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THE UNIVERSITY OF TEXAS AT AUSTIN RADIONAVIGATION LABORATORY

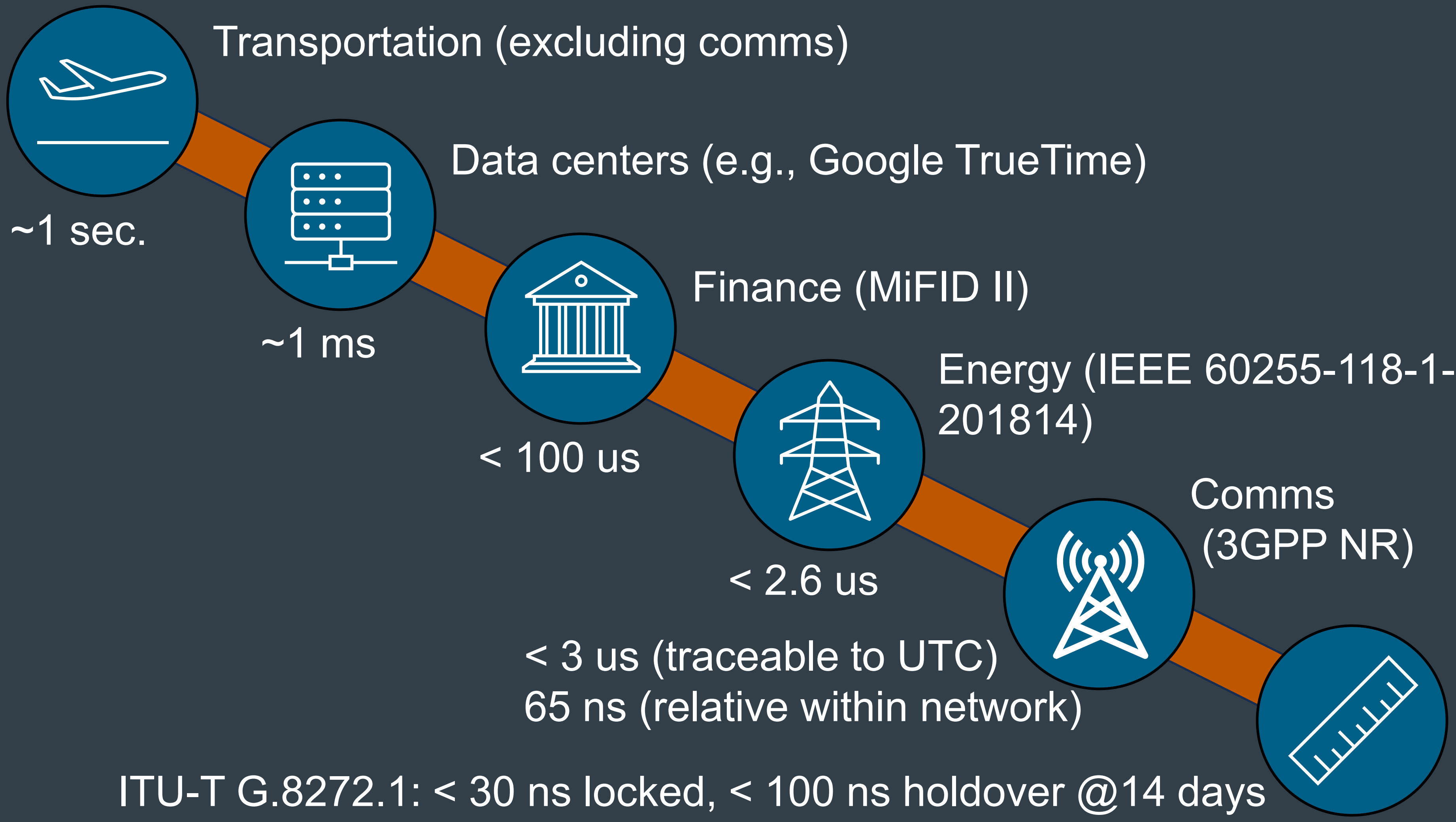
Extracting Precise Timing from LEO Megaconstellations

Todd Humphreys

The University of Texas at Austin

WSTS | May 6, 2026

The key timing accuracy and continuity requirements for the modern world are not so hard to meet.


Transportation (excluding comms)
~1 sec.
Data centers (e.g., Google TrueTime)
~1 ms
Finance (MiFID II)
< 100 us
Energy (IEEE 60255-118-1-201814)
< 2.6 us
Comms (3GPP NR)
< 3 us (traceable to UTC)
65 ns (relative within network)
ITU-T G.8272.1: < 30 ns locked, < 100 ns holdover @14 days

Article

A hybrid optical–wireless network for decimetre-level terrestrial positioning

https://doi.org/10.1038/s41586-022-05315-7

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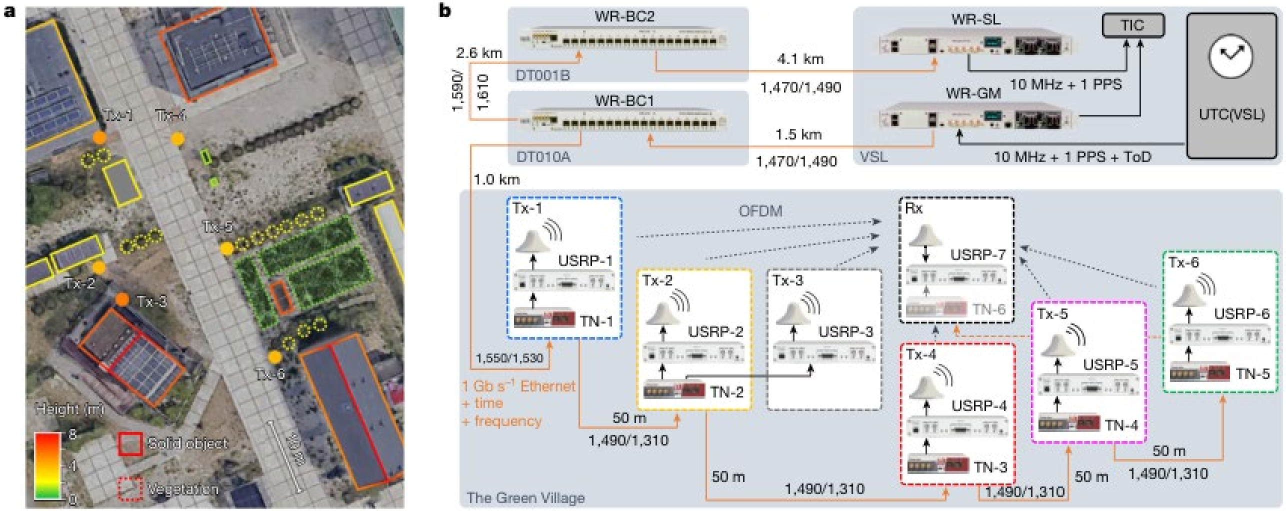
Check for updates

Jeroen C. J. Koelemeij[1], Han Dun[2], Cherif E. V. Diouf[2], Erik F. Dierikx[3], Gerard J. M. Janssen[2] & Christian C. J. M. Tiberius[2]✉

