

Robust Doppler Compensation for LEO-OFDM Radar Sensing Using Hierarchical 2-D Grid Search

1st Zahra Zarei
School of Electrical Engineering
Korea University
Seoul, Republic of Korea
zahraz@korea.ac.kr

2nd Fitsum Debebe Tilahun
School of Electrical Engineering
Korea University
Seoul, Republic of Korea
fitsum_debebe@korea.ac.kr

3rd Chung G. Kang
School of Electrical Engineering
Korea University
Seoul, Republic of Korea
ccgkang@korea.ac.kr

Abstract—In low Earth orbit (LEO) integrated sensing and communication (ISAC) systems, orthogonal frequency-division multiplexing (OFDM) waveforms encounter severe Doppler shifts and Doppler rate variations arising from the rapid motion of satellites and targets. These time-varying distortions disrupt subcarrier orthogonality and smear the range-Doppler response, causing conventional FFT-based estimation to fail. This work investigates a robust Doppler compensation framework for LEO-OFDM radar sensing. To address this, a hierarchical two-dimensional grid search is introduced to jointly estimate the dominant Doppler frequency and Doppler rate, maximizing a coherence-based metric across OFDM symbols. The results confirm that the proposed 2-D Doppler compensation effectively improves detection reliability.

Index Terms—LEO ISAC, OFDM radar sensing, Doppler compensation, 2-D estimation.

I. INTRODUCTION

The application of OFDM waveforms in ISAC has gained significant attention due to their compatibility with modern communication standards. However, LEO satellite systems face challenges from large Doppler shifts and rates due to rapid orbital motion, which distort conventional FFT-based range-Doppler processing [1]. To address these issues, various techniques have been developed. For instance, a phase-based Doppler estimation method in [2] improves SNR and detection resolution in binary phase-coded radar, while [3] proposes low-complexity algorithms for Doppler correction in LEO OFDMA systems. Additionally, [4] uses polynomial phase modeling for time-varying Doppler estimation. Though effective for communication, these techniques fall short for ISAC sensing, which demands sharp range profiles and focused range-Doppler maps. To address this, we propose a hierarchical two-dimensional grid search to jointly estimate Doppler frequency and rate, maximizing coherence across OFDM symbols. Our work extends Doppler-rate compensation to ISAC sensing, validating improved radar resolution under high-dynamics LEO conditions.

II. SYSTEM MODEL AND PROBLEM FORMULATION

We consider an ISAC system operating in LEO, where the sensing waveform is based on OFDM. The system consists of a transmitter (satellite) and a reflecting target at range R . Due to the high orbital velocity and acceleration of the

satellite, the received waveform is affected by both a *constant Doppler frequency shift* and a *time-varying Doppler rate*. Let the OFDM system employ N subcarriers with subcarrier spacing Δf , giving a useful symbol duration of $T = \frac{1}{\Delta f}$ with cyclic prefix duration T_{cp} , and total OFDM block length is $T_s = T + T_{cp}$. The baseband transmitted signal in the m -th OFDM block is written as

$$s_m(t) = \sum_{k=0}^{N-1} X[k, m] e^{j2\pi k \Delta f (t - mT_s)}, \quad (1)$$

where $X[k, m]$ is the symbol transmitted on subcarrier k of block m , $k = 0, 1, \dots, N-1$ is the subcarrier index, m is the OFDM symbol index, and t is the continuous time variable [5]. The signal experiences a round-trip propagation delay $\tau = \frac{2R}{c_0}$, where c_0 is the speed of light. In addition, the LEO channel introduces a Doppler frequency shift $f_{d,0}$ (Hz) and a Doppler rate $\dot{f}_d$ (Hz/s), due to the satellite's velocity and acceleration relative to the target. After carrier removal, the received baseband signal is modeled as

$$r(t) = s(t - \tau) \exp\left(j2\pi\left(f_{d,0}t + \frac{1}{2}\dot{f}_d t^2\right)\right) + n(t), \quad (2)$$

where $n(t)$ is additive noise. The phase distortion is polynomial in time, i.e., $\phi(t) = 2\pi\left(f_{d,0}t + \frac{1}{2}\dot{f}_d t^2\right)$. With instantaneous Doppler frequency $f_D(t) = f_{d,0} + \dot{f}_d t$. Considering the frequency-domain representation, after cyclic prefix removal and FFT, the received signal on subcarrier k of block m is $Y[k, m] = X[k, m]H[k, m] + W[k, m]$, where $W[k, m]$ is noise and $H[k, m]$ is the channel. In standard OFDM radar processing, the target range profile is obtained via an inverse FFT (IFFT) across subcarriers as $z[r, m] = \frac{1}{N} \sum_{k=0}^{N-1} \frac{Y[k, m]}{X[k, m]} e^{j2\pi \frac{r}{N} k}$, where r denotes the discrete range bin. Range-Doppler (R-D) maps are then formed by applying an FFT across block m . However, in the LEO setting, the quadratic phase distortion from $(f_{d,0}, \dot{f}_d)$ leads to loss of inter-carrier orthogonality, and smearing of range peak. The problem is thus to **jointly estimate and compensate Doppler**

and Doppler rate before coherent integration as follows:

$$(\hat{f}_{d,0}, \hat{f}_d) = \arg \max_{(f_{d,0}, \dot{f}_d)} \left| \sum_{m=0}^{M-1} \bar{Z}[m] e^{-j2\pi(f_{d,0}t_m + \frac{1}{2}\dot{f}_d t_m^2)} \right|, \quad (3)$$

where $\bar{Z}[m] = \frac{1}{N} \sum_{k=0}^{N-1} \frac{Y[k, m]}{X[k, m]}$ is the deconvolved average across subcarriers at symbol m . The resulting estimates are applied as symbol-level phase corrections using $\tilde{Y}[k, m] = Y[k, m] e^{-j2\pi(\hat{f}_{d,0}t_m + \frac{1}{2}\hat{f}_d t_m^2)}$, which realigns the distorted symbols.

