I am Not Afraid of the Jammer: Navigation in GPS-Denied Environments with Terrestrial Cellular Signals

Ad Astra: Navigation with Megaconstellation Starlink LEO Satellites

Zak Kassas, Ph.D.

Director, DOT CARMEN: Center for Automated Vehicle Research with Multimodal AssurEd Navigation
Director, ASPIN Laboratory: Autonomous Systems Perception, Intelligence, and Navigation

Space-Based PNT National Advisory Board Meeting | Redondo Beach, CA | November 16, 2022

GNSS RFI Threats to Aviation

The Ohio State University

Inte

WC

Agenda Item 30: Other i

AN URGENT

(Preser
Associa
Associations

The global navigation s
supporting flight and air
been received on harmf
Telecommunication Uni
and implement measure
GNSS, as it can adversel

Action: The Assembly is
a) to implement appro *System (GNSS) Man* difficulties to ICAO;
b) to recognize the unir caution to the maxi exercises and operati
c) to establish and ens allocated GNSS freq
d) to ensure that contir providers and airspa Instrument Landing S
e) to support the mult (APNT) strategy and ICAO and airspace u

Strategic Objectives:	This wor Strategic

[1] Arabic, Chinese, English, Fre

International Civil Aviation Organization | Organisation de l'aviation civile internationale

Tel.: +1 514-954-8219 ext. 67

Ref.: AN 7/5-20/89

Subject: Strengthening of comr and surveillance (CNS) sy mitigation of interference to gl system (GNSS)

Action required: Note the critic importance of action by States use of the ICAO guidance provi *Navigation Satellite System (* taking any other measures as app

Sir/Madam,

1. I have the honou on 22 June 2020, agreed with tl 40th Session of the Assembly navigation, and surveillance (CN navigation satellite system (GNS

2. The agreed acti A40-WP/82, A40-WP/352 and A its Member States[1], by Saudi Ara Associations (IFATCA), the Int International Air Transport Ass CNS systems and the associated systems, such as GNSS. They hi the safety and efficiency of ai protection of GNSS signals from States and ICAO in coordination

[1] Austria, Belgium, Bulgaria, Croatia, the Cz Lithuania, Luxembourg, Malta, the Netherl

999 Robert-Bourassa Boulevard Montréal, Quebec Canada H3C 5H7 | Tel.: +1 514 Fax: +1 514

Complementary Technologies D

Sections

Andrew Hansen, Ph.D.
Stephen Mackey
Hadi Wassaf, Ph.D.
Vaibhav Shah
Eric Wallischeck
Christopher Scarpone
Michael Barzach
Elliott Baskerville

January 2021
DOT-VNTSC-20-07

Prepared for:
Office of the Assistant Secretary for Research
Department of Transportation

5

Foundational Cyberse Resp Navigation, a

Radiocommunication Bureau (BR)

Circular Letter
CR/488

8 July 2022

To Administrations of Member States of the ITU

Subject: **Prevention of harmful interference to Radio Navigation Satellite Service Receivers in the 1559 – 1610 MHz frequency band**

Following its initial report to the 2019 World Radiocommunication Conference, the Radiocommunication Bureau has been informed of a significant number of cases of harmful interference to the radionavigation-satellite service (RNSS) in the 1 559 – 1 610 MHz frequency band affecting receivers onboard aircrafts and causing degradation or total loss of the service for passenger, cargo and humanitarian flights. In some cases, this has also led to misleading information provided by RNSS receivers to pilots. Based on in-flight monitoring of air transport category aircraft GNSS receivers by one major aircraft manufacturer, 10 843 radio-frequency interference events were detected globally in 2021. The majority of these events occurred in the Middle East region, but several events were also detected in the European, North American and Asian regions.

The Bureau has noted with great concern the increasing number and range of impact of such harmful interference on safety-of-life radiocommunication services used for the navigation of aircraft (see No. **4.10**[1]). In accordance with RR No. **13.2**, the Bureau reported such cases to the Radio Regulations Board (RRB), together with its recommendations.

At its 89th meeting in March 2022, the ITU Radio Regulations Board (RRB) considered the situation and instructed the Bureau to issue a circular letter to the Member States to disseminate its decisions and other background information about the prevention of harmful interference to RNSS receivers.

Following this instruction, the Bureau has prepared the present circular letter. It summarizes the RRB's decisions on the issue, formulates recommendations concerning mitigation of harmful interference to the radionavigation-satellite service and provides the list of the relevant ITU-R reference documents.