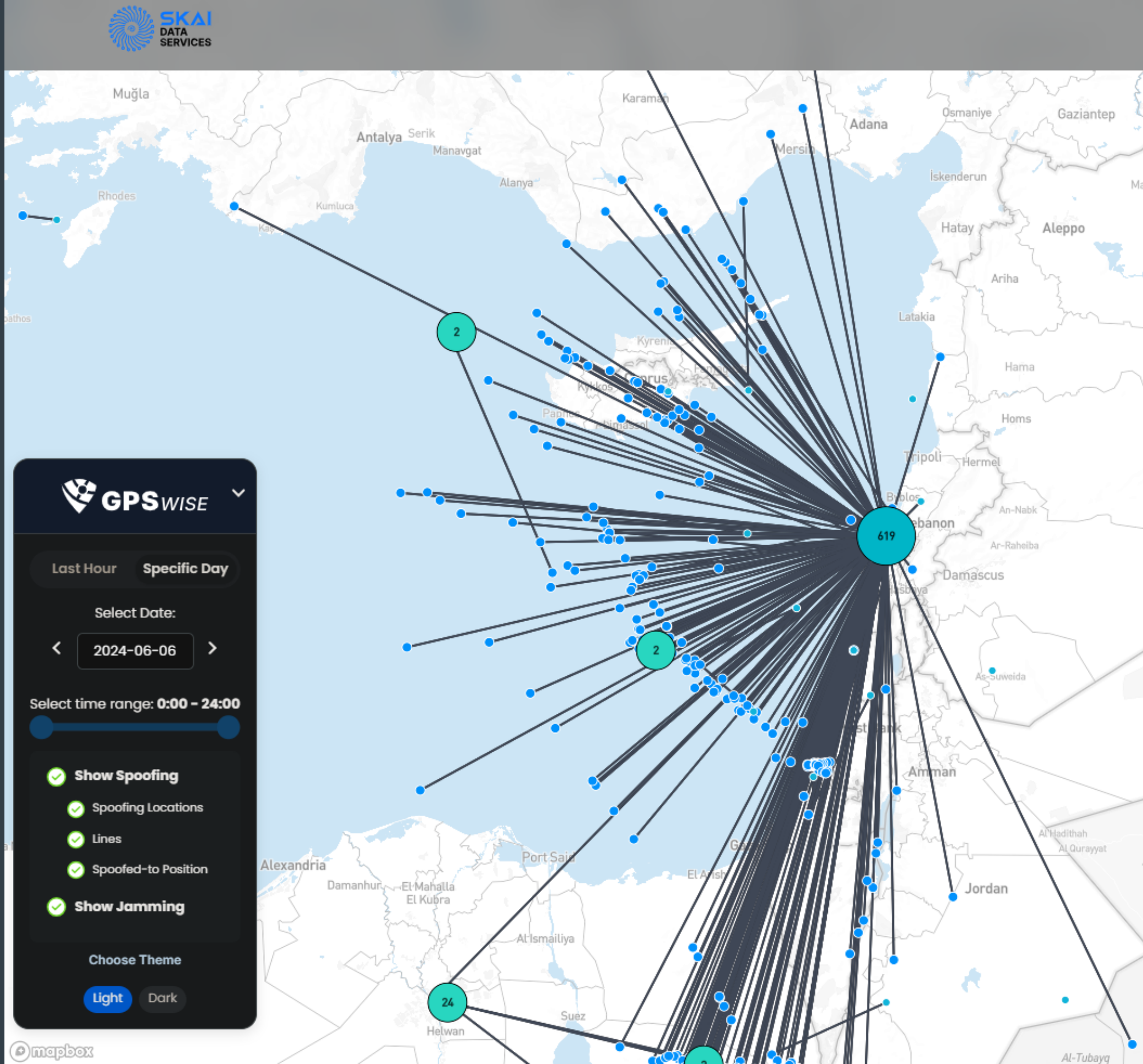


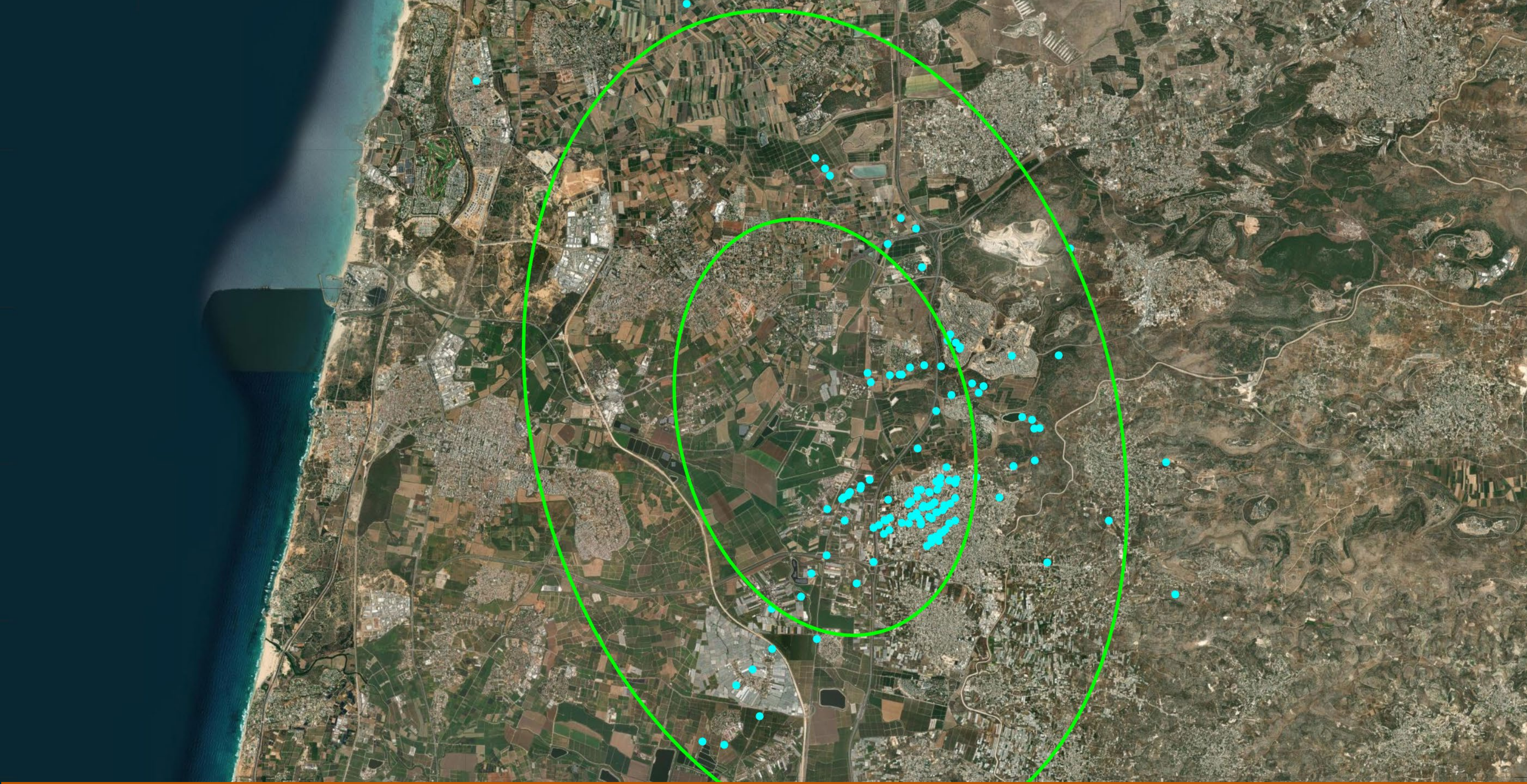
Time accuracy demands beyond ITU-T G.8272.1 are driven by ISAC

Widespread GNSS interference over the past few years has been much more disruptive for positioning than for timing.

Broadcast spoofing:

2024: Hundreds of flights per day spoofed in eastern Mediterranean.





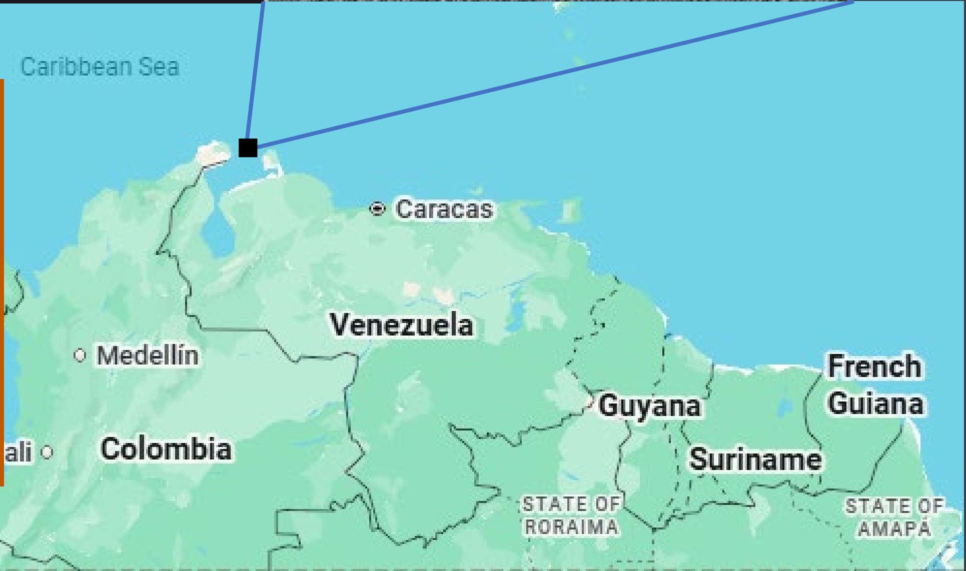
Major source of spoofing around Israel during 2024: an IDF airbase.

Tens of thousands of aircraft and millions of devices were affected by the intense GNSS interference around Israel in 2024. But there were no reports of significant interruption to telecommunications, finance, or Internet provision.

U.S. and Venezuela Jam Caribbean GPS Signals to Thwart Attacks, Raising Flight Hazard

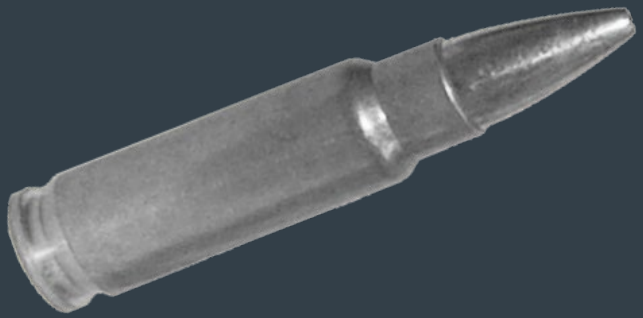
Military brinkmanship between President Trump and Nicolás Maduro of Venezuela has led to an increase in electronic warfare in the region.

The New York Times



Likewise, the GNSS interference near Venezuela in December 2025 and January 2026 disrupted aviation and ground traffic, but not comms, finance, Internet provision.

Secure, accurate, and resilient timing is a fundamentally easier problem than positioning with the same attributes: For timing, accurate position and velocity is typically known, which means the problem reduces from 8 to 2 parameters (clock offset and drift).



