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Influence of Oscillator Phase Noise in Frequency-Based Location Methods for Mobile Exploration Robots

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Abstract

Multi-Robot systems for Space exploration are an interesting alternative versus traditional large monolithic rovers in terms of performance and reliability.

However, for a community of cooperative autonomous robots to achieve complex exploration goals, a solid infrastructure of communications and location determination (as a supporting resource for navigation through the scenario) must exist in advance, which traditionally is built over radiofrequency-based technologies due to its robustness and suitability for extreme environmental conditions, such as in typical Space exploration scenarios.

This contribution discusses on the impact of electronic oscillators phase noise in the error introduced in the relative location and velocity determination based on frequency measurement techniques, such as Frequency of Arrival (FoA) or Frequency Difference of Arrival (FDoA). A noise model is obtained for a hypothetic scenario consisting in a system for position and relative speed determination on a lunar surface exploration mission, where different options for local oscillators are proposed, considering practical aspects such as size, volume and power consumption against phase noise. The impact of the phase noise in global velocity and position error is determined, analysed and discussed for different commercial oscillators and configurations.

1. Introduction

When considering lunar exploration missions, an approach consisting in a cooperative multi-robot system has multiple advantages over traditional single rovers such as increased robustness, higher reliability, larger area researched versus rover mass and power budget etc. Nevertheless, for a distributed robotic system to succeed, an effective mapping and navigation mechanism must be implemented, which are not simple either to conceive or deploy.

Previously to autonomous navigation and other high-level functionalities leading to the achievement of complex mission goals, an accurate and reliable method for mobile robots location is necessary to support local navigation processes as well as the organization of the robotic system during the course of the exploration process. For this purpose, Frequency Difference of Arrival (FDOA) methods based in Doppler shift for velocity determination can contribute to improve the position estimation [1], in combination with absolute (i.e. non incremental) position determination by, for instance, Multilateration (MLAT) Time-of-Flight (TOF) or Time-of-Arrival (ToA) procedures.

However, phase instabilities both in long (frequency thermal or ageing drifts) and short (frequency jitter) terms can jeopardize position and velocity measurements. In this contribution, we will analyze the effects of phase noise introduced by crystal oscillators leading to frequency jitter effects, which introduce uncertainty in the determination of relative velocity from the measurement of Doppler frequency shift.

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In order to analyse the impact of phase noise in a radiofrequency based location system, we must define a hypothetical exploration scenario and take some assumptions in order to define the case under study.

2. Methods and Materials

Figure 1 shows the proposed scenario. The exploration system consists in a hybrid robotic system formed by large robots providing the communications and navigation infrastructure (Tracking stations) and a number of smaller robots carrying instrumentation (mobile nodes) intended to travel across the research area.

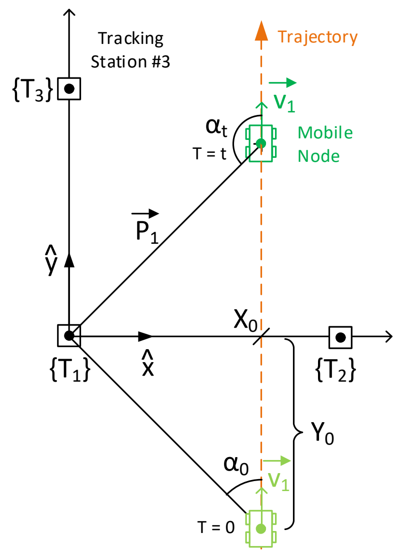

Figure 1: Coordinate reference system proposed for a robot in a Lunar exploration scenario.

The hypothesis presented considers a mobile robot running across a straight path parallel to Y axis over an area of 1000 m x 1000 m, which is comparable with the distance travelled by current space exploration rovers [4]. The analysis is considered for a two dimensions flat area due to the lower relevance of Z axis in a Lunar exploration mission. The non-geodetic approach is based in the small exploration area compared with the Moon radius [3].

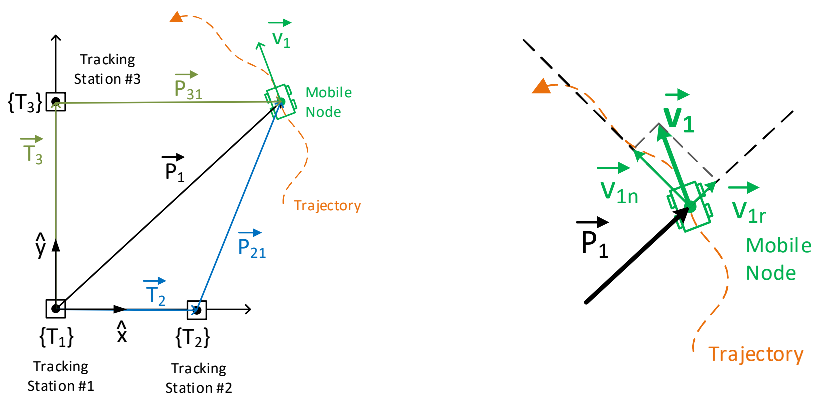

Figure 2: (Left) Location and velocity definition for a mobile robot travelling across the scenario. (Right) Composition of mobile robot velocity vector from normal and radial components.

