Inter-Satellite Ranging in the Low Earth Orbit

Mohammad Alawieh[1], Niels Hadaschik[1], Norbert Franke[1] and Christopher Mutschler[2,1]

[1] Fraunhofer Institute for Integrated Circuits IIS, Locating and Communication Systems Dept., Germany
[2] Friedrich-Alexander-University Erlangen-Nürnberg (FAU), Programming Systems Group, Germany

{firstname.lastname}@iis.fraunhofer.de

Abstract—**Many satellite systems require knowledge about inter-satellite distances. Inter-satellite links provide direct connectivity between satellites and may be used for ranging, while they remove the need of dedicated hardware.**

This paper addresses inter-satellite ranging at the Low Earth Orbit (LEO) using S-Band signals. We take the requirements from recent missions and future applications into account and analyze the factors that limit ranging. We show how these factors affect the quality of distance estimation in terms of the Cramér-Rao Lower Bound for ranging. Two-way-ranging (TWR) provides the best accuracy and sustains the low-cost objective of small satellites. We further propose an enhanced TWR message exchange that enables on-the-fly delay calibration and sub-sample corrections. We implemented the transceiver modules on a Software-Defined Radio (SDR) platform and evaluated them with real-world data. The results show that the proposed ranging algorithm achieves an accuracy of few centimeters.

Keywords—Ranging; TWR; Flying formation satellites; CubeSat

I. INTRODUCTION

Inter-Satellite ranging is one key application that provides estimates for the distance separating two or more satellites. This information is fundamental for dozens of applications including satellites that fly in formation for coordinated measurements of remote sensing space missions [1]. Current solutions rely on laser technologies, binocular cameras or GNSS relative positions to determine the distance measurements [2]. However, no relevant investigations have been carried to analyze the potential of inter-satellite ranging based on RF signals.

With the increased interest in small satellite technology, the communication is no more a single link between satellite and ground station but also inter-satellite communication becomes relevant as shown in Fig. 1. A Given the inter-satellite link, applications requiring distance measurements can benefit without the need for extra dedicated hardware. One example is the Generic SDR-bAsed Multifunctional space LINK (GAMALINK) project that aims at developing a CubeSat [3] compatible communication platform to provide a tailored solution for small satellite missions and validates several new technologies in space. The hardware platform is based on a Software-Defined Radio (SDR) that can adapt to various waveforms and modes of operation, including ranging. In GAMALINK, a group of small satellites called CubeSats are released at different altitudes in the Low Earth Orbit (LEO).

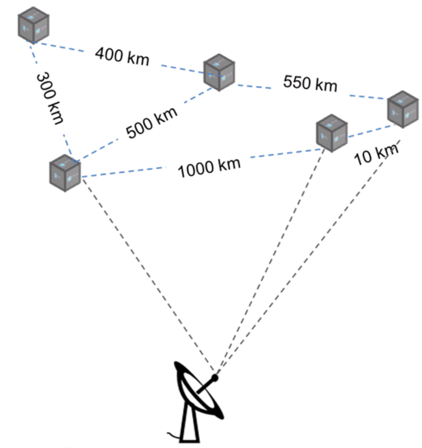


Fig. 1. Inter-satellite and ground station communication overview.

The prime focus of our work is a ranging system that achieves high accuracy and that takes the constraints for LEO small satellites into account. We adapted TWR as it provides high accuracy with still lower complexity compared to other techniques. Since CubeSats are operating at high altitudes, terrestrial effects that influence the ranging accuracy (such as jamming or multipath) are minimal. However, other effects like propagation delay clock offsets, as well as Doppler and atmosphere attenuation become relevant.

The rest of the paper is structured as follows. Sec. II presents an analysis of several ranging methods before it estimates the Cramér-Rao Lower bound on the estimation error. Then we present our main contributions:

- Sec. III investigates the error sources in LEO such as propagation delay clock offset, Doppler and atmosphere attenuation and provides methods to mitigate their effects.
- Sec. IV presents our ranging architecture including a novel TWR message exchange scheme that enables the ranging node to include calibration correction and sub-sample estimates for each range calculation.
- Sec. V describes our SDR-based transceiver signal design. Sec. VI evaluates our ranging solution before Sec. VII concludes.