The *silver bullet* timing solution is …

- globally available
- as economical to integrate as GNSS
- accurate to <15 ns
- secure against deception
- resilient to interference/outage/indoor use

- Global
- Economical
- Accurate
- Resilient
- Secure

Requirements for Secure Clock Synchronization

Lakshay Narula, *Student Member, IEEE*, and Todd E. Humphreys, *Member, IEEE*

***Abstract*—This paper establishes a fundamental theory of secure clock synchronization. Accurate clock synchronization is the backbone of systems managing power distribution, financial transactions, telecommunication operations, database services, etc. Some clock synchronization (time transfer) systems, such as the global navigation satellite systems, are based on one-way communication from a master to a slave clock. Others, such as the network transport protocol, and the IEEE 1588 precision time protocol (PTP), involve two-way communication between the master and slave. This paper shows that all one-way time transfer protocols are vulnerable to replay attacks that can potentially compromise timing information. A set of conditions for secure two-way clock synchronization is proposed and proved to be necessary and sufficient. It is shown that IEEE 1588 PTP, although a two-way synchronization protocol, is not compliant with these conditions, and is therefore insecure. Requirements for secure IEEE 1588 PTP are proposed, and a second example protocol is offered to illustrate the range of compliant systems.**

DCF77 [6], etc.); both wired and wireless clock synchronization are used extensively. Synchronization by GNSS is the method of choice in systems with the most stringent accuracy requirements. Equipped with atomic clocks synchronized to the most accurate time standards available, GNSS satellites can synchronize any number of stations on Earth to within a few tens of nanoseconds [7]. NTP is usually only accurate to a few milliseconds, but essentially comes for free whenever the host device is connected to a network.

One-way clock synchronization protocols are based on unidirectional communication from the time master station, A, to the slave station, B. In such protocols, A acts as a broadcast station and may send out timing signals either continuously or periodically. The principal drawback of one-way wireless clock synchronization protocols is their vulnerability to delay

Secure timing requires bi-directional signaling with known minimum path latency between nodes being synchronized.

There is no silver bullet, nor should we feel entitled to one.

But over the past 5 years several *bronze bullets* have emerged. These are good if imperfect solutions among which at least one is probably adequate for your needs.

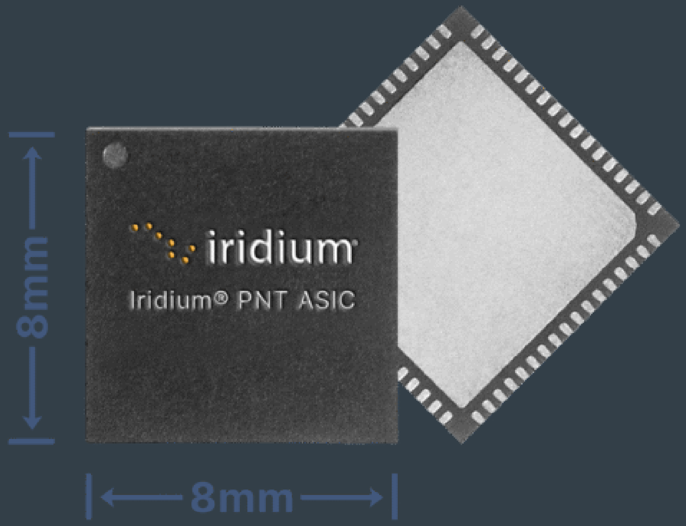
Multi-constellation, multi-frequency GNSS with Galileo OSNMA

- Global
- Economical
- Accurate
- Resilient
- Secure

Optical time distribution over metro-sized areas with White Rabbit (IEEE 1588-2019 HA)

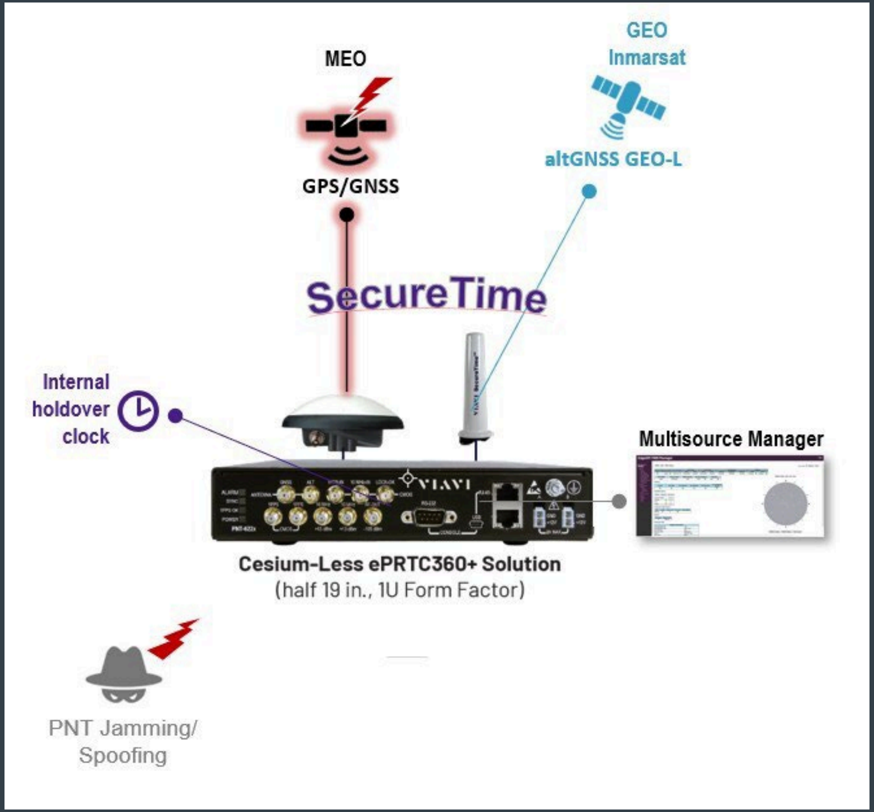
- Global
- Economical
- Accurate
- Resilient
- Secure

Iridium PNT (formerly STL): Strong LEO signals with crypto tags



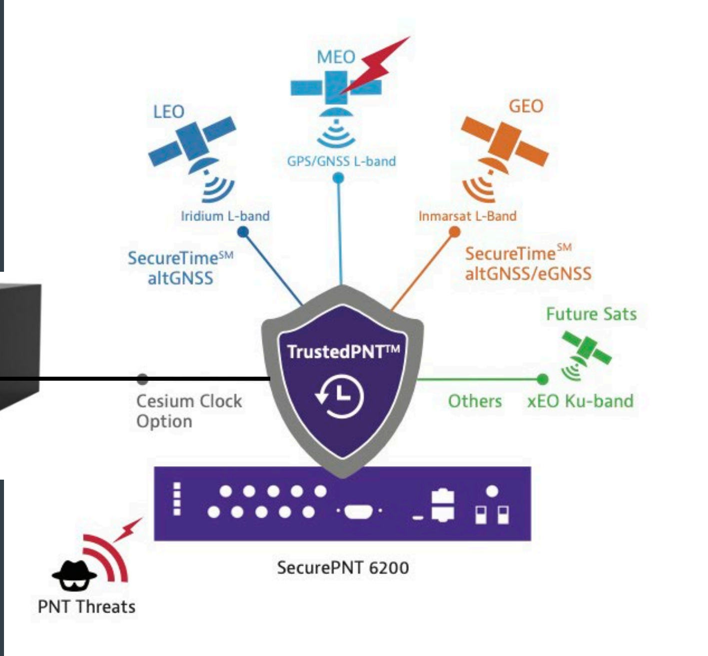
- Global
- Economical
- Accurate
- Resilient
- Secure