[1] *"Member States recognize that the safety aspects of radionavigation and other safety services require special measures to ensure their freedom from harmful interference; it is necessary therefore to take this factor into account in the assignment and use of frequencies."*

International Telecommunication Union • Place des Nations, CH-1211 Geneva 20, Switzerland •
Tel: +41 22 730 5111 • E-mail: itumail@itu.int • Fax: +41 22 733 7256 • www.itu.int


THE TRUTH IS OUT THERE

Navigation with Signals of Opportunity (SOPs)

The Ohio State University

AM/FM Radio

[Moghtadaiee *et al.* '14]
[Park *et al.* '18]
[Psiaki '19]

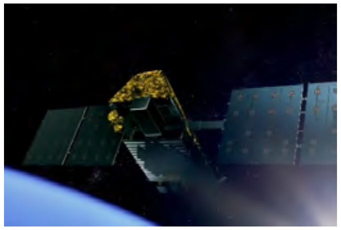
Cellular

[Gentner *et al.* '16]
[Kassas *et al.* '17]
[Shamaei *et al.* '21]

Digital Television

[Thevenon *et al.* '11]
[Yang *et al.* '14]
[Chen *et al.* '16]

Iridium

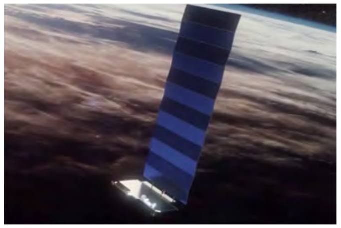


[Benzerrouk *et al.* '19]
[Tan *et al.* '19]
[Orabi *et al.* '21]

Orbcomm

[Rabinowitz *et al.* '00]
[Khalife *et al.* '19]
[Kassas *et al.* '19]

Starlink



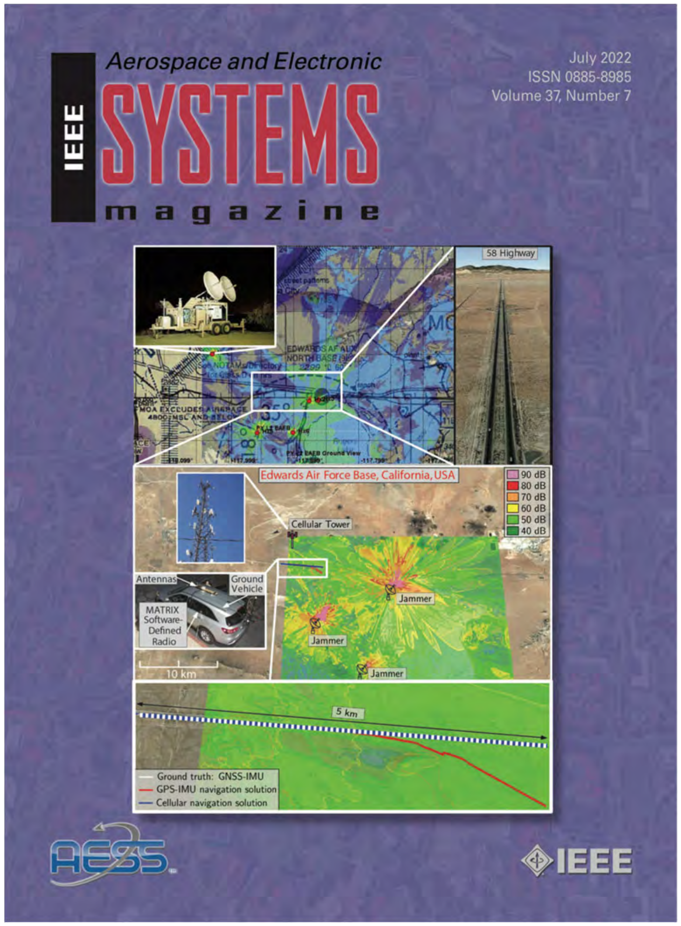
[Khalife *et al.* '20]
[Iannucci *et al.* '20]
[Kassas *et al.* '21]

Ground Vehicle Navigation with Cellular SOPs in a GPS-Jammed Environment at NAVFEST