II. Overview and Theoritical Analysis

Different ranging methods can be applied to calculate the distance between satellites. The main factors that influence the choice of the best technology for GAMALINK are the accuracy, covered range, update rate, and algorithm complexity.

A. Overview of Common Ranging Methods

The most common ranging methods are Received Signal Strength Indication (RSSI), one-way-ranging, and TWR.

1) Received Signal Strength Indication (RSSI)

RSSI is very attractive due to the widespread availability of received signal strength indication in wireless transceivers and the simplicity of its implementation. In RSSI systems the distance between a transmitter and a receiver is determined by converting the value of the signal strength at the receiver into a distance measurement based on the known signal output power. However, in practice given a long range d, estimated distances are unreliable [4][5] due to the small gradient of the received power $P'_{RX}(d) \propto 1/d^3$ and a weak SNR.

2) One-way ranging

While one-way-ranging requires both the transmitter and receiver to be synchronized, the accuracy is directly affected by the quality of the synchronization. Clock drifts and offsets between nodes introduce errors in the order of microseconds. This error is too large for reasonable applications.

3) Two-way ranging (TWR)

TWR sends ranging signals and measures the time until the ranged object replies. Hence there is no need to synchronize satellite clocks. In basic TWR, one ranging node is set as initiator and a second as reflector. The initiator controls the ranging mechanism and calculates the distance. Meanwhile, the reflector is in charge of sending a reply signal once the ranging signal from initiator is received. TWR has been widely adopted for ranging implementations [6] [7].

Given the drawbacks of one-way-ranging and RSSI, TWR is the most adequate solution for inter-satellite ranging. Throughout the rest of the paper we focus on TWR.

B. Cramér-Rao Lower Bound (CRLB)

The CRLB [8] gives a lower bound for the error variance of unbiased estimators. Considering the propagation delay estimator, the CRLB of a bandlimited signal of bandwidth B, is approximated by:

$$\boldsymbol{CRLB_{TOA}} \approx \frac{\boldsymbol{1}}{(\boldsymbol{2\pi})^2\boldsymbol{2T_{obs}}\frac{\boldsymbol{P_{RX}}}{\boldsymbol{N_0}}\int_{-\infty}^{\infty}\boldsymbol{f^2S(f)df}}\ .$$

The received signal power $P_{RX} = P_{RX}(d)$ depends on the travelled distance d and $N_0 = k_{Bolzmann}\Theta$, which is the power spectral density of the additive white Gaussian noise (AWGN) depending on the temperature Θ in Kelvin. Furthermore, $S(f)$ describes the power spectrum of the signal pulse shape $p(t)$.

Considering TWR, the estimation error occurs twice (in both receivers) and – at least for AWGN – these errors remain independent, such that in the statistical observation their error variance adds up. However, since the distance is equivalent to a one-way instead of a two-way propagation, the actual distance halves. Consequently, the total error variance is only half the simple delay

$$\boldsymbol{CRLB_{TWR}} = \frac{\boldsymbol{CRLB_{TOA}}}{\boldsymbol{2}}.$$

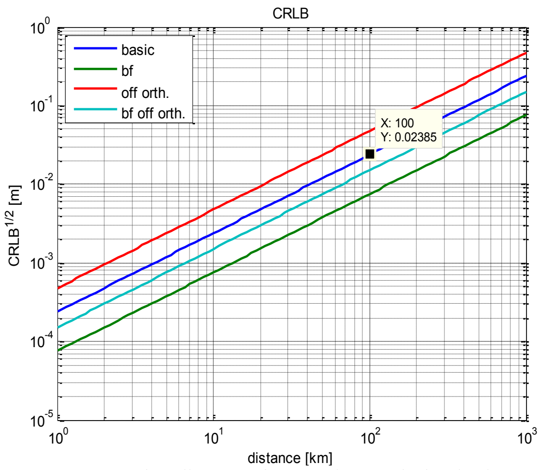


Fig. 2. CRLB vs. the distance for ranging and the basic settings (basic), beamforming (bf), considering worst case angles (off orth.), and beamforming off orthogonal (bf off orth.).