VIAVI ePRTC360+ primary reference time clock

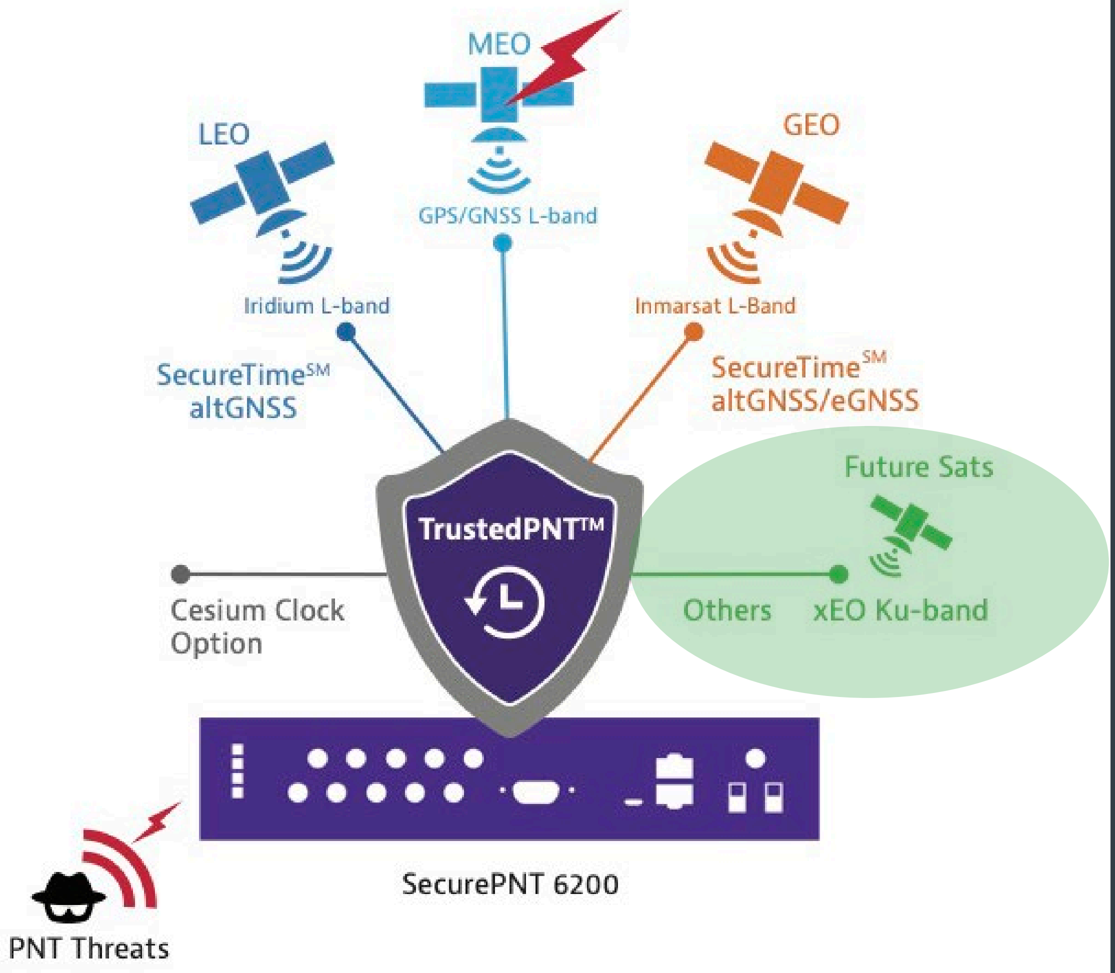


- Global
- Economical
- Accurate
- Resilient
- Secure

VIAVI SecurePNT 6200 with Cesium clock input and STL option



- Global
- Economical
- Accurate
- Resilient
- Secure



MEO
LEO
GEO
GPS/GNSS L-band
Iridium L-band
Inmarsat L-Band
SecureTime℠ altGNSS
SecureTime℠ altGNSS/eGNSS
Future Sats
TrustedPNT™
Cesium Clock Option
Others
xEO Ku-band
SecurePNT 6200
PNT Threats

LEO mega-constellations such as Starlink, OneWeb, and Amazon Leo offer the promise of resilient and secure timing from LEO with unprecedented precision …

… with some caveats.

If tight T is what matters to you,
Then Doppler-based methods eschew!
For P they're ok,
If you don't mind delay,
But for time only ranging will do!

578v3 [eess.SP] 30 Aug 2023

Signal Structure of the Starlink Ku-Band Downlink

Todd E. Humphreys*,
*Department of Aerospace E
†Department of Elec

Abstract—We develop a technique f
tion of the Starlink downlink signal
band and present a detailed picture of
portantly, the signal characterization o
exact values of synchronization sequenc
that can be exploited to produce pse
Such an understanding of the signal
efforts that seek to dual-purpose Starli
navigation, and timing, despite their
broadband Internet provision.

Index Terms—Starlink, signal identi
synchronization, low Earth orbit

I. INTRODUCTI

In addition to revolutionizing
recently-launched broadband low-E
constellations are poised to revolutio
navigation, and timing (PNT). Comp
navigation satellite systems (GNSS),
wider bandwidth, more rapid multi
the possibility of stronger authenti
ephemeris, all of which will enabl
greater resilience against jamming an
With over 3000 satellites already in

1.05302v1 [eess.SP] 9 Jan 2025

Timing Properties of the Starlink Ku-Band Downlink

Wenkai Qin*, Andrew M. Graff†, Zachary
*Department of Aerospace Engineering
†Department of Electrical and (

Abstract—We develop signal capture and analys
for precisely extracting and characterizing the fra
the Starlink constellation's Ku-band downlink trans
aim of this work is to determine whether Starlink
has sufficient short-term stability to support pseud
opportunistic positioning, navigation, and timing (PN
goal is to determine whether frame timing is dis
common time scale such as GPS time. Our analysis r
timing characteristics not previously known that
implications for PNT. On the favorable side, perio
jitter in frame arrival times across all satellite vers
that Starlink hardware is fundamentally capable
term stability required to support GPS-like PNT.
several unfavorable characteristics that, if not ad
make GPS-like PNT impractical: (1) The v1.0 and
satellites exhibit once-per-second abrupt frame ti
ments whose magnitude (as large as 100s of ns) and
unpredictable. Similar discontinuities are also prese
Mini frame timing, though smaller and irregularl
Episodic 15-s periods of high frame jitter routine
the nominal low-jitter frame arrival timing. (3) St
timing is disciplined to GPS time, but only loosely
few ms by adjustments occurring every 15 s; otherw
drift that can exceed 20 ppm. These unfavorable c
are essentially incompatible with accurate PNT. Fort
appear to be a consequence of software design
hardware limitations. Moreover, they could be comp
third-party-provided corrections.

ess.SP] 2 Feb 2026

Pilots and Other Predictable Elements of the Starlink Ku-Band Downlink

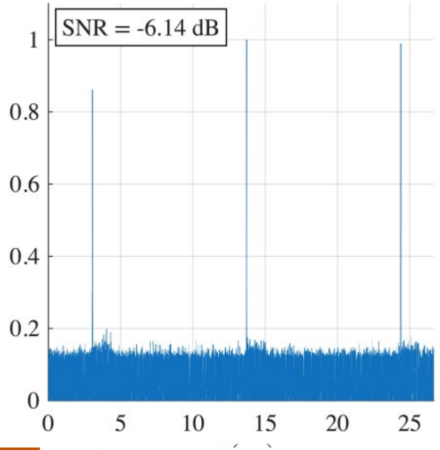
Wenkai Qin*, Mark L. Psiaki†, John R. Bowman†, Todd E. Humphreys*
*Department of Aerospace Engineering and Engineering Mechanics, The University of Texas at Austin
†Department of Aerospace and Ocean Engineering, Virginia Tech

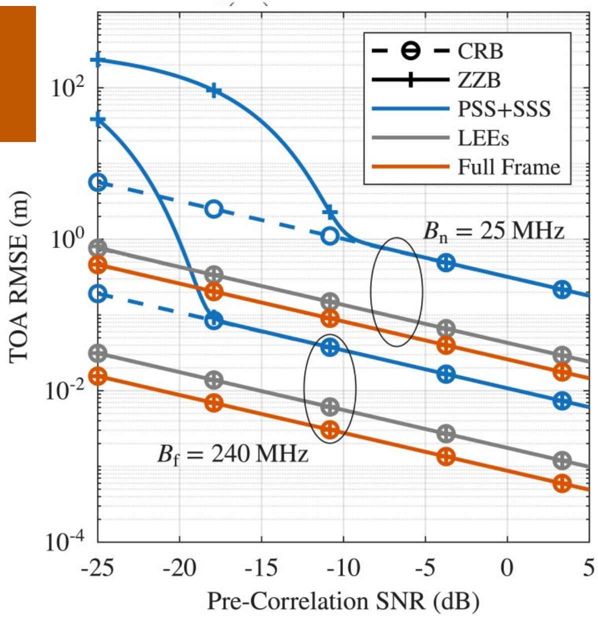
***Abstract*—We identify and characterize dedicated pilot symbols and other predictable elements embedded within the Starlink Ku-band downlink waveform. Exploitation of these predictable elements enables precise opportunistic positioning, navigation, and timing using compact, low-gain receivers by maximizing the signal processing gain available for signal acquisition and time-of-arrival (TOA) estimation. We develop an acquisition and demodulation framework to decode Starlink frames and disclose the explicit sequences of the *edge pilots*—bands of 4QAM symbols located at both edges of each Starlink channel that apparently repeat identically across all frames, beams, channels, and satellites. We further reveal that the great majority of QPSK-modulated symbols do not carry high-entropy user data but instead follow a regular tessellated structure superimposed on a constant reference template. We demonstrate that exploiting frame-level predictable elements yields a processing gain of approximately 48 dB, thereby enabling low-cost, compact receivers to extract precise TOA measurements even from low-SNR Starlink side beams.**