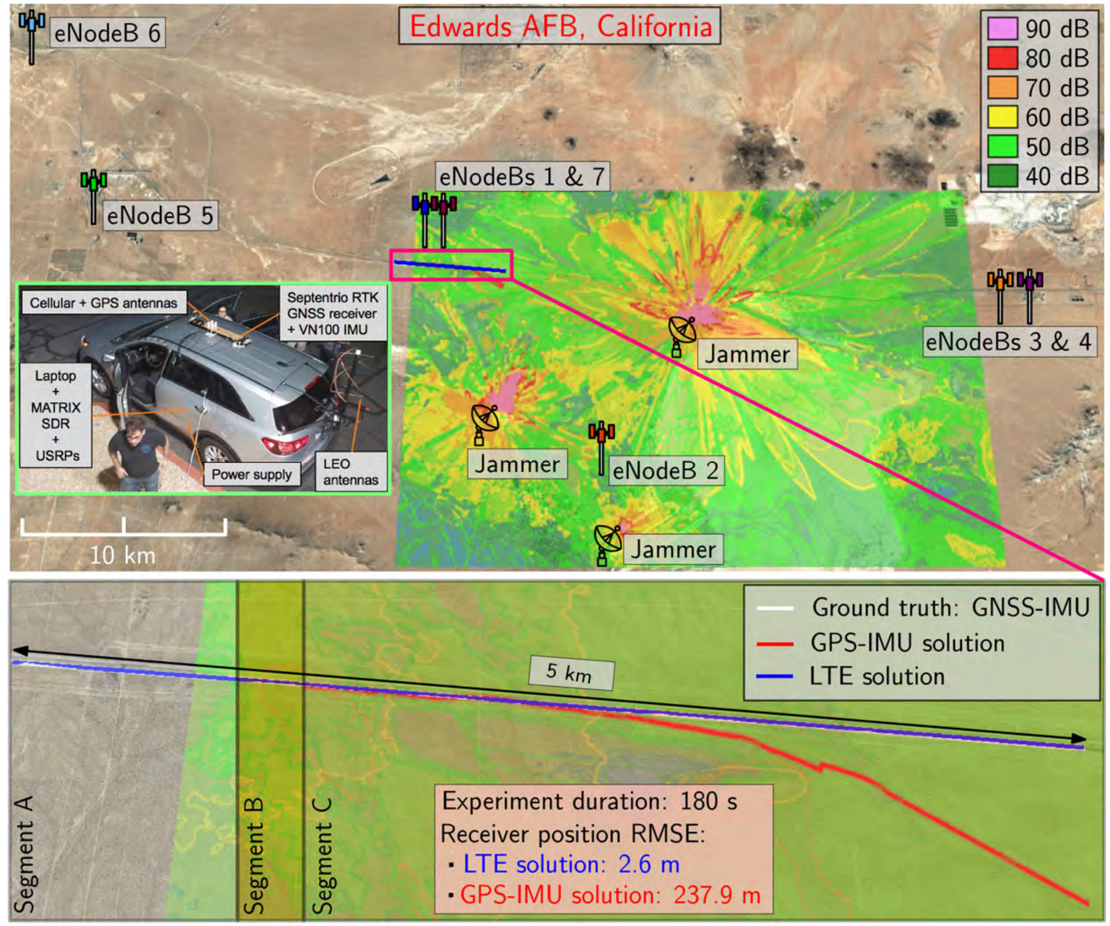
The Ohio State University

Ground Vehicle Navigation at NAVFEST

THE OHIO STATE UNIVERSITY



Kassas, Khalife, Abdallah, & Lee (2022). I Am Not Afraid of the GPS Jammer: Resilient Navigation via Signals of Opportunity in GPS-Denied Environments. *IEEE Aerospace and Electronic Systems Magazine* (July 2022 cover article).



Kassas, Abdallah, & Lee (2022). Demo: I am not afraid of the GPS jammer: exploiting cellular signals for accurate ground vehicle navigation in a GPS-denied environment. *ACM Workshop on Automotive and Autonomous Vehicle Security* (Best demo award runner-up).

[redacted]