Figure 2 represent the definition of both location and velocity for a mobile robot in the exploration scenario. In this case, the robot location is relative and defined by three reference (tracking) station T_1 to T_3. Velocity vector is tangent to the trajectory, and can be defined by normal and radial components (V_{in} and V_{ir} respectively for i=1 to 3). The

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definition of radial velocity here is of special relevance since that is the velocity vector component related with the Doppler shift component, which will be measured to calculate the modulus of the radial velocity on each location. Figure 3 presents a One-Way position and Doppler frequency shift determination method, based in Time-of-Arrival (ToA) and Frequency Difference of Arrival (FDoA) methods respectively [2]. As mentioned above, Doppler shift will yield information about the relative velocity of the mobile rover along the direction between the rover and each tracking station, that is, the velocity vector radial component.

As it can appreciated, a message is sent from reference station T_1 to the Mobile robot to request for a location and velocity sample. The Robot sends a message with the local time stamp to the station in order to calculate the range by Time-of-Arrival. The station also measures the frequency deviation from the nominal (measured at the beginning of the experiment with the robot in stationary mode), which corresponds to the Doppler shift.

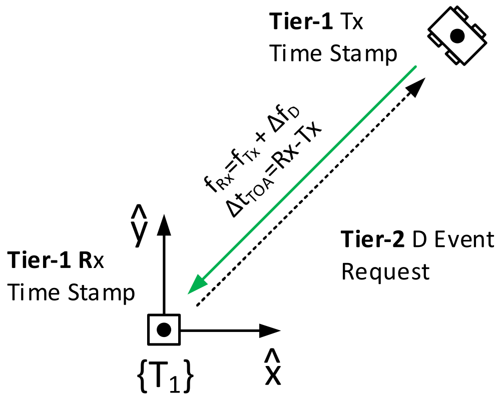

Figure 3: One-Way RF Ranging and Velocity determination method.

The relation between the frequency shift due to the Doppler Effect produced by the movement (in the radial direction defined by the vector joining reference stations and mobile robot) and the radial velocity can be defined as:

$$\Delta f_D = f_{measured} - f_{real} = \frac{f_c \cdot v_r}{c} = -\frac{f_c}{c|P_1|}\left(\vec{v_1} \cdot \vec{P_1}\right) \quad (1)$$

For the specific case of the determination of velocity from Doppler frequency shift, noise sources must be considered. Short term phase noise, being the most important contributor to frequency stability, must be analysed in the frame of a complete noise model. Such model is presented as it can be appreciated in Figure 4. Different contributors are considered such as local oscillator frequency noise, thermal noise and quantization noise.

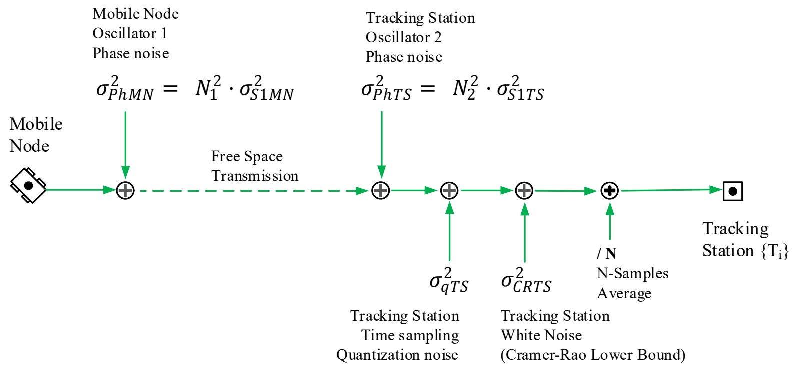

Figure 4: One-Way frequency noise model.

As it can be appreciated, main uncertainty contributors are related with oscillators' short-term stability. The most relevant contributors to this short term (i.e. fast) frequency stability is the thermal noise and phase noise of the system, where oscillators are the main phase noise contributors in a RF system. Additionally, PLL's used for RF signal

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synthesisers multiply the effect of phase noise generated by the oscillators (N_1 and N_2 in Figure 4), whilst adding its own phase noise, mainly produced by phase detectors nonlinearities. Finally, Quantization errors, introduced by the limitation in the precision of the numerical representation of the sampled measurements, is also an important contributor to short-term stability, implying a significant noise generator. Phase noise introduced by oscillators depend on manufacturing and conditioning aspects once the oscillators are manufactured [5]. Table 1 provide noise quality information from an analysis of different commercial oscillators.