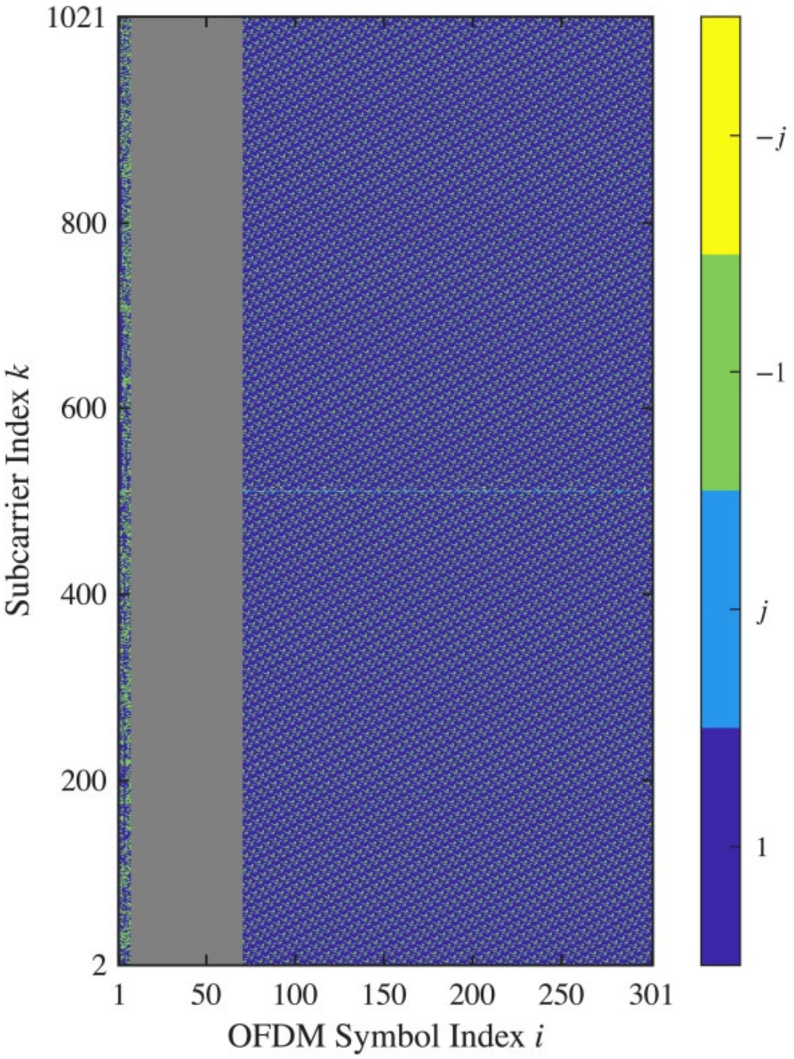
adversarial interference and great potential for PNT precision. But despite the significant potential and low marginal cost of fusing a PNT service with an existing broadband LEO communications service [4], no major constellation operators have announced plans to bring forward a PNT service whose accuracy would match or exceed that of legacy GNSS. Meanwhile, researchers have developed techniques to opportunistically exploit LEO communications signals for PNT, with efforts from several groups already bearing fruit [5]–[13]. While many constellations' signals have been shown to be exploitable [5], [7], [13], Starlink remains the most attractive candidate for opportunistic navigation: with a constellation of over 10,000 satellites, Starlink's dense, geometry-rich coverage reaches nearly the entire globe and offers a promising foundation for multilaterated PNT [14].

Nonetheless, several challenges remain before Starlink-

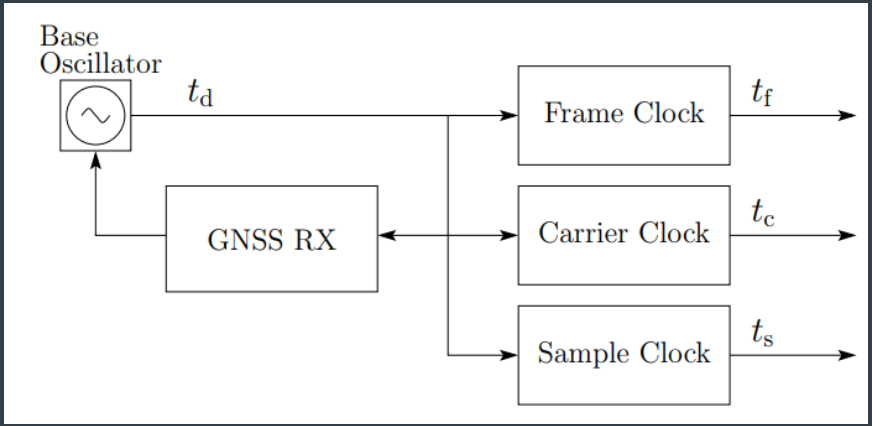
Good

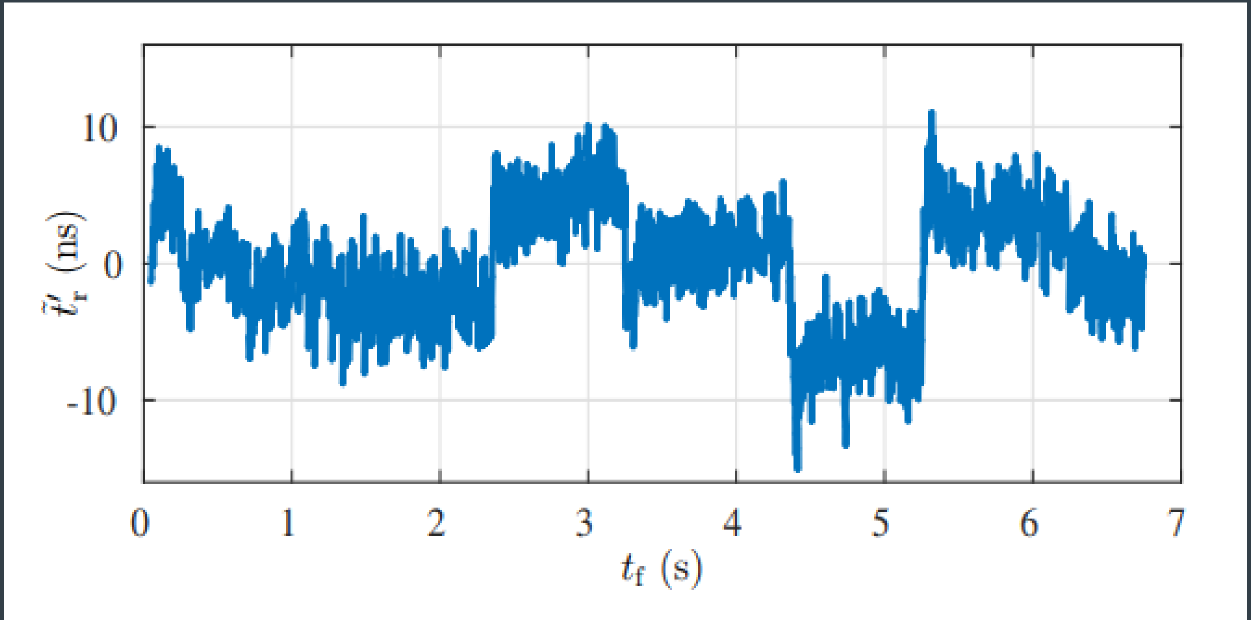

SNR = -6.14 dB
1
0.8
0.6
0.4
0.2
0
0
5
10
15
20
25


CRB
ZZB
PSS+SSS
LEEs
Full Frame
B_n = 25 MHz
B_f = 240 MHz
TOA RMSE (m)
10^2
10^0
10^{-2}
10^{-4}
-25
-20
-15
-10
-5
0
5
Pre-Correlation SNR (dB)

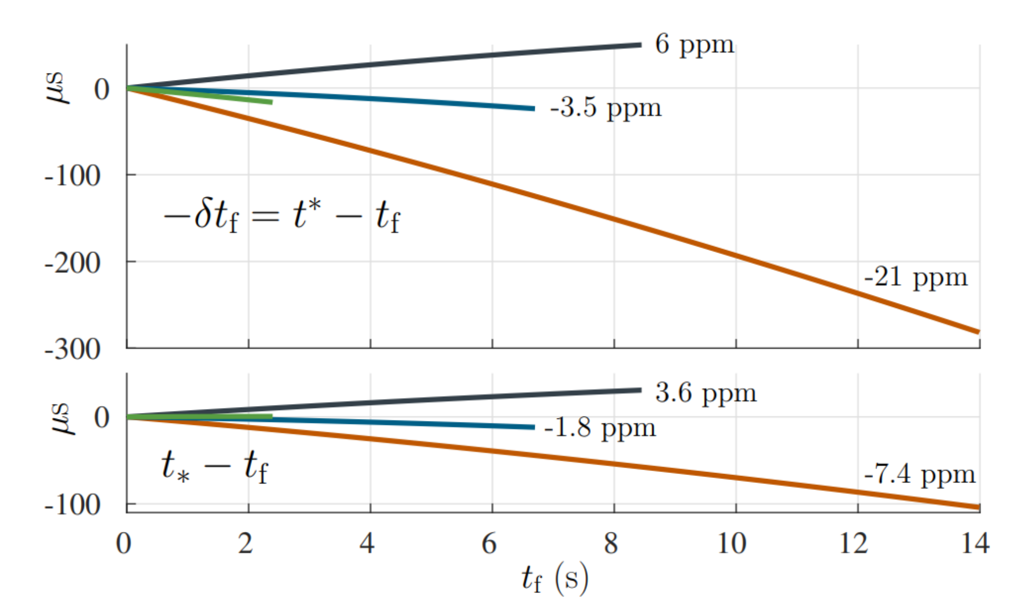

1021
800
600
400
200
2
Subcarrier Index k
1
50
100
150
200
250
301
OFDM Symbol Index i
$-j$
-1
j
1