THE OHIO STATE UNIVERSITY

High-Altitude Aircraft Navigation with Terrestrial Cellular SOPs

Cellular 4G LTE SOPs

4G

Gentner *et al.*, *IEEE/ION PLANS*, 2016

Driusso *et al.*, *IEEE TVT*, 2017

Del Peral-Rosado *et al.*, *IEEE Access*, 2018

Lee *et al.*, *ICCAS*, 2019

Shamaei & Kassas, *ION GNSS+* , 2019

Yang *et al.*, *ION ITM*, 2020

Abdallah & Kassas, *IEEE TVT*, 2021

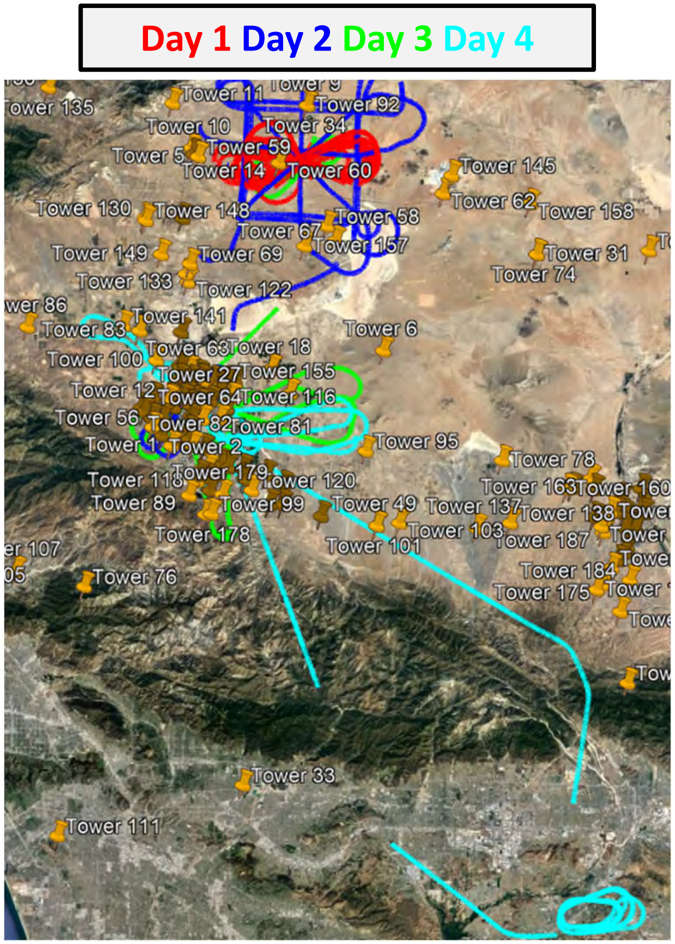
Wang *et al.*, *IEEE TAES*, *2021*

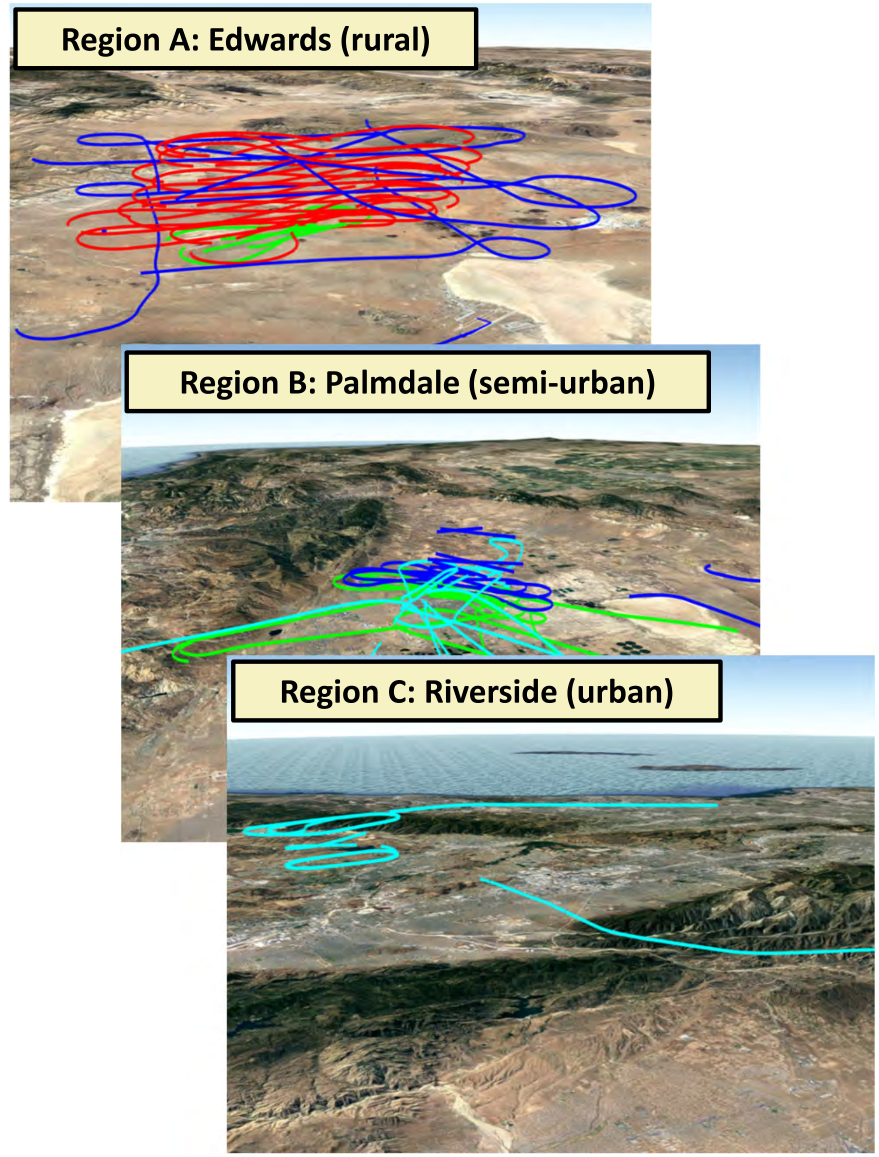
What About High-Altitude Aircraft Navigation?

