STM JOURNALS

Recent Trends in
Electronics & Communication Systems

ISSN: 2393-8757
Volume 12, Issue 2, 2025
May–August
DOI (Journal): 10.37591/RTECS

https://journals.stmjournals.com/rtecs

Research RTECS

Doppler Limits of LoRa in LEO: A Critical Review of the First In-Orbit Flight Tests

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Abstract

This study provides a comprehensive review of the seminal work by Zadorozhny et al., which presented the first in-orbit flight test results evaluating the impact of Doppler effects on LoRa modulation for Low Earth Orbit (LEO) satellite communications. The review summarizes the original study's methodology using the NORBY CubeSat, details its key findings regarding the operational limits imposed by static and dynamic Doppler shifts across various LoRa configurations (Spreading Factor (SF), Bandwidth (BW)), and analyzes the significance of these results. It contextualizes the original findings within the rapidly evolving landscape of Satellite IoT (SatIoT), discussing subsequent research on Doppler compensation techniques, the emergence of competing technologies like 3GPP NTN, and the trend towards hybrid terrestrial-satellite networks. The review concludes that the work by Zadorozhny et al. provides a critical empirical foundation for understanding LoRa's performance in LEO, highlighting the trade-offs between sensitivity and Doppler robustness, while also noting the ongoing efforts to mitigate identified limitations.

Keywords: LoRa, satellite IoT, doppler effect, LEO

INTRODUCTION

The proliferation of the Internet of Things (IoT) has driven demand for connectivity solutions that can reach remote and underserved areas. While terrestrial networks like cellular and Wi-Fi dominate urban environments, satellite-based IoT (SatIoT) offers a compelling alternative for global coverage, particularly leveraging constellations of satellites in Low Earth Orbit (LEO). Among the candidate technologies for the physical layer of SatIoT, Long Range (LoRa) modulation has emerged as a strong contender [1].

LoRa, patented by Semtech [2], utilizes Chirp Spread Spectrum (CSS) modulation. In CSS, data is encoded using wideband signals where the frequency varies linearly over time (chirps) [3]. This technique offers significant advantages, including enhanced receiver sensitivity (up to 20 dB better than FSK), enabling longer communication ranges or reduced transmission power, and inherent robustness against channel impairments like multipath fading and interference [3]. These characteristics make LoRa well-suited for power-constrained IoT devices and have led to its widespread adoption in terrestrial low power wide area networks (LPWANs).

The potential of LoRa for SatIoT, especially using cost-effective CubeSat platforms, has been recognized [4, 5]. Projects like Lacuna Space, EchoStar Mobile, and others are actively building LEO constellations and services based on LoRaWAN, and several CubeSats incorporating

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Received Date: April 25, 2025
Accepted Date: May 07, 2025
Published Date: June 09, 2025

Citation: Paavan H. Shah, Mayur M. Sevak. Doppler Limits of LoRa in LEO: A Critical Review of the First In-Orbit Flight Tests. Recent Trends in Electronics & Communication Systems. 2025; 12(2): 21–27p.

LoRa transceivers have been launched [1]. However, the LEO environment presents a unique and significant challenge: the Doppler effect. The high relative velocity between a LEO satellite (often >7 km/s) and a ground station causes substantial shifts in the received signal frequency (static Doppler effect) and rapid changes in that frequency shift over time (dynamic Doppler effect). While LoRa is known for some Doppler tolerance, the precise limits of its applicability, particularly for different parameter configurations (Spreading Factor (SF), Bandwidth (BW)) under the extreme conditions of LEO passes, remained largely unquantified by real-world space testing prior to the work by Zadorozhny *et al*. [1].

Previous studies investigated LoRa's Doppler robustness through laboratory simulations [6] and theoretical analysis [7]. Laboratory experiments suggested high immunity for wider bandwidths (BW≥125 kHz) in orbits above 550 km, but hinted at potential issues due to the dynamic Doppler effect for SF=12 in lower orbits or with narrower bandwidths [6]. However, laboratory conditions cannot fully replicate the complexities of the actual satellite-to-ground channel.