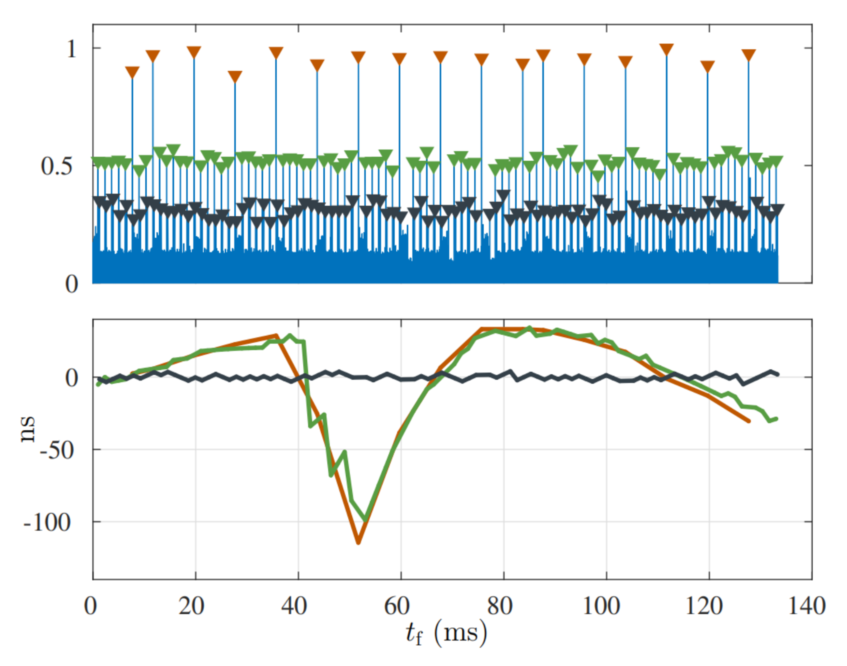
Bad


Base
Oscillator
t_d
Frame Clock
t_f
GNSS RX
Carrier Clock
t_c
Sample Clock
t_s


10
0
-10
$\tilde{t}_r$ (ns)
0
1
2
3
4
5
6
7
t_f (s)

Ugly





Big caveat: Opportunistic use of Starlink signals for time distribution is only possible (for now) with *network aiding*.

A Mock Implementation of Fused LEO GNSS

Samuel C. Morgan*, Zacharias M. Komodromos†, Wenkai Qin†, Zachary L. Clements*,
Andrew Graff‡,W. Jeremy Morrison*, Todd E. Humphreys*
**Department of Aerospace Engineering and Engineering Mechanics, The University of Texas at Austin*
†*Department of Electrical and Computer Engineering, The University of Texas at Austin*
‡*CesiumAstro*

***Abstract*—This paper presents the first experimental demonstration of fused low Earth orbit (LEO) GNSS using pseudorange measurements, achieved through a mock implementation that distributes orbit and clock models as if supplied by the constellation operator. Obtaining resilient and accurate position, navigation, and timing (PNT) from broadband LEO constellations is a topic of vigorous ongoing research. Such constellations offer key advantages over traditional GNSS: proliferated satellite coverage, high power, wideband signals, and the potential for near-zero age-of-data clock and orbit models. SpaceX's expanding Starlink constellation and known frame structure make it an especially compelling candidate for LEO PNT. But recent analysis of its downlink frame timing and its published orbits indicates that stand-alone opportunistic use of Starlink signals (i.e., without cooperation from Starlink nor access to accurate third-party models) could not provide pseudorange-based PNT competitive in performance with traditional GNSS. By contrast, a fused LEO GNSS approach in which Starlink supplies real-time clock and orbit corrections to subscribers, offers a promising pathway to accurate PNT despite frame timing irregularities. This study develops downlink-beam-specific parameterized orbit and clock models tailored to Starlink's frame clock variations. Then, as**

low-resolution position soluti
service offered directly to users
mechanism to support a user t

The use of LEO constellati
studied in the literature [2], [3
plement or backup to GNSS an
ming and spoofing [4]–[8]. Br
have been identified. Table I
terms of deployment costs, av
and dependency on traditional
give an overview of several
while the authors in [11] devel
such a constellation—Xona Sp
LEO GNSS concept of operatio
and methods for extracting hi
using existing communication
LEO GNSS paradigm are pres

Two recent examples of ne

npj | wireless technology

Article

https://doi.org/10.1038/s44459-025-00013-y

Signal parameter estimation and demodulation of the OneWeb Ku-band downlink

Network-Aided Pseudorange-Based LEO PNT from OneWeb

Zacharias M. Komodromos*, Samuel C. Morgan†, Zachary L. Clements†, Wenkai Qin†, W. Jeremy Morrison†, Todd E. Humphreys†

*Department of Electrical and Computer Engineering, The University of Texas at Austin

†Department of Aerospace Engineering and Engineering Mechanics, The University of Texas at Austin

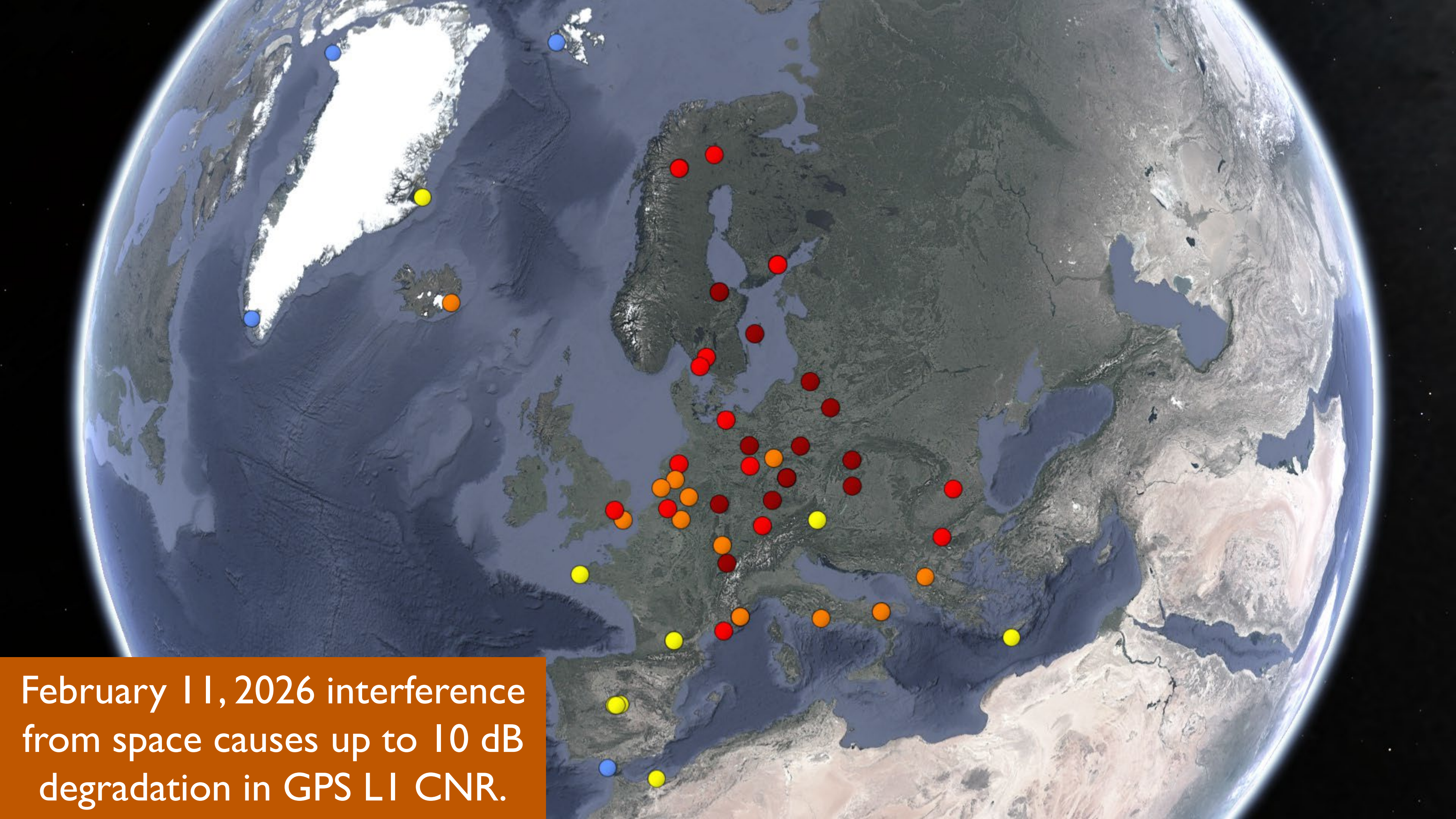
Abstract—**This paper presents a framework and first experimental results for pseudorange-based positioning, navigation, and timing (PNT) exploiting OneWeb's Ku-band downlink signal and a reference network. As the demand for accurate and resilient positioning and timing solutions grows, the proliferation of low Earth orbit (LEO) satellites, including approximately 650 in OneWeb's constellation, offers promising opportunities for powerful new PNT services. Newly discovered synchronization sequences embedded in the OneWeb signal open the way for third-party provision of highly accurate clock and orbital models for each OneWeb satellite. Model parameters would be continually estimated by a sparse network of reference stations at known locations having access to an accurate universal time scale such as UTC. Subscribers to the third party's data feed could treat OneWeb much like a traditional GNSS, extracting pseudorange, carrier phase, and Doppler observables directly from the OneWeb signals, either by exploiting only the newly**

OneWeb's polar orbits offer global coverage, and their space-to-Earth link operates in the reasonably accessible 10.7—12.7 GHz band.