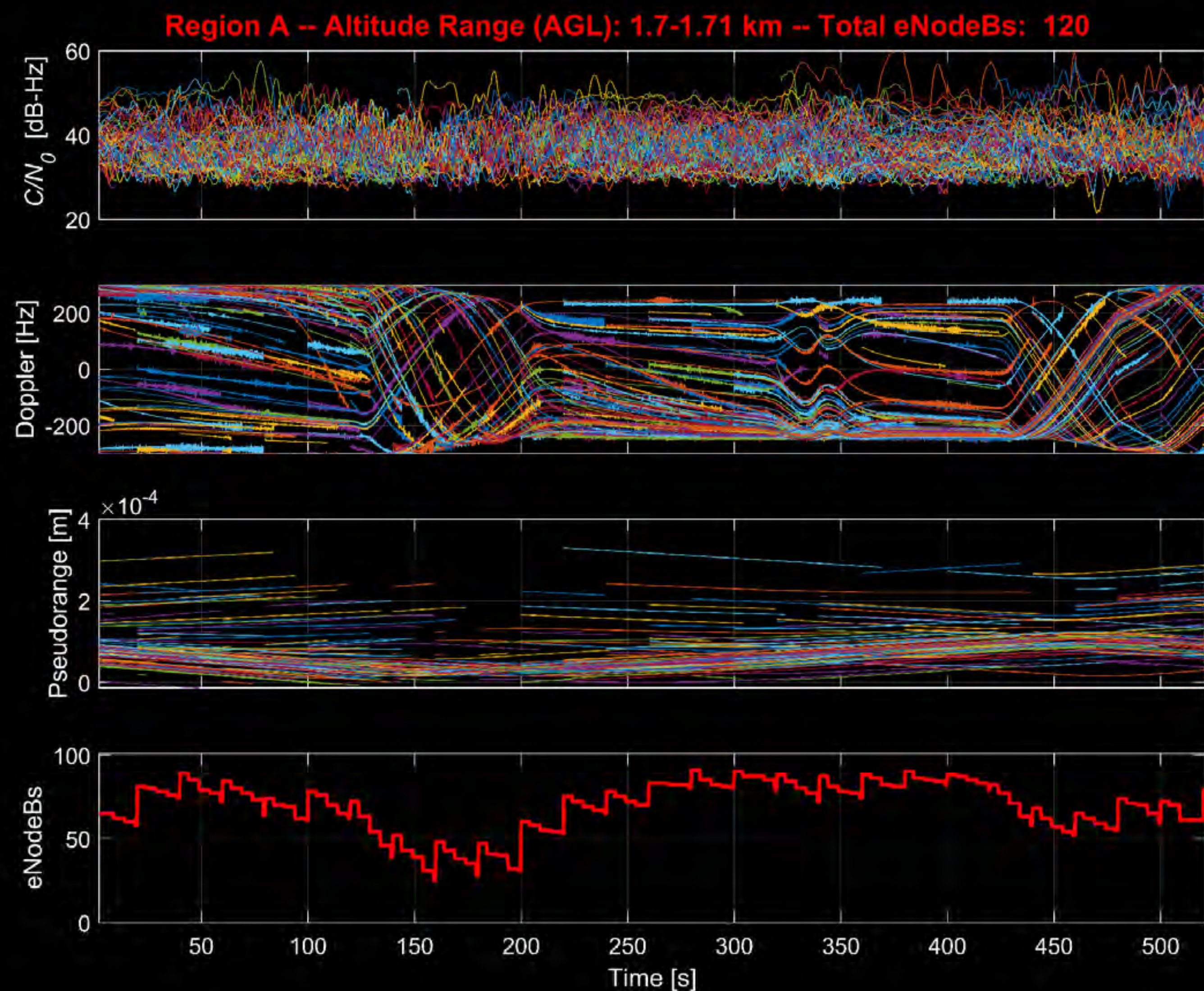
ASPiN

U.S. AIR FORCE

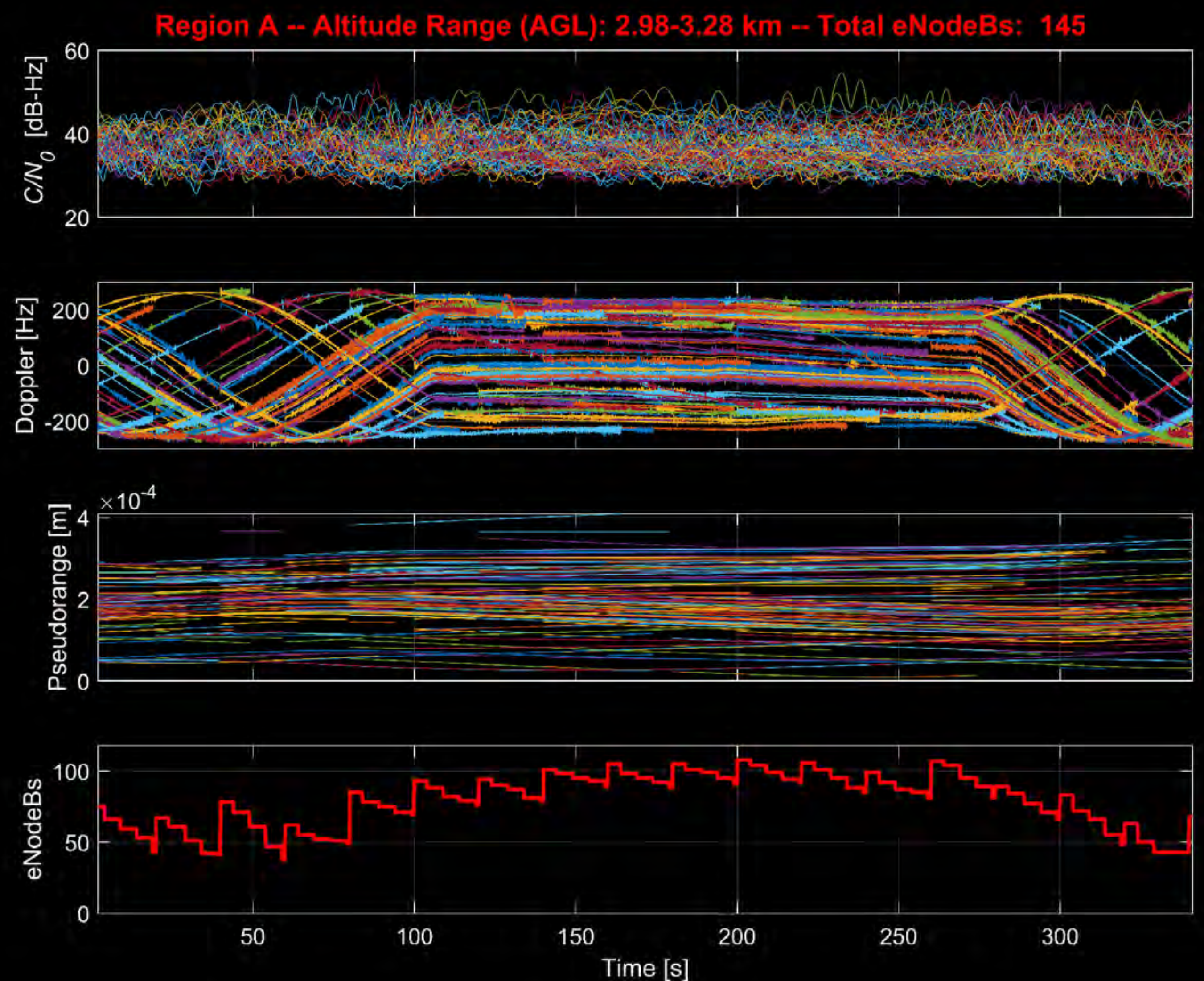
Signals of opportunity for **N**avigation **I**n **F**requency-**F**orbidden **E**nvi**R**onments


