208002635GHz in non-coherent mode, and the payload transponder 2.267520608GHz. The Doppler shift measurements of a satellite pass over a tracking station present a S shape, called Doppler curve of the pass, crossing the zero at the closest satellite approach, i.e. the highest elevation above the horizon. Fig. 2 shows the profile for one of the passes of the data set.

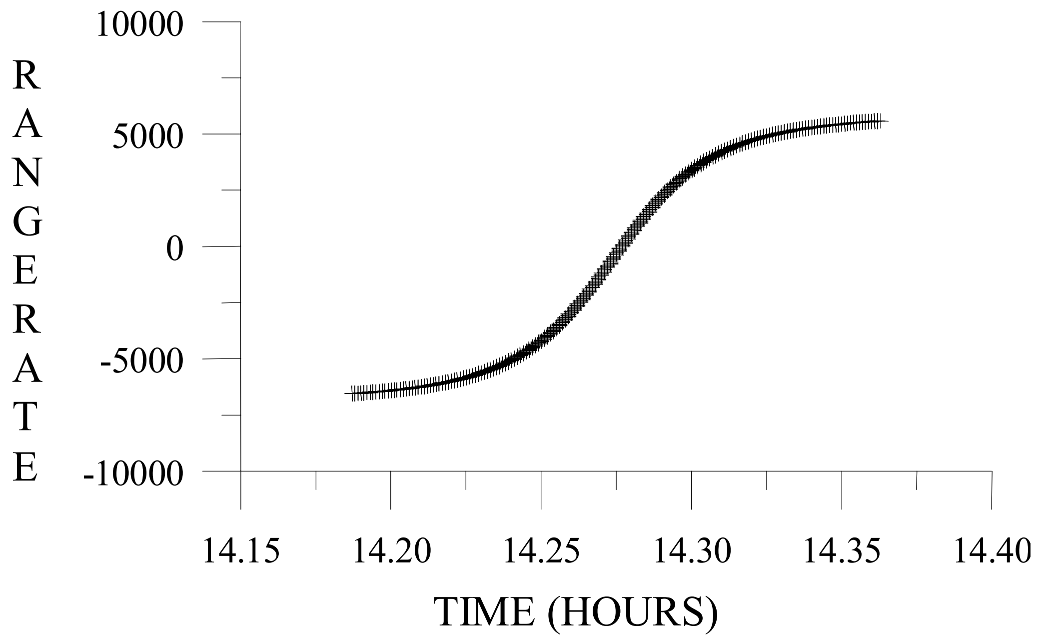

Fig. 2. Doppler curve of a typical satellite pass

Table 2 shows a summary of the measurements collected during the campaign. The file name TRAN# comes after service TRANsponder of ranging, whereas TPCD# stands for payload transponder.

Table 2. Summary of Doppler measurements

Date	Time UTC (HH:MM:SS)	# of measurements	File Name
27/08/96	14:09:43 - 14:22:53	791	TRAN1
27/08/96	17:44:39 - 14:54:09	571	TRAN2
28/08/96	11:38:50 - 11:51:01	732	TRAN3
28/08/96	16:59:34 - 17:09:51	618	TRAN4
28/08/96	13:26:05 - 13:36:22	618	TPCD1
28/08/96	15:12:34 - 15:23:00	627	TPCD2
29/08/96	12:41:36 - 12:50:47	552	TPCD3
29/08/96	14:28:05 - 14:38:03	599	TPCD4

MEASUREMENT STATISTICS

In order to verify the quality of the collected measurements, it was realized a comparison between the measurement residuals and the expected Doppler shift, based on reference orbits. The reference orbits were generated by OD using 2-way ranging, which presented standard deviation better than 7m, consistent with the expected ranging accuracy. For OD, one used the software package ODEM [3], modified to process one-way Doppler measurements. Measurements below 10^{o} elevation were rejected in order to minimize atmosphere difraction influence. Table 3 shows the statistics for the one-way measurements using the service transponder TRAN.