The great majority of opportunistic LEO PNT methods presented in the literature are Doppler-based [13]. But compared to pseudorange-based PNT techniques, Doppler-based techniques have worse timing accuracy by many orders of magnitude (milliseconds vs. nanoseconds), even under optimistic measurement noise and satellite clock offset rate assumptions [4], [14], [15]. Recognizing that many PNT applications of practical interest require accurate timing, we focus on pseudorange-based PNT, or PNT based on time-of-arrival (TOA) measurements.

The extraordinary bandwidth of the OneWeb signal is a

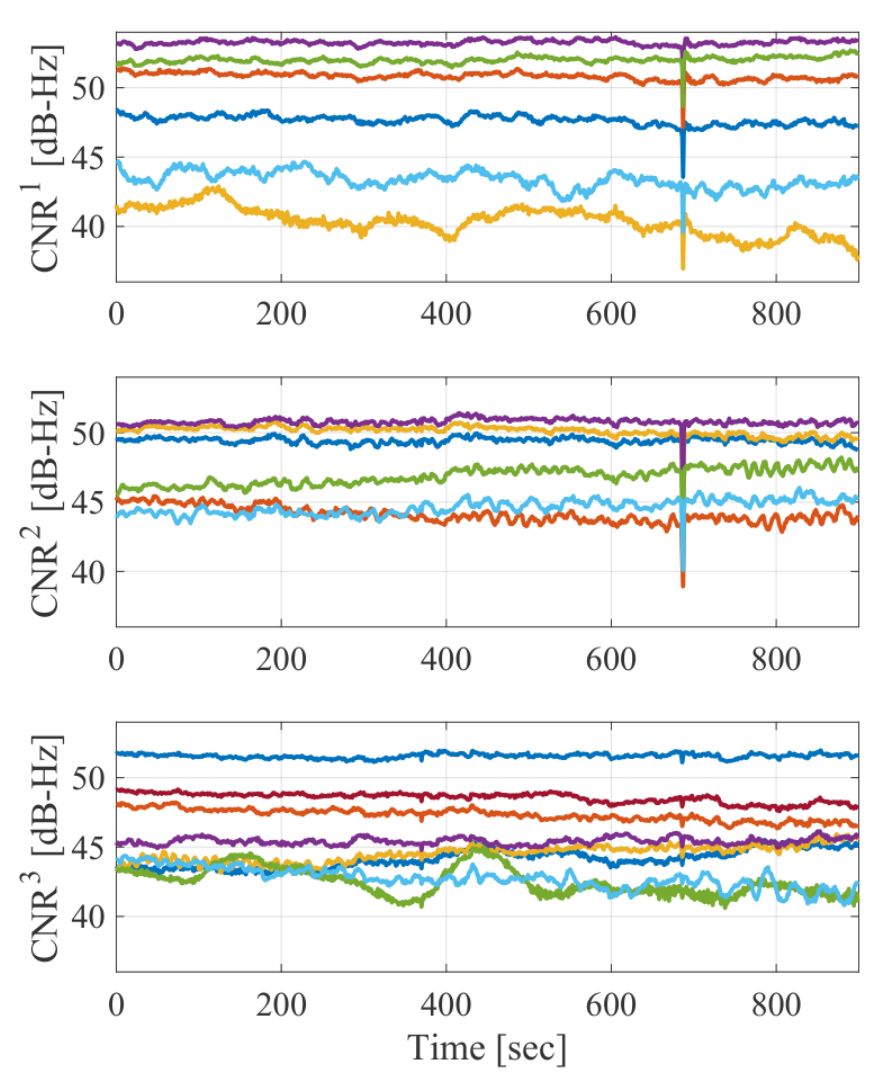
Beware interference from above – it can be continental rather than local/regional, implying that time backups distributed over nation-sized areas yet still dependent on GNSS may not be effective.

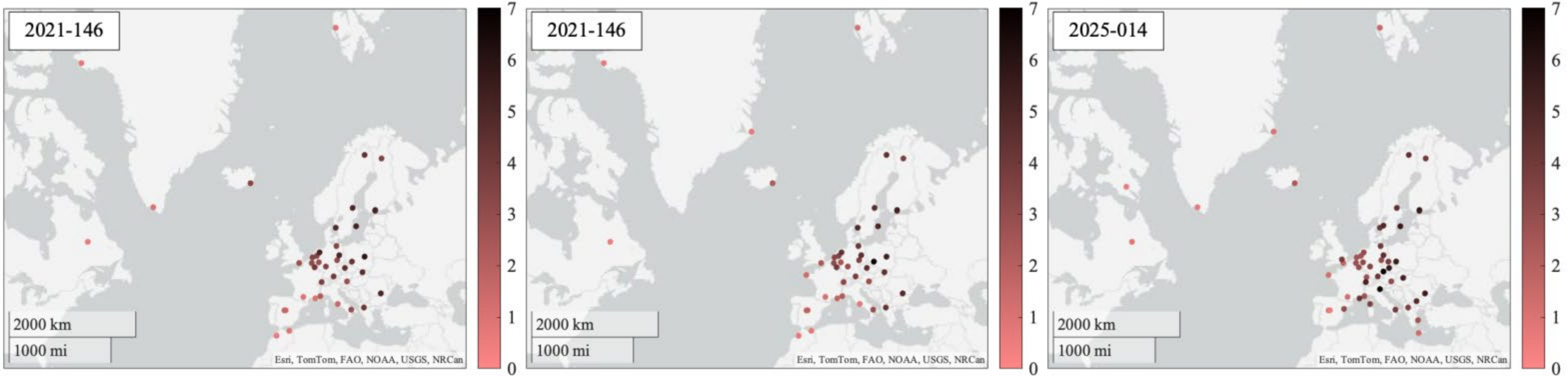


February 11, 2026 interference from space causes up to 10 dB degradation in GPS L1 CNR.

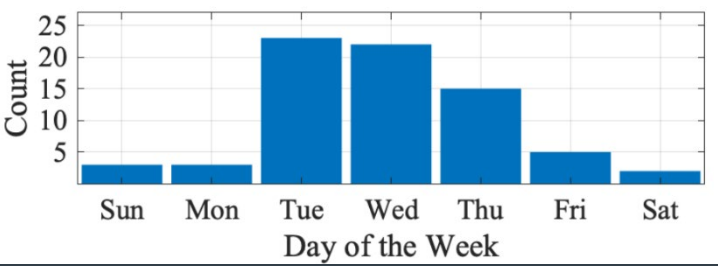
Interference is *transient*, lasting only 3-5 seconds.

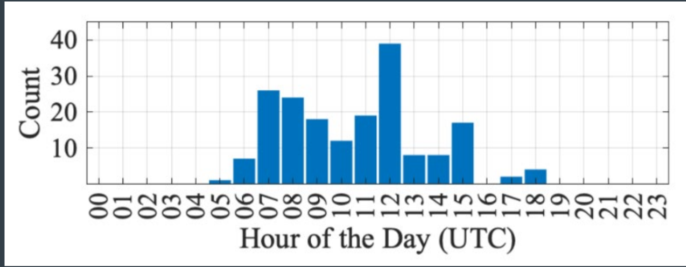
Even weak CNR drops are detectable due to *simultaneous effect* across many continuously operating reference stations.