Table 1: Calculated Jitter values for a set of selected oscillators

Model	Manufacturer	Nominal Freq. f_c (MHz)	L(f) offset (KHz)	σ Jitter (Rad)	σ Jitter (ps)	3σ Jitter (ps)	Δf_D at 3σ (Hz)	Doppler Error ε_D at 3σ (m/s)
OCXO DS 9700	Symmetricon	10	100	3,169E-05	0,5043	1,5130	151,2950	56,4534
OCXO DS 9600QT	Symmetricon	5	100	8,924E-06	0,2841	0,8522	21,3049	7,9496
9960 TCXO	Symmetricon	10	100	0,0003805	6,0557	18,1672	1816,3858	677,7559
RK410 AV OCXO	Rakon	10	10	1,865E-05	0,2968	0,8904	89,0394	33,2236
TE400 OCXO	Rakon	40	10	0,0016964	6,7497	20,2491	32372,2704	12079,2054
LNO 100 OCXO	Rakon	100	100	3,055E-05	0,0486	0,1459	1458,5427	544,2324
TE 300 TCXO	Rakon	10	10	0,0016966	27,0019	81,0057	8094,0107	3020,1532
HT700 TCXO	Rakon	10	100	0,0016964	26,9990	80,9971	8093,1593	3019,8355
QT806-X TCXO	Q-Tech	10	100	0,0095394	151,8245	455,4735	45340,8331	16918,2213
EX209 EMXO	VECTRON	20	100	0,0001	0,7962	2,3885	955,3496	356,4737

As it can be appreciated. OCXOs (Oven-Controlled Crystal Oscillators) are the most stable, that is, with lower phase noise reported. Phase noise can be defined by means of statistical deviation (σ) or jitter for an average period, as it is expressed in the table. Temperature Controlled Crystal Oscillators (TCXOs) are a suitable alternative for OCXOs when mass/volume or power consumption is a restriction.

A number of simulations have been performed in order to assess the impact of the phase noise in the determination of the velocity. Figure 5 shows the results obtained for the scenario depicted in Figure 1. A Symmetricon DS-9700 has been considered for the tracking station because of its high stability, whilst a Rakon HT-700 TCXO for the mobile robot due to its low power consumption. A time sampling resolution of 16 bits has been assumed for the noise model.

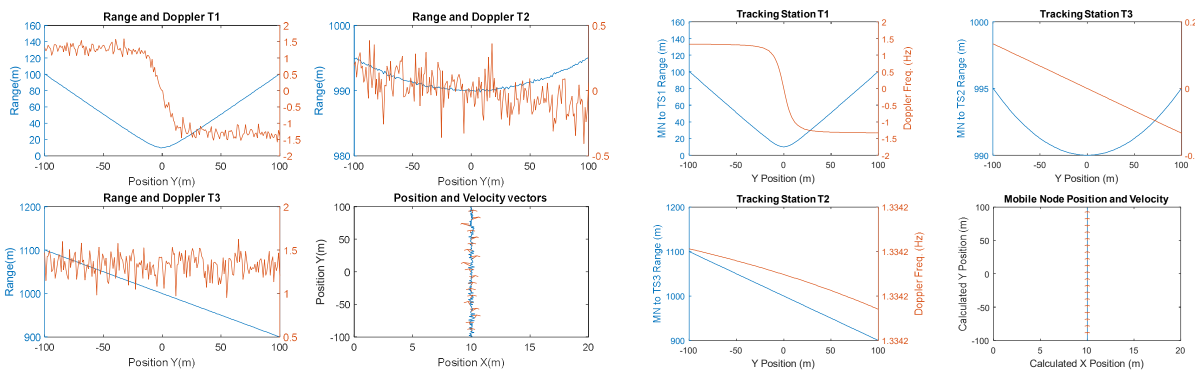

Figure 5: (Right) Range and Doppler signals with Position and Velocity reconstruction from noisy signal with noise in range σ^2_{T1W} = 0.156 ns^2 and Doppler σ^2_{T1W} = 1.56·10^{-4} ns^2. Measured at f_{IF}=100 KHz. (Left) Range and Doppler signals with Position and Velocity reconstruction from ideal data (without noise)

As one can appreciate in Figure 5, phase instabilities have a strong influence in velocity determination. Even at low noise values, which could be achievable in a scenario with high quality oscillators like those presented in Table 1, velocity vector estimations differ strongly from the theoretical values (Figure 5 Right). Those effects are less dramatic in position determination; therefore, a very frequent position sampling would be necessary for a precise navigation.

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3. Summary and Conclusions

Effect of phase noise have been on position and relative velocity determination have been presented and analysed for a hypothetic Lunar exploration scenario. Error introduced by short-term phase noise effects as those related with frequency instability of crystal oscillators, even those of high quality ones like OCXOs or TCXOs can seriously jeopardize position and velocity measurements unless some effective filtering technique is used. Extended Kalman filtering methods and other adaptive filtering techniques could be effective for such purpose at a low computational cost.

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