Day 1 Day 2 Day 3 Day 4
Tower 135
Tower 11
Tower 9
Tower 92
Tower 10
Tower 34
Tower 5
Tower 59
Tower 14
Tower 60
Tower 145
Tower 62
Tower 158
Tower 130
Tower 148
Tower 58
Tower 67
Tower 157
Tower 149
Tower 69
Tower 31
Tower 74
Tower 133
Tower 122
Tower 83
Tower 141
Tower 6
Tower 100
Tower 63
Tower 18
Tower 27
Tower 155
Tower 12
Tower 64
Tower 116
Tower 56
Tower 82
Tower 81
Tower 95
Tower 1
Tower 2
Tower 78
Tower 118
Tower 179
Tower 120
Tower 163
Tower 160
Tower 89
Tower 99
Tower 49
Tower 137
Tower 138
Tower 178
Tower 103
Tower 187
Tower 101
Tower 184
Tower 76
Tower 175
Tower 33
Tower 111

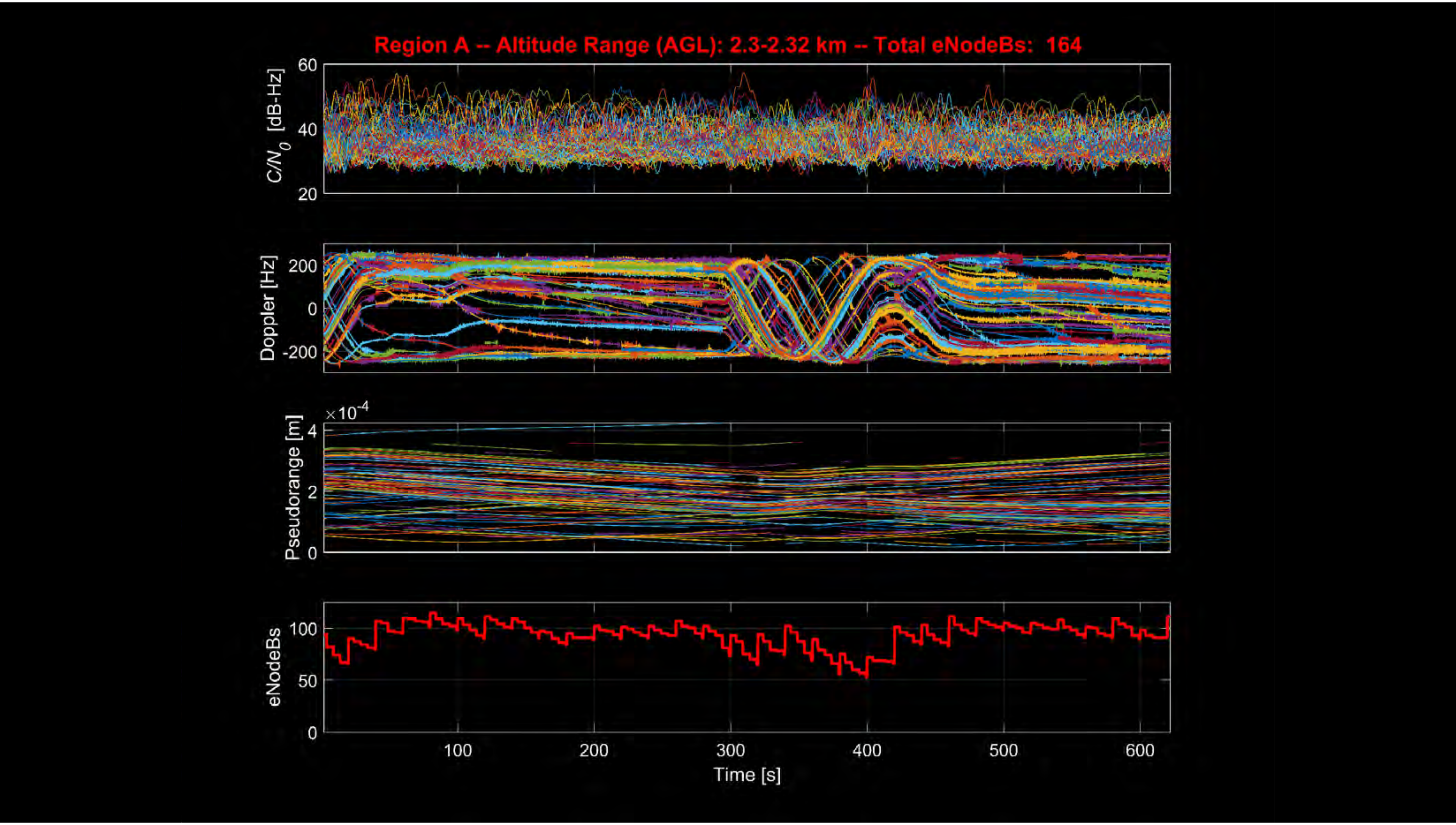

Region A: Edwards (rural)
Region B: Palmdale (semi-urban)
Region C: Riverside (urban)



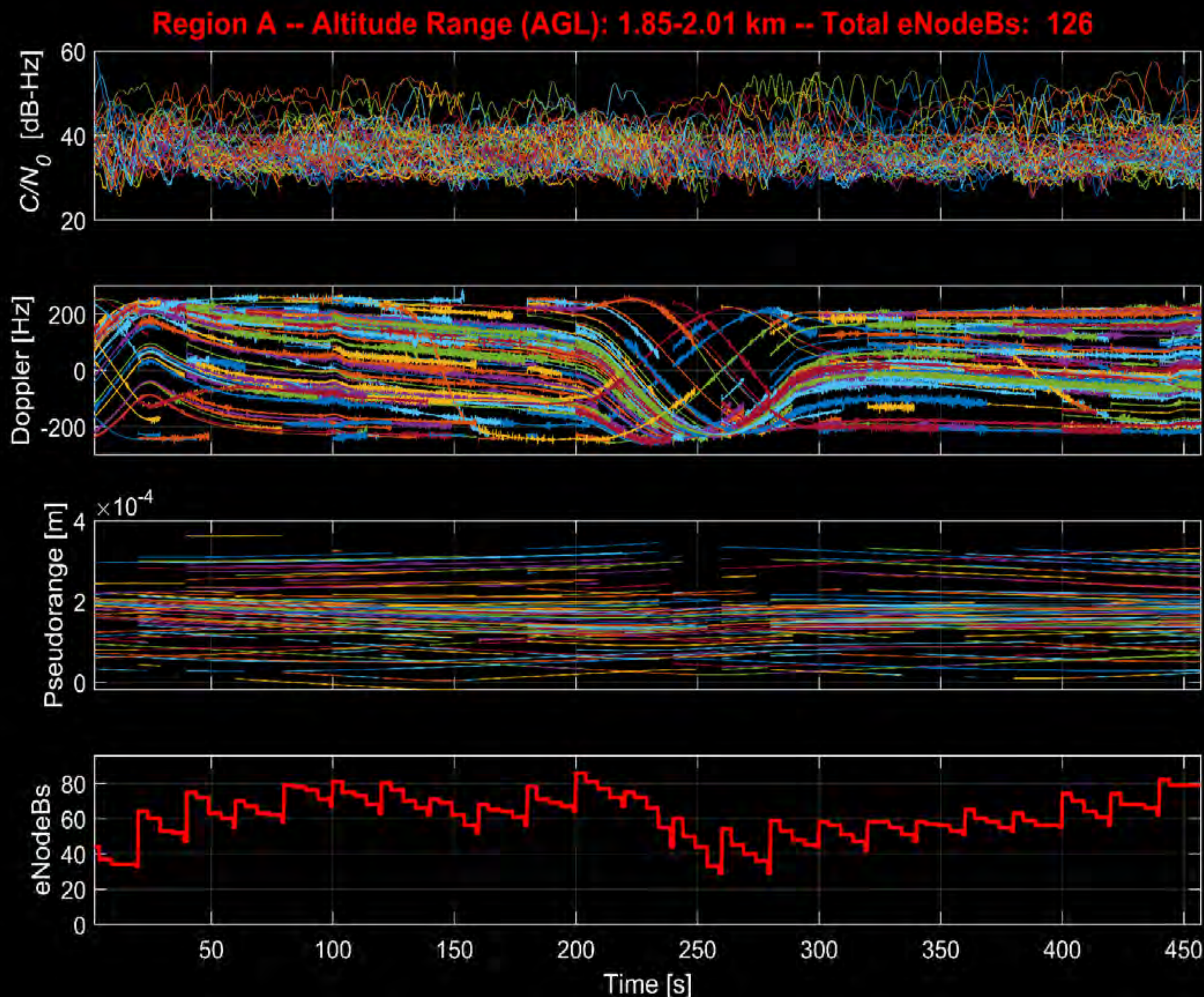
Region A -- Altitude Range (AGL): 1.7-1.71 km -- Total eNodeBs: 120
C/N0 [dB-Hz]
Doppler [Hz]
Pseudorange [m]
×10^-4
eNodeBs
Time [s]