Table 3. Statistics for the one-way Doppler measurements using the service transponder

File	Max. Elevation (°)	Noise (cm/s)	bias (cm/s)	Time bias (s)
TRAN1	59.545	0 ± 96	-48649.8 ± 0.6	-0.159 ± 0.007
TRAN2	12.940	0 ± 103	-48636.4 ± 4.0	-0.370 ± 0.009
TRAN3	29.789	-1 ± 114	-48800.8 ± 0.7	0.601 ± 0.005
TRAN4	15.978	0 ± 92	-48915.8 ± 2.2	-0.409± 0.008

It can be noticed that after estimating the measurement biases and time biases, remaining noise is zero mean with 100cm/s standard deviation. Fig. 3 shows the final residuals for the pass corresponding to file TRAN1. Similar shapes are obtained to the other files TRAN2, TRAN3, e TRAN4.

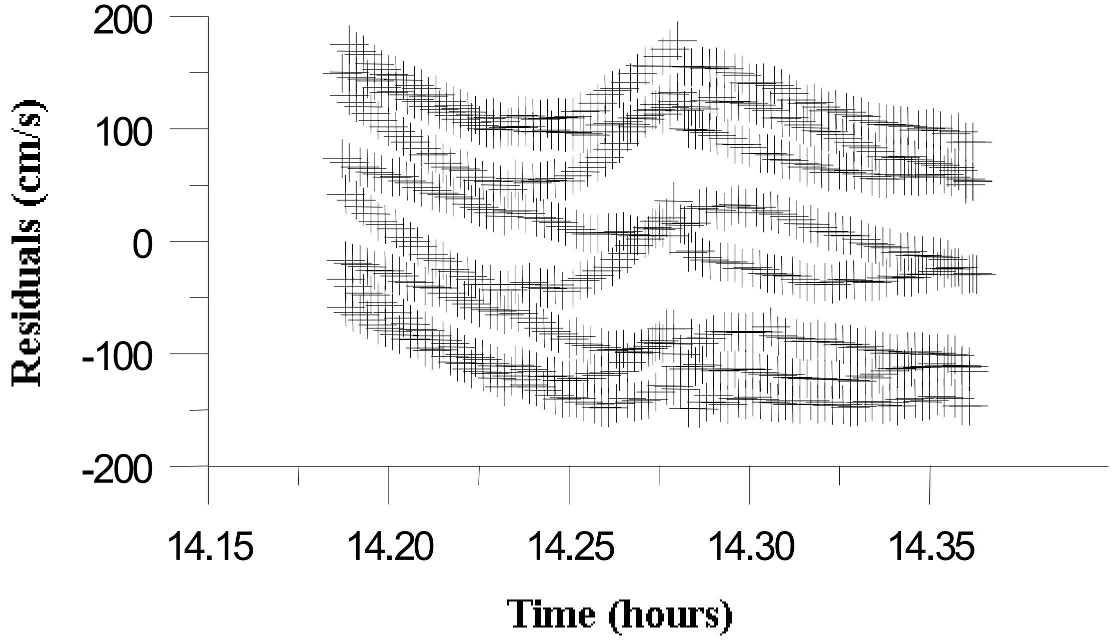

Fig. 3. Residuals for the pass TRAN1

However, the measurements collected by the payload transponder TPCD, presented a non-typical profile as depicted in Fig. 4. It is noticeable a non-random biased measurement residuals.

The most probable explanation for this strange behaviour is due to the fact that the payload transponder is switched ON and OFF in every pass of the satellite over the tracking station. Therefore it causes a transient at the beginning that tends to stabilize to the end of the pass. The major source of the warm-up transient is thus of thermal nature as this transponder was designed without thermal isolation, without dissipators, and has no active thermal control at all. Other papers have also reported how thermal effects can influence the one-way Doppler measurements, for instance Ref. [4].