The paper "First flight-testing of LoRa modulation in satellite radio communications in low-Earth orbit" by Zadorozhny *et al.* directly addresses this critical knowledge gap [1]. It presents the pioneering results from in-orbit experiments conducted using the NORBY CubeSat specifically designed to systematically evaluate LoRa's performance limits when subjected to the Doppler effect in a realistic LEO scenario. This review provides a detailed summary and analysis of their methodology, findings, and conclusions, placed in the context of ongoing developments in the field.

EXPERIMENTAL SETUP AND METHODOLOGY

The study employed a rigorous methodology involving a dedicated CubeSat platform, a ground station, and a carefully planned experimental procedure [1].

The NORBY CubeSat Platform

- *Satellite:* The experiments utilized NORBY, a 6U CubeSat developed by Novosibirsk State University, launched in September 2020 into a near-polar LEO (inclination 97.7°, altitude ~545–579 km) [1].
- *On-Board Radio Complex (BRC):* NORBY features redundant BRCs, each incorporating a Semtech SX1278 transceiver [8]. This chip supports LoRa modulation alongside traditional FSK/GFSK modes. The BRC operates in the UHF band at 436.7 MHz with adjustable transmitter power (0.1 to 4 W). For the experiments, maximum power (4 W) was used to mitigate signal strength as a variable.
- *Antenna:* The active BRC used a pair of quarter-wave vibrators mounted on one end of the satellite body. Calculated radiation patterns indicated a non-uniformity of approximately 7 dB, although experimental data suggested actual variations could be larger.
- *Attitude Control:* While NORBY possesses an Attitude Determination and Control System (ADCS), it was still under debugging during the tests. The satellite's rotation was slowed but not fully stabilized or pointed, meaning the antenna orientation relative to the ground station varied unpredictably during passes [1].
- *Navigation:* An onboard GLONASS receiver provided real-time position and velocity data, crucial for calculating the actual Doppler shift experienced during the experiments.

Ground Station

- *Location:* Situated at Novosibirsk State University.
- *Transceiver:* Utilized a matching Semtech SX1278-based system [8].
- *Antenna System:* Employed a steerable system with two crossed Yagi-Uda antennas (Gain: 14.5 dBi, Beamwidth: ~30°) mounted on a mast.
- *Tracking:* An azimuth-elevation rotator pointed the antenna using trajectory predictions from Gpredict software based on Two-Line Element (TLE) sets from SATCAT.

- *Keyhole Problem:* The authors explicitly acknowledge the "keyhole problem" inherent in Azimuth-elevation mounts when tracking satellites passing near the zenith. High angular velocities required for tracking near-zenith passes can exceed the rotator's capability, leading to pointing errors and potential signal attenuation. Using maximum transmitter power helped mitigate the impact of this during the tests.

Experimental Procedure

- *Pass Selection:* Experiments were conducted during NORBY passes with high maximum elevation angles (>80°) to ensure the satellite experienced the highest possible Doppler rates when passing near the ground station's zenith.
- *Test Activation:* Upon receiving a beacon signal from NORBY, the ground station commanded the satellite to enter a test mode. This command specified the LoRa parameters (SF, BW), packet size (L), number of packets (N), and transmitter power (4 W).
- *Data Transmission:* NORBY then transmitted a sequence of N data packets. Each packet included its sequence number, current GLONASS data (time, coordinates, velocity), and basic telemetry.
- *Parameter Space:* A range of LoRa configurations were tested:
  - *SF:* 7, 10, 11, 12
  - *BW:* 500, 125, 62.5, 31.25 kHz
  - *Packet Length (L):* 55 and 143 bytes
  - *Coding Rate (CR):* 4/5 (error detection only)
  - *Low Data Rate Optimize:* Enabled