Fig. 2 presents the CRLB for a signal with 20MHz bandwidth in four scenarios. The first is the basic scenario where no directivity losses are included. The second scenario is with beamforming using three antennas, while the third and fourth scenarios consider the reduced antenna gain of signals arriving from maximum off-orthogonal directions (± 60°). If observing the minimum root mean square error (RMSE) for 100 km in the basic setting 2.38cm accuracy is achievable, but in worst case direction for the antenna gain this increases to 4.7 cm. If beamforming is assumed the minimum RMSE in this case is still 1,5 cm. The CRLB shows that beamforming improves the performance and hence leads in a better ranging accuracy. For distances above 100 km applying beamforming becomes more relevant; however at lower distances it can be omitted.

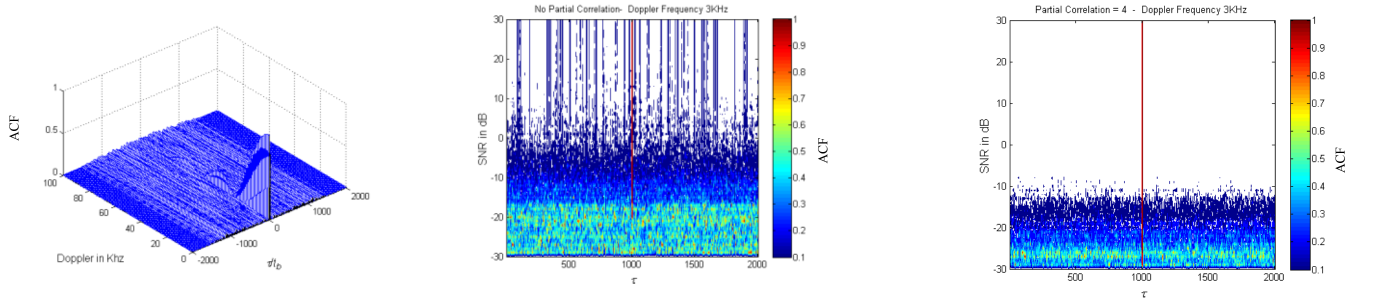
III. Error Sources and Ranging Limitations

Beyond the received signal power, the accuracy of the range measurements is influenced by *(A)* temperature and solar influence, *(B)* transceiver delays, and *(C)* Doppler shift.

A. Orbit: temperature and solar influence

CubeSats mainly consist of low-power off-the-shelf components. The temperature in orbit can vary strongly, which influences the behavior of electronic components inside the CubeSat. Rising temperatures also increase the (internal) thermal noise that adds to the external noise sources in addition to carrier frequency jitter.

In the thermosphere the impact of high energy particles as emanating, e.g. from solar winds, is less problematic than for satellites in higher atmospheric layers. However, strong solar activity adds distortion. If the antenna faces the sun its temperature increases significantly, and to a smaller extent,



(a) ACF as a function of delay and Doppler. (b) Full correlation over SNR with 3KHz Doppler. (c) Partial correlation over SNR with 3KHz Doppler.

Fig. 3. Effect of Doppler shift on the ACF.

but more probably, if it faces the Earth. It is then an important source of additive Gaussian noise that may harm the estimation accuracy or that may even lead to a link-loss.

B. *Clock offset and jitter*

While TWR eliminates the time synchronization requirement, still skew and frequency offset of crystal oscillators results in delay measurement errors. The accuracy of TWR is sensitive to the quality of the clock. If the clocks of two devices jitter differently, the offset adds a bias to the measurement.

In GAMALINK, the CubeSats are separated by a few hundred kilometers. Assuming a maximum ranging distance of 1000 km, the signal takes around 3.3 ms from one CubeSat to another.