In order to get some piece of indication about the accuracy of this transponder, it was selected manually, for each pass, the period in which such measurements seem stabilized. In other words only the final span of the pass was selected. For instance, for the pass TPCD1 it was picked out the interval 13:34 to 13:37 to fit the reference orbit and assess the accuracy. Table 4 shows the final result. The passes TPCD3 and TPCD4 did not present any selectable stabilized region. For the selected periods, the noise characteristics of the useful region of passes TPCD1 and 2 are quite similar to those of the service transponder in Table 3. Therefore, we come to the conclusion that the random noise is for both transponders of the order of 100cm/s.

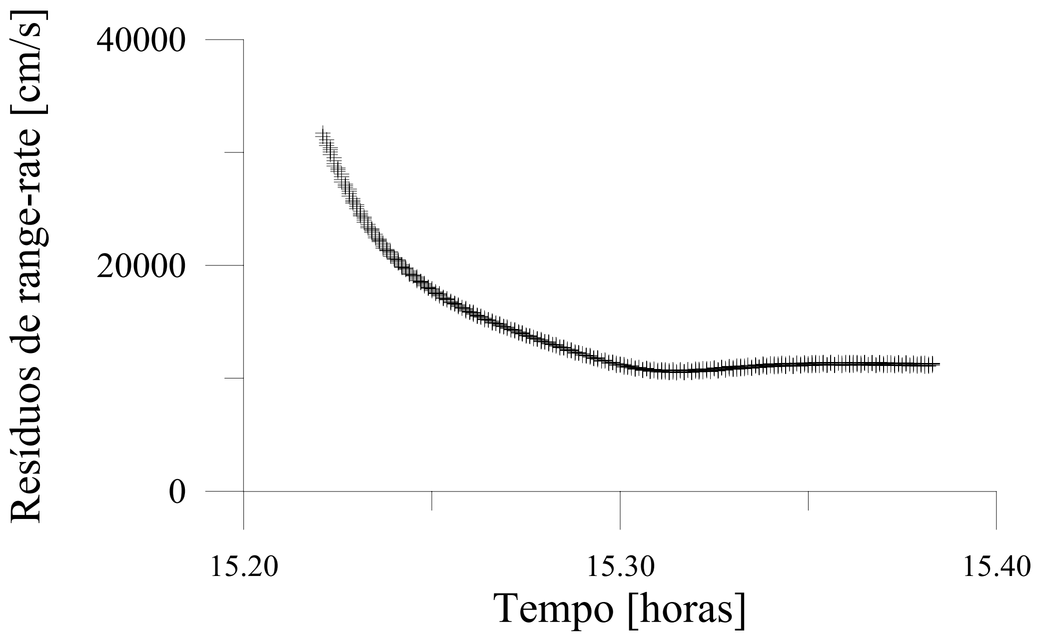

Fig. 4 - Residuals shape for pass TPCD4

Table 4. Statistics for partial set of measurements of the payload transponder

File	Selected interval	Max. Elevation (°)	Noise (cm/s)	bias (cm/s)	Time bias (s)
TPCD1	13:34 to 13:37	31.0	00 ± 98	11404.6 ± 2.4	No
TPCD2	15:21 to 15:23	29.5	00 ± 99	11205.4 ± 1.9	No
TPCD3	unstable	-	-	-	No
TPCD4	unstable	-	-	-	No

ORBIT DETERMINATION

In this section it is verified the achievable accuracy in the Orbit Determination (OD) using these sets of one-way Doppler measurements. The OD solution was compared to the reference orbit generated with two-way ranging measurements, which is the procedure conventionally used in the INPE's control center.

Table 5 summarizes the OD results for the one-way Doppler measurement sets using either the service transponder TRAN or the payload transponder TPCD. The column with symbol Δ represents the deviation between the OD and the reference orbit, the other ones with σ represent the standard deviation computed by the OD package [3] through the covariance matrix.The subscripts x, y, z are the axes in the inertial coordinate system.