Data Collection and Analysis

- *Ground Reception:* The ground station logged all successfully received packets. Packets received with errors (based on CRC check with CR 4/5) were considered lost.
- *Recorded Metrics:* For each *received* packet, the ground station recorded:
  - RSSI (Received Signal Strength Indicator),
  - SNR (Signal-to-Noise Ratio), and
  - FER (Frequency Error indication - the difference between the received carrier frequency and the receiver's local oscillator frequency) [8].
- *Doppler Calculation:*
  - The theoretical Doppler shift (ΔFD) was calculated using the standard formula based on satellite velocity (v), speed of light (c), and the angle (β) between the velocity vector and the direction to the ground station. Velocity and position data were obtained from both onboard GLONASS (for received packets) and TLE predictions (for all transmitted packets, including lost ones).
  - The total measured frequency offset (ΔF) reported by the receiver's FER includes both the Doppler shift (ΔFD) and any offset between the transmitter and receiver reference oscillators (ΔFRT).
- *Analysis Focus:* The analysis correlated packet loss events with the calculated Doppler shift (ΔFD) and Doppler rate (ΔFD′, the time derivative of ΔFD), as well as the measured total frequency offset (ΔF) and its rate of change (ΔF′), while accounting for potential confounding factors like low RSSI/SNR due to antenna orientation or interference.

EXPERIMENTAL RESULTS AND FINDINGS

The flight tests, encompassing 20 distinct communication sessions and over 5200 transmitted packets, yielded significant, quantifiable results on LoRa's Doppler robustness [1]. The findings are summarized below, categorized by the dominant effect observed.

High Robustness Regimes (SF≤11, BW≥62.5 kHz)

- Experiments conducted with SF=7 (BW=500, 125, 62.5 kHz), SF=10 (BW=62.5 kHz), and SF=11 (BW=62.5 kHz) demonstrated excellent performance.

- Across these configurations, packet loss was minimal and primarily attributed to factors *other* than the Doppler effect, such as:
    - Temporary weak signal (low RSSI/SNR) due to unfavorable satellite orientation (exacerbated by antenna pattern nulls and satellite rotation).
    - Potential ambient noise/interference (e.g., from nearby construction), indicated by sporadic low SNR values despite adequate RSSI.
    - A few isolated packet losses remained unexplained.
- Crucially, no correlation was found between packet loss and high Doppler shift or high Doppler rate in these modes. Communication remained stable throughout the passes, from horizon to horizon, including the period of maximum Doppler shift/rate near zenith.
- This confirms the high immunity of these LoRa modes to the Doppler conditions experienced in the ~560 km LEO environment.

Static Doppler Effect Limitations (BW=31.25 kHz, SF≤10)

- Experiments using the narrowest bandwidth, BW=31.25 kHz, with SF=7 and SF=10 clearly showed the impact of the static Doppler effect.
- The maximum Doppler shift in NORBY's orbit (~10.2 kHz) exceeds the theoretical tolerance of the SX1278 transceiver for this bandwidth (ΔFmax=0.25×BW=0.25×31.25≈7.8 kHz) [8].
- *Observation:* In these tests, communication was consistently lost when the satellite was at lower elevation angles (start and end of the pass) where the absolute magnitude of the Doppler shift |ΔFD| was greater than ~7.7–7.8 kHz. Communication was only possible during the central portion of the pass, near zenith, where |ΔFD| dropped below this threshold.
- *Quantification:* The measured total frequency offset (ΔF) at the points where communication dropped/resumed consistently clustered around ±*7.73 kHz*. This represents *~24.7% of the bandwidth,* providing strong experimental validation of the 0.25×BW specification under real flight conditions [8].
- *Impact:* The static Doppler effect significantly reduced the duration of the usable communication window for these configurations.

Dynamic Doppler Effect Limitations (SF=12, BW=62.5 kHz)

- Experiments with SF=12 and BW=62.5 kHz isolated the impact of the dynamic Doppler effect. This bandwidth is wide enough ($\Delta F_{max}\approx. 15.6$ kHz) to tolerate the static Doppler shift.
- *Observation:* In these tests, communication failed specifically during the period when the satellite was near zenith, coinciding precisely with the time when the *rate of change* of the Doppler shift (Doppler rate, |ΔFD′|) was maximal. Communication was successful at the beginning and end of the pass where the Doppler rate was lower, creating a distinct communication outage "hole" in the middle of the pass.
- *Quantification:* Packet reception ceased when the absolute value of the measured rate of change of the total frequency offset, |ΔF′|, exceeded a threshold. The average critical value determined from these experiments was ~36.6 Hz/s.
- *Significance:* This provided the first direct, in-orbit experimental evidence of LoRa communication failure caused purely by the dynamic Doppler effect, confirming predictions from earlier laboratory studies regarding the sensitivity of SF=12 [6].