Fig. 4 shows the influence of the clock quality on the ranging resolution. The reply time at the reflector is set to 20µs. A clock oscillator with 5 ppm tolerance results in 5 m ranging error if the distance is 1000km. This error can be 10 times improved with a 0.5 ppm oscillator.

To reduce the error from crystal tolerances of the devices usually an additional ranging signal is sent. Two common concepts are symmetric double-sided two-way ranging (SDS-TWR) [9] and asymmetric double sided two-way ranging (ADS-TWR) [10]. Both methods work by introducing more traffic on the channel as the ranging device sends its measurement twice. This extra message exchange reduces the error. However, with decreasing reply time its effect on the error correction becomes negligible. This is because the time of flight is much larger than the reply time and hence its effect of the reply time on the error is very small.

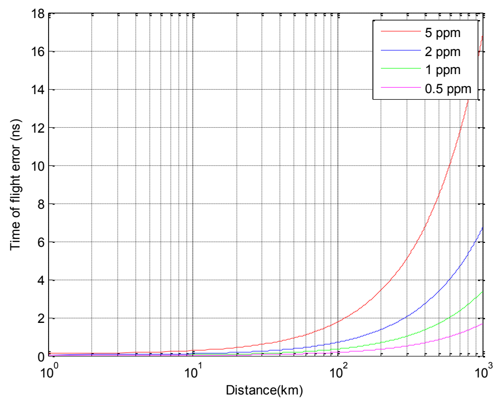


Fig. 4. Time of flight error for different oscillator tolerances.

Accordingly, the results from SDS-TWR and ADS-TWR are similar to standard TWR and can hence not be used to replace highly stable oscillators. Based on this analysis, an oscillator with 1 ppm tolerance was used for the satellite SDR platform.

C. *Doppler shift*

Relative movement of satellites on their respective orbits leads to frequency offsets. These orbits are little different at launch, but their differences increase massively over time. Additionally, elliptic orbits already cause relative velocities between satellites at different positions in the same orbit. The operating range of the relative velocity has been upper-bounded to 120 m/s in the specification, w.r.t the satellite life time and the difference of the starting and final orbit. The resulting maximum expected Doppler shift expected during operation is around 2KHz.

The processing gain of the despreading of the received signal enables to recover signal and the modulated data at low SNR values. Despreading compresses the received signal energy in a smaller bandwidth and achieves, there, a positive SNR. One main drawback of using a long code in a direct sequence spread spectrum (DSSS) [11] system is that the Doppler and frequency offsets degrade more strongly and affect the detection performance.

Fig. 3 (a) shows how the auto correlation function (ACF) degrades as Doppler increases. The Doppler shift becomes more relevant for lower SNR. One way to compensate its effect on the correlation is by performing partial correlation [12]. Partial correlation dividing the burst into $N_{interval}$ smaller correlation intervals of length $T_{interval}$ compensates sub-optimally for this degradation with

$$T_{obs} = N_{interval} T_{interval}.$$

The received signal intervals themselves are coherently despread with their counterpart of the transmitted sequence $x(t)$, and summed up (or integrated) non-coherently

$$C_{partial} = \sum_{n=0}^{N_{interval}-1} \left| \int_{nT_{interval}}^{nT_{interval}-1} y(t)x^*(\tau - t)dt \right|.$$

The partial correlation is analyzed for a frequency shift of 3 kHz as presented in Fig. 3 (b) and (c). Therein, the code consists of 8192 samples and the correlation function peak magnitude for different SNR values demonstrates in Fig. 3 b that detection below -12dB is no longer feasible without partial correlation. Setting $N_{interval} = 4$, a probability of detection of around 1 is achieved at SNR= -20dB.

IV. TWR Procedure in GAMALINK

Filters, amplifiers and transmission lines add delays to the signal, making a calibration necessary before measuring consistently. The most practical solution for delay calibration is to introduce a signal loopback for delay variation measurements which is often used in Two Way Satellite Time and Frequency Transfer systems [13]. We send a calibration signal through the transmission system and feed it back through the receiving module. Afterwards we estimate the internal delays and gains from the sampled backcoupling signals. These estimates are then used for calibrating communication and ranging signals.