III. PROPOSED SOLUTION

To overcome phase distortion in the received signal caused by high velocity, we propose a *hierarchical* two-dimensional (2-D) search algorithm, motivated by [2], [6], and [7]. The method jointly estimates the Doppler frequency $f_{d,0}$ and Doppler rate $\dot{f}_d$ by maximizing a coherence metric defined over the received pilot symbols. The processing flow begins with QAM-modulated OFDM transmission, where the received signal $Y[k, m]$ is divided by the known pilots $X[k, m]$ to extract the effective channel $Z[k, m]$. A range FFT is applied across subcarriers to form $z[r, m]$, followed by a preliminary range-Doppler map $Z_{RD}[r, \nu]$. Since motion-induced Doppler and Doppler-rate distortions smear the energy, a hierarchical 2-D search is then performed. First, a coarse grid over $(f_{d,0}, \dot{f}_d)$ provides an initial estimate $(\tilde{f}_{d,0}, \tilde{\dot{f}}_d)$, followed by a refined grid around this point to obtain accurate estimates $(\hat{f}_{d,0}, \hat{\dot{f}}_d)$. Each symbol is then re-phased by multiplying with $e^{-j2\pi(\hat{f}_{d,0}t_m + \frac{1}{2}\hat{\dot{f}}_d t_m^2)}$, yielding the compensated signal $Z_{\text{comp}}[k, m]$. These corrected data are finally used for range-Doppler mapping. Simulation results show that this procedure produces well-focused range-Doppler maps, enabling reliable OFDM-based sensing under high-dynamics LEO conditions.

IV. SIMULATION SETUP AND RESULTS

To evaluate the proposed Doppler and Doppler-rate compensation scheme in LEO-OFDM sensing model, we consider carrier frequency $f_c = 30$ GHz ($\lambda \approx 1$ cm), OFDM grid with $K = 64$ subcarriers and $M = 32$ symbols, subcarrier spacing $\Delta f = 960$ kHz, target range $R = 50$ m ($\tau \approx 0.33$ μ s), radial velocity $v_r(0) = 1500$ m/s ($f_{d,0} \approx 3.0 \times 10^5$ Hz), radial acceleration $a_r = -6$ m/s² ($\dot{f}_d \approx -600$ Hz/s), QPSK modulation, and SNR = 5 dB. As it can be seen in the simulation results, the algorithm estimated $\hat{R} = 50.01$ m, $\hat{f}_{d,0} = 316.6$ kHz, and $\hat{\dot{f}}_d \approx -1.2$ KHz/s.

The range-Doppler maps in Fig.1 illustrate the effectiveness of the proposed compensation. Specifically, in the pre-compensation case (Fig.1 (Top)), the target located at approximately 50 m appears smeared across Doppler frequencies, shifted around +300 kHz, which highlights the impact of Doppler misalignment and makes detection less reliable. In contrast, after applying the 2D compensation (Fig.1 (Bottom)), the target energy becomes tightly localized both in range and Doppler, producing a concentrated spot near 0 Hz Doppler at 50 m. This demonstrates that the proposed approach effectively

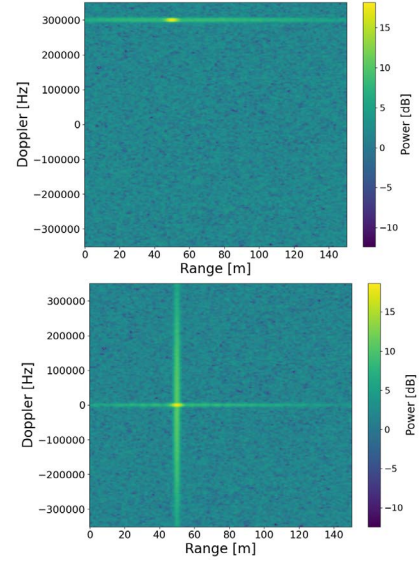


Fig. 1. Doppler compensation analysis: (Top):Before compensation, (Bottom):After compensation)

corrects the motion-induced phase errors, and sharpens the target response..

V. CONCLUSION

This work addressed the challenge of Doppler-induced distortions in LEO-OFDM sensing systems, where uncompensated Doppler shifts and rates disrupt subcarrier orthogonality and produce smeared range-Doppler responses. To resolve this, we proposed a two-dimensional grid search for joint Doppler and Doppler-rate estimation and compensation. Future work will examine the complexity-performance trade-offs between exhaustive search and the proposed method, and extend the approach to multi-target scenarios and cooperative LEO satellites.

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