Combined Doppler Effect Catastrophe (SF=11 and 12, BW=31.25 kHz)

- The configurations combining high spreading factors (SF=11, 12) with the narrowest bandwidth (BW=31.25 kHz) proved unusable for LEO communication in this orbit.
- *Observation:*
    - For SF=12, BW=31.25 kHz, no packets were received during the entire pass.
    - For SF=11, BW=31.25 kHz, communication was almost entirely disrupted. Only four packets were received in a very brief ~25-sec window during the approach phase.

- *Interpretation:* In these modes, the system is susceptible to *both* the static Doppler effect (due to BW=31.25 kHz, |ΔFD| exceeds ΔFmax) *and* the dynamic Doppler effect (due to SF=11/12, |ΔFD′| exceeds ΔFmax′ during the high-elevation part of the pass). The combined effect essentially prevents reliable communication throughout the pass. The brief reception likely occurred during a moment where the static shift had decreased sufficiently, but the dynamic rate had not yet increased enough to cause failure. From this brief window, thresholds of ΔFmax≈7.9 kHz and ΔFmax′≈41 Hz/s were estimated for SF=11, BW=31.25 kHz.

Other Factors

- *Packet Size:* The study found no discernible difference in Doppler robustness between using 55 and 143-byte packets for the tested configurations.
- *SF=12, BW=125 kHz:* (SF=12, BW=125 kHz) showed robust communication, with only isolated packet losses unrelated to Doppler. This aligns with laboratory findings [6], suggesting this mode is generally robust at ~560 km altitude, although it might be susceptible to dynamic Doppler in lower orbits (<550 km) where Doppler rates exceed the ~143 Hz/s maximum experienced by NORBY.

ANALYSIS AND DISCUSSION

The experimental results presented by Zadorozhny *et al.* offer profound insights into the practical application of LoRa for LEO SatIoT, establishing a crucial baseline for understanding its performance [1]. Analyzing these findings in the context of subsequent research and evolving market trends provides a richer perspective.

Validation and Refinement of Doppler Limits

The flight tests provided strong, real-world validation for the Semtech SX1278 datasheet specification regarding static Doppler tolerance (ΔFmax≈0.25×BW) [8]. This empirical confirmation remains a significant contribution. Furthermore, the study's pioneering in-orbit observation of communication failure due solely to the dynamic Doppler effect (particularly for SF=12) highlighted a critical limitation not fully captured by static analysis. Subsequent research has further explored these limits. For instance, Ullah *et al.* [9] provided additional perspectives on Doppler limits for LoRa Direct-to-Satellite (DtS) links, reinforcing the challenges identified by Zadorozhny *et al.*

Operational Boundaries and the Rise of Compensation

The clear delineation of robust, limited, and unusable LoRa modes by Zadorozhny *et al.* was a vital output for system designers. However, the "unusable" or "limited" nature of high-sensitivity modes (like SF11/12 at BW=31.25 kHz) is being actively challenged by ongoing research into Doppler compensation techniques. Studies have proposed and evaluated various methods, including pre-compensation at the transmitter based on predicted Doppler shifts (Ullah *et al.*, 2025) [10], and hardware-based compensation using LoRa chipsets themselves [11]. The successful implementation of such techniques could potentially reclaim the usability of these high-sensitivity modes, altering the operational boundaries defined by the original NORBY experiments and making the trade-off between link budget and Doppler robustness less severe. This highlights that the practical limits are not fixed but depend on the sophistication of the transceivers and network management systems employed.