Both, initiator and reflector compute their internal delays by calibration measurements in addition to the arrival time estimation at subsample resolution. An accurate distance estimate strongly requires both pieces of information to be available at the initiator node. The information can be transferred on a separate communication channel after every ranging event. This approach adds latency to the system and depends on other applications, e.g. from communication link.

A more simplistic approach is realized by sending two correction signals to the initiator after the completion of the basic TWR packets exchange, see Fig. 5. After the reply signal t_{reply}, we send two corrections

$$t_{corr1} = t_{sDelay} + t_{sCorr}, \text{ and}$$

$$t_{corr2} = t_{subDelay} + t_{subCorr}$$

where t_{sCorr} and $t_{subCorr}$ represent the sampling and subsampling reflector estimated delays whereas t_{sDelay} and $t_{subDelay}$ are predefined time offsets.

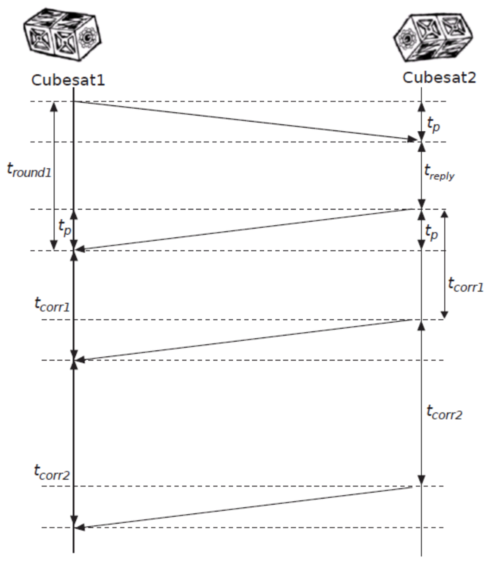


Fig. 5. TWR signal exchange in GAMALINK.

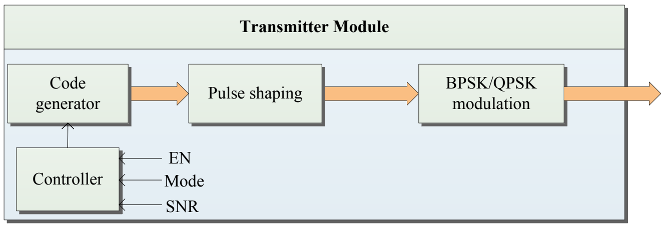


Fig. 6. Baseband block diagram for the ranging transmitter.

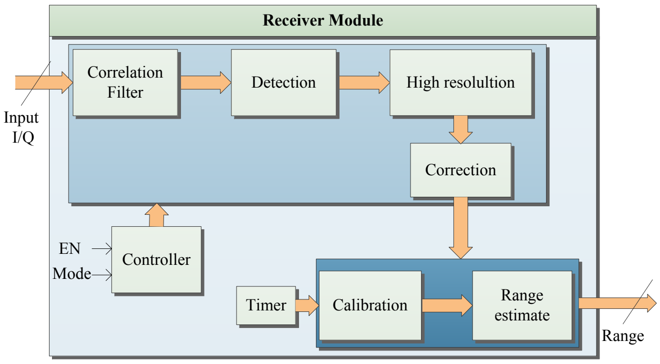


Fig. 7. Baseband block diagram for the ranging receiver.

The suggested packet exchange mechanism between initiators and reflectors applies for full-duplex RF transceivers as well as transceivers with calibration loop. One TWR measurement is sufficient for distance calculation. However, adding a measurement quality and accordingly weighted averaging over a number of distances results in more accurate distance estimates.

V. Transceiver Signal Design

For ranging we use DSSS modulation, which uses the code sequence to directly modulate the carrier. Hence, we spread the signal over the operating bandwidth is spread of 20MHz. Fig. 6 shows a block diagram of the transmission baseband model. We spread the transmission signal spread over a wide spectrum accurately recover timing from the spread sequences (not user data). The generated and modulated sequences are passed through a pulse shaping filter and sent through the DAC. We choose code sequences on the basis of their auto-correlation properties for a given code length: with ranges between 10km and 1000km a sufficient code processing gain should be exhibited to recover the signal from the resulting SNR degradation. The platform supports both BPSK and QPSK.