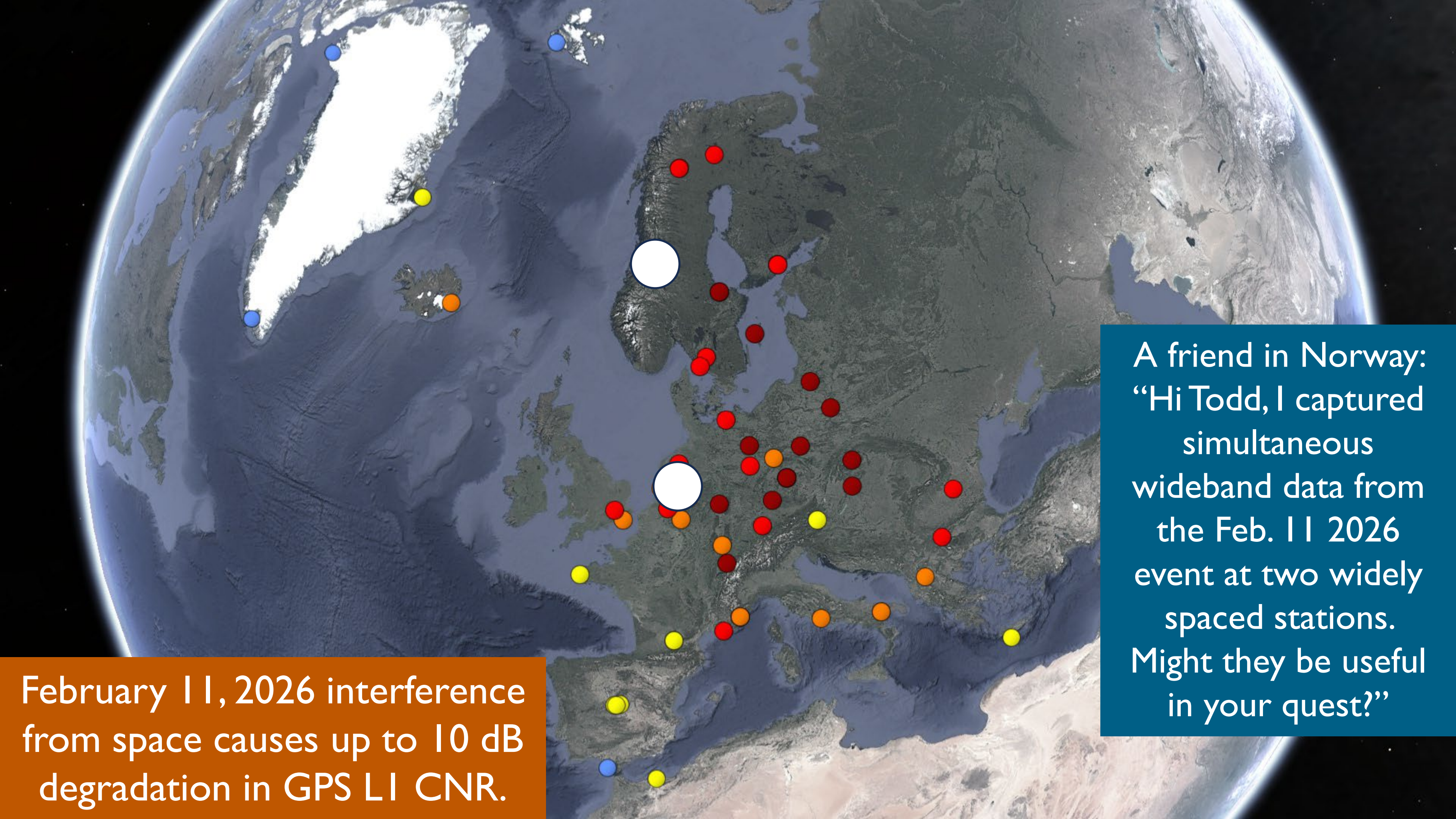


	2019	2020	2021	2022	2023	2024	2025	2026	Total
Count	8	17	5	7	15	9	12	2	75



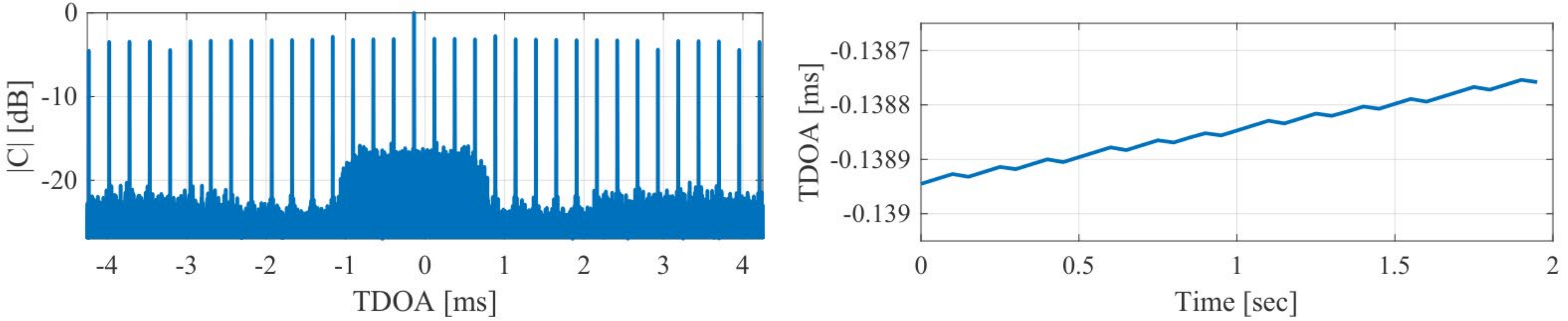


The pattern has been evident since 2019

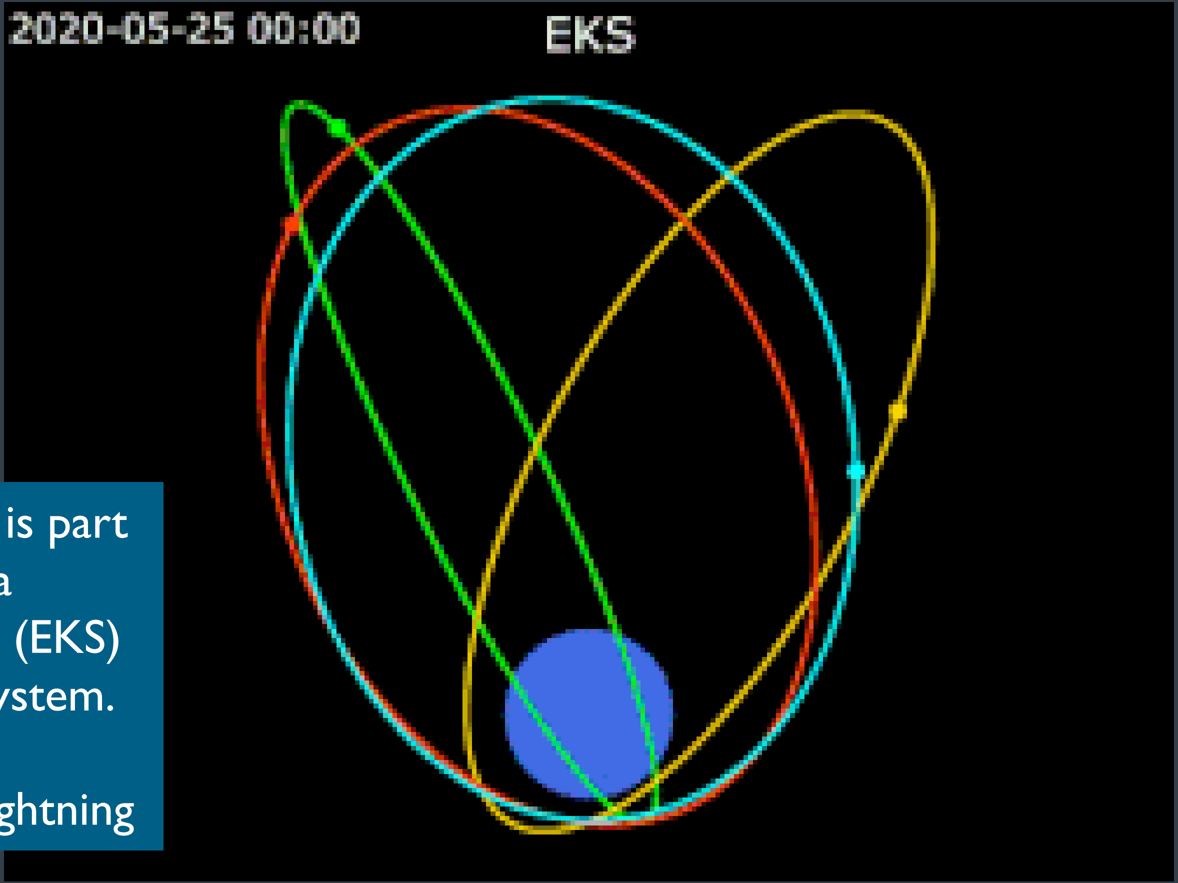


February 11, 2026 interference from space causes up to 10 dB degradation in GPS L1 CNR.

A friend in Norway: “Hi Todd, I captured simultaneous wideband data from the Feb. 11 2026 event at two widely spaced stations. Might they be useful in your quest?”



With some fancy processing, we were able to measure the TDOA time history to better than ~10 ns, which allowed us to obtain a high-confidence identification of the offending SV …



KOSMOS 2546 (green) is part of Russia’s Edinaya Kosmicheskaya Sistema (EKS) early missile warning system.

Молния = Molniya = Lightning

“Нам плевать на ваши драгоценные RNSS-частоты”

REGULAR PAPERS

Chasing Lightning: Detecting, Characterizing, and Identifying a Powerful Space-Based GNSS Interferer

Zachary L. Clements*[1] | Argyris Kriezis[2] | Todd E. Humphreys[1]

[1]Department of Aerospace Engineering and Engineering Mechanics, The University of Texas at Austin, Texas, USA

[2]Stanford University

Correspondence

*Zachary L. Clements, Department of Aerospace Engineering and Engineering Mechanics, The University of Texas at Austin, Austin, TX 78712
Email: zclements@utexas.edu

Abstract

This paper presents the analysis and identification of a space-based Global Navigation Satellite System (GNSS) interference source responsible for scores of powerful transient wide-area interference events over continental Europe, Greenland, and Canada since 2019. While terrestrial or near-terrestrial sources are primarily responsible for the recent uptick in GNSS interference worldwide, space-based interferers are of special concern given their potential for vast geographic reach and their portent of a qualitative escalation in GNSS interference. Based on observables from a network of terrestrial GNSS reference stations collected from 2019 to 2026, this paper (1) develops a received-power-based detection framework; (2) details the spatial, temporal, and spectral patterns of wide-area interference events caused by the source; (3) presents and analyzes identification techniques that seek to optimally blend received-power and

Journal paper will fuller analysis forthcoming.

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