Implications for SatIoT Design in a Competitive Landscape

The findings underscore the critical trade-offs in LoRa parameter selection for LEO SatIoT. The need to balance sensitivity against Doppler tolerance remains central. However, the SatIoT landscape is evolving rapidly. While LoRaWAN, often operating in unlicensed ISM bands, has established a significant presence with operators like Lacuna Space [12] and EchoStar Mobile [13], it faces growing comparison and potential competition from standardized cellular technologies adapted for Non-Terrestrial Networks (NTN) under the 3GPP framework (Release 17 and onwards) [14]. Technologies like NB-IoT and LTE-M, operating in licensed spectrum, are being tested and deployed for DtS connectivity [15], offering potential advantages in terms of interference management and integration with existing cellular ecosystems. Furthermore, the evolution within LoRaWAN itself, such as the development of Long Range Frequency Hopping Spread Spectrum (LR-FHSS), aims to improve scalability and robustness against interference in dense DtS scenarios [14]. The choice of technology for SatIoT now involves comparing LoRa/LoRaWAN not only on its intrinsic performance (including Doppler limits) but also against these emerging licensed-band, standardized alternatives.

Broader Context: Constellation Growth and Hybrid Networks

The study by Zadorozhny *et al.* occurred as the LEO SatIoT market was gaining momentum. Since then, the deployment of large LEO constellations dedicated to or supporting IoT has accelerated dramatically [16]. This rapid growth increases the availability of satellite connectivity but also raises questions about spectrum coordination and interference management. A significant trend emerging alongside pure satellite solutions is the development of hybrid terrestrial-satellite networks [13]. These systems allow IoT devices equipped with dual-mode capabilities to seamlessly switch between networks, leveraging terrestrial infrastructure where available and falling back to satellite in remote areas. This approach optimizes cost and performance, and LoRa technology is actively being integrated into such hybrid solutions [13]. The findings of Zadorozhny *et al.* on Doppler limitations are particularly relevant in this hybrid context, as they define the performance envelope specifically for the satellite leg of the communication.

Revisiting Study Limitations

The limitations acknowledged in the original study remain relevant. The results are specific to the ~560 km orbit and the 436.7 MHz UHF band. Extrapolating Doppler impact to different altitudes and frequencies requires careful scaling. However, the fundamental behaviors observed: static Doppler limiting narrow bandwidths and dynamic Doppler limiting high SFs, are expected to hold qualitatively. The growing body of research on Doppler compensation directly addresses the core limitation identified [10, 11]. Furthermore, ongoing deployments by commercial operators across various LEO altitudes and frequency bands (including S-band and potentially others for LoRa-based systems [13]) will provide broader datasets complementing the foundational work done by Zadorozhny *et al.*

CONCLUSION

The research presented by Zadorozhny *et al.* represents a landmark contribution to the field of satellite IoT. By conducting the first dedicated in-orbit flight tests using the NORBY CubeSat, they have provided crucial empirical data on the performance limits of LoRa modulation under the influence of the Doppler effect in a LEO environment.

The study successfully validated the manufacturer's specifications for static Doppler tolerance and, significantly, provided the first direct observation from space of communication failure caused by the dynamic Doppler effect, particularly impacting the high spreading factor mode SF=12. The results clearly mapped out which LoRa configurations (SF/BW combinations) were robust, which suffered reduced communication availability due to static or dynamic Doppler effects, and which were essentially unusable without compensation in a ~560 km orbit.

Viewed through the lens of subsequent developments, this work remains foundational but also highlights the dynamic nature of the field. While the identified Doppler limitations are inherent to the modulation scheme under specific conditions, ongoing advancements in Doppler compensation techniques [10, 11] promise to mitigate these challenges, potentially expanding the usable parameter space for LoRa in LEO. Furthermore, the increasing deployment of commercial LEO IoT constellations [16] and the rise of standardized alternatives like 3GPP NTN [14] place LoRa's performance within a broader competitive context. The trend towards hybrid terrestrial-satellite networks [13] also underscores the need to understand the specific performance envelope of the satellite link, as defined by studies like this one.

The work by Zadorozhny *et al*. underscores the critical importance of considering Doppler effects in the design of LEO SatIoT systems using LoRa. It highlights the fundamental trade-off between achieving maximum sensitivity and maintaining Doppler robustness, while also implicitly pointing towards the future need for sophisticated mitigation strategies or careful parameter selection in the face of growing technological alternatives. The findings provide invaluable guidance for engineers, and the planned future work on NORBY-2 promises to extend these vital findings to other relevant frequency bands.

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