The receiver, shown in Fig. 7, recovers the sent signals which may be hidden in noise for low SNR. Thus it first performs an acquisition algorithm that searches for the desired ranging signal from the raw ADC data. The real-time correlation filter compares the complex input data with a reference sequence. It is designed for both QPSK and BPSK modulation schemes. Once we calculated the correlation magnitude, we forward the values to the detection module. A sliding mean detection filter is used to identify the presence of the signal from the correlation magnitude values.

VI. Performance Analysis

We evaluate the estimation accuracy with real world data recorded by an evaluation platform based on a ML605 Xilinx FPGA [14] and an FMCOMMS1 RF-board (analog front-end) from Analog Devices [15]. We measure single-shot ranges to better evaluate the accuracy of the proposed algorithms. The tests are grouped in three categories:

- *(A)* investigates the accuracy of the calibration loop by measuring the time the signal took from the transmitter to the receiver side.
- *(B)* measures the accuracy and precision of the system in the absence of disturbances. The result of this test gives an approximation on the expected accuracy for a LEO scenario where the assumption of LOS reception is valid.
- *(C)* evaluates the functionality of the TWR mechanism from Sec. IV. Channel disturbances and multipath effects are expected to influence the measured distances.

A. *Calibration loop test*

First, we analyze the accuracy of the calibration estimation and measure the delay difference between different coaxial cables and another short cable connection (50cm) with a loop-back from the transmitter to the receiver of the same board. The initial cable delay is used to compensate for the time delays of the transceiver chains. Fig. 8 shows the error measurement for four different cable lengths. The measurements consider the delay in reference to a 50cm cable. Errors resulting from reflections at the connectors and initial calibration add up to the error of the distance estimates in this test. Despite these effects the error in estimation the relative cable length is less than 10cm. This test was repeated over 15 measurements, increasing the cable length by 25cm interval. The absolute average error was around 7.4cm. This concludes that, independent of the distance between satellites, the suggested calibration loop can accurately correct the transceiver delays.

B. *TWR with LOS signal*

The second test analyzes the ranging implementation without multipath effects. Two platforms are used, where the transmitter of each platform is connected to the receiver of the second platform via coaxial cables. Fig. 9 a. shows the setup connection with two 100cm cables.

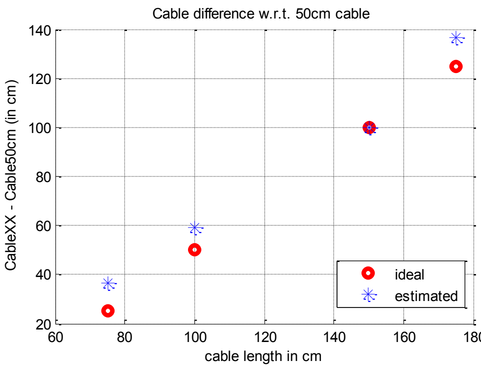
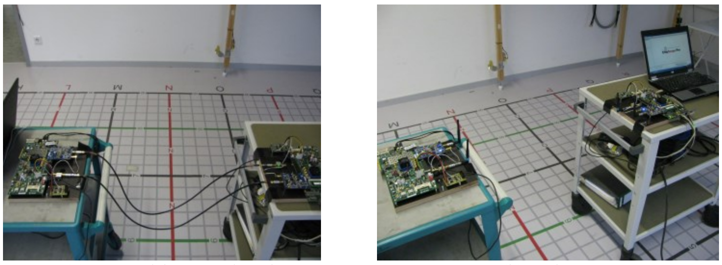


Fig. 8. Absolute estimation error vs. calibrated cable length.



(a) Test with LOS signals. (b) Indoor test.

Fig. 9. LOS and indoor test setups.