Table 5. Comparison of OD with reference OD

Set	Δx (km)	σ_x (km)	Δy (km)	σ_y (km)	Δz (km)	σ_z (km)	Residuals (cm/s)
TRAN	1.851	1.876	1.050	0.528	-3.262	0.478	0.8±98.2
TPCD	-44.631	20.145	-21.846	9.150	2.552	8.824	0.0±96.6

The set of measurements TRAN presented deviations of up to 3.2 km with respect to the reference orbit, more or less in accordance with the computed σ-s, and somewhat within the expected range of error, as compared to the covariance analysis shown formerly in Table 1. The data set TPCD comprised only two passes of 3 and 2 minutes of measurements respectively, as shown in Table 4, clearly below the minimum acceptable to yield a reliable OD. Besides that represented only the final region of the Doppler curve of the passes, therefore being a broken Doppler curve which provokes serious problems of observability for the OD system. Thus it is not so surprising that it produced discrepancies of more than 40 km.

CONCLUSION

This paper showed the expected level of errors for an Orbit Determination (OD) system using a single tracking station collecting one-way Doppler measurements, which is being designed to be used in the FBM (French Brazilian Micro-satellite) mission [1]. In our particular case, near equatorial low Earth orbits with a tracking station situated at low south latitudes were analysed.

Theoretical analysis was based upon covariance analysis software [2], which estimated OD errors to lie between hundreds of meters up to 3 km, depending on several factors such as oscillator stability, random and bias noise, and dynamical model errors. The error growing aspect was also outlined to size the on-board orbit propagator along with the ephemeris upload rate. It was depicted that an error rise up to 15km in 10 days can be expected, without compromising the mission.

Another analysis was performed using actual one-way Doppler measurements collected from the flying SCD1 Brazilian satellite, which presents similar orbit characteristics of the envisaged FBM mission. There were used measurements collected by both the service (ranging) transponder and payload transponder. They presented essentially the same level of random noise around 100cm/s. The measurement bias had to be estimated every pass, that is, bias-per-pass police was applied due to short period unstabilities of the on-board oscillator and thermal transients for day or night passes [4, 5]. It was noticed a high transient in Doppler measurements from the payload transponder which is turned on and off every pass. This transponder delivered very few useful measurements due to such transients, resulting in an OD error greater than 40km. However the service transponder yielded a data set of measurements which, processed by the OD system [3] resulted in deviation around 3km compared to the reference orbit, and residual fitting of 98cm/s of standard deviation.

Based upon the considerations given above, it is concluded the feasibility of deploying a ground segment consisting of a single tracking station collecting one-way Doppler measurements solely for the FBM mission. That took into account aspects of accuracy, space and ground equipment cost, long term endurance, and low computational burden.

REFERENCES

[1] Suarez, M.C.; Leibold, A. *"Modular orbit determination error analysis software using covariance matrix UD factorization"*. Oberpfaffenhoffen, GSOC, 1988 (GSOC IB-88/1).

[2] Kuga, H.K.; Furlan, M.B.P. *"Error analysis for routine orbit determination of the French Brazilian Micro-satellite"*.Advances in Space Dynamics 3: Applications in Astronautics, O.C.Winter and A.F.Bertachini A.Prado, Editors, pp. 80-87, 2002.

[3] Kuga, H.K.; Gill, E. *"ODEM - Orbit Determination User Manual"*. Oberpfaffenhofen, Germany, DLR/GSOC, 1995 (DLR-GSOC IB 94-07).

[4] Comps, A. *"FISOR An efficient orbit determination software dedicated to local user terminal"*. Proceedings of the 12th International Symposium on Space Flight Dynamics, Darmstadt, Germany, 2-6 June 1997 (ESA SP-403 Aug. 1997).

[5] Aksnes, K.; Andersen, P.H.; Haugen, E. "A precise multipass method for satellite Doppler positioning". *Celestial Mechanics*, 44, p. 317-338, 1988.