In Fig. 10 we plotted the calculated cable length for four pairs of length 100, 150, 300 and 500cm respectively over ten measurements. Fig. 11 is a zoom for the 300cm measurement and it shows that calculated distances are within few cm accuracy and are highly stable. This scenario does match with the inter-satellite communication with good SNR. For GAMALINK this means that given a LOS signal at distances bellow 100km, an accuracy bellow 25cm is achievable.

C. *Indoor measurments*

A LOS signal was provided however multipath is expected to influence the estimated range as shown in the test setup in Fig. 9 b. In the preliminarily final test, four non-directional antennas are connected to the transmitter and receiver connections on both evaluation boards. Calibration is automatically performed by employing the signal coupling from the transmitter to the receiver antenna of the same device as described in Sec. IV. Measurements are carried out at several distances, e.g. 1, 2, 3 and 5 meters. The measured distance calculated at the initiator node for 10 measurements is shown in Fig. 12.

At close distances where a clear LOS signal and high SNR is available the estimate error ranges around 20cm. When the distance separating the two platforms is more 2m channel distortion in addition to multipath effects results in higher errors, which exceeds 45cm in some occasions. However such factor is not likely to occur at the LEO.

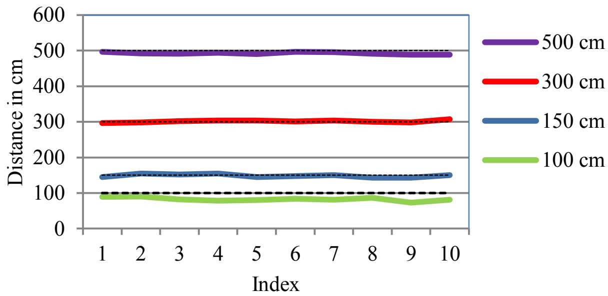


Fig. 10. Estimated distance using TWR from different cable length.

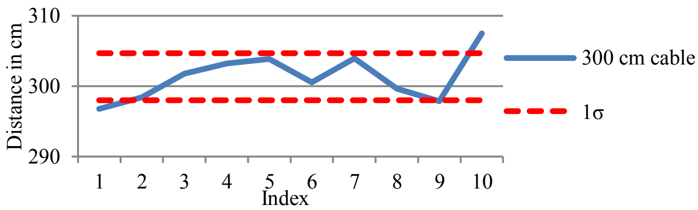


Fig. 11. Standard deviation in the estimated distance using TWR.

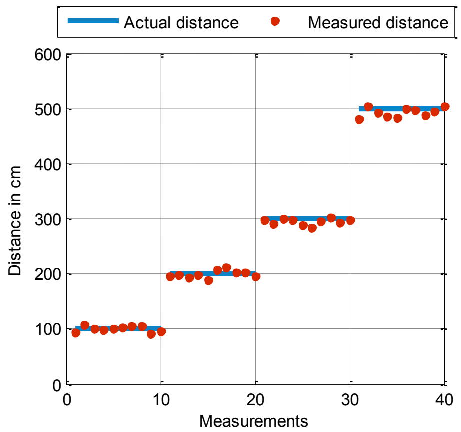


Fig. 12. Indoor range measurements over several distances.

VII. CONCLUSION

This paper investigated inter-satellite ranging for small satellites flying at the low-earth-orbit. Two-Way-Ranging offers the highest accuracy when compared to other ranging techniques. The Cramér-Rao Lower Bound was used to examine the performance taking into consideration the enhancement from applying beamforming.

The different factors that influence the accuracy such as temperature variations, transceiver delays, clock errors and frequency offsets should be minimized both at the algorithm and the hardware level such as the calibration feedback loop. We showed that low performance resulting from the Doppler shift or carrier offset is compensated by partial-correlation. Numerical results show that the signal can always be detected at low SNR of -20dB and Doppler within 3Khz.

We proposed an enhanced TWR mechanism to perform calibration and include sub-sample corrections. We evaluated our TWR module implementation with real-world data, the achieved accuracy is bellow 25cm under a strong LOS and an SNR above 0dB. Given GAMALINK inter-satellite communication link budget a similar performance can be foreseen for satellites separated by distances bellow 100km.

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