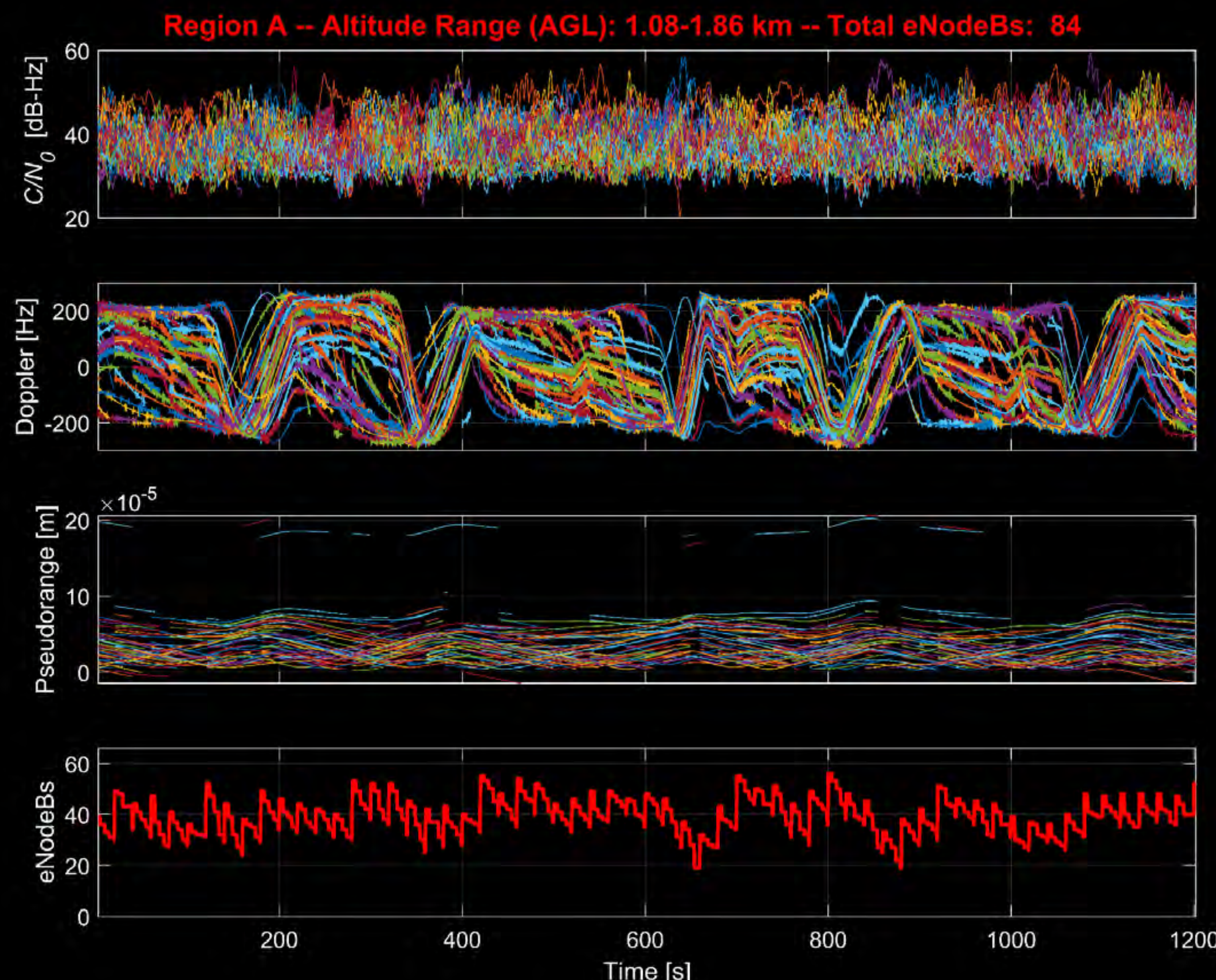
Region A -- Altitude Range (AGL): 2.98-3.28 km -- Total eNodeBs: 145
C/N0 [dB-Hz]
Doppler [Hz]
×10^-4
Pseudorange [m]
eNodeBs
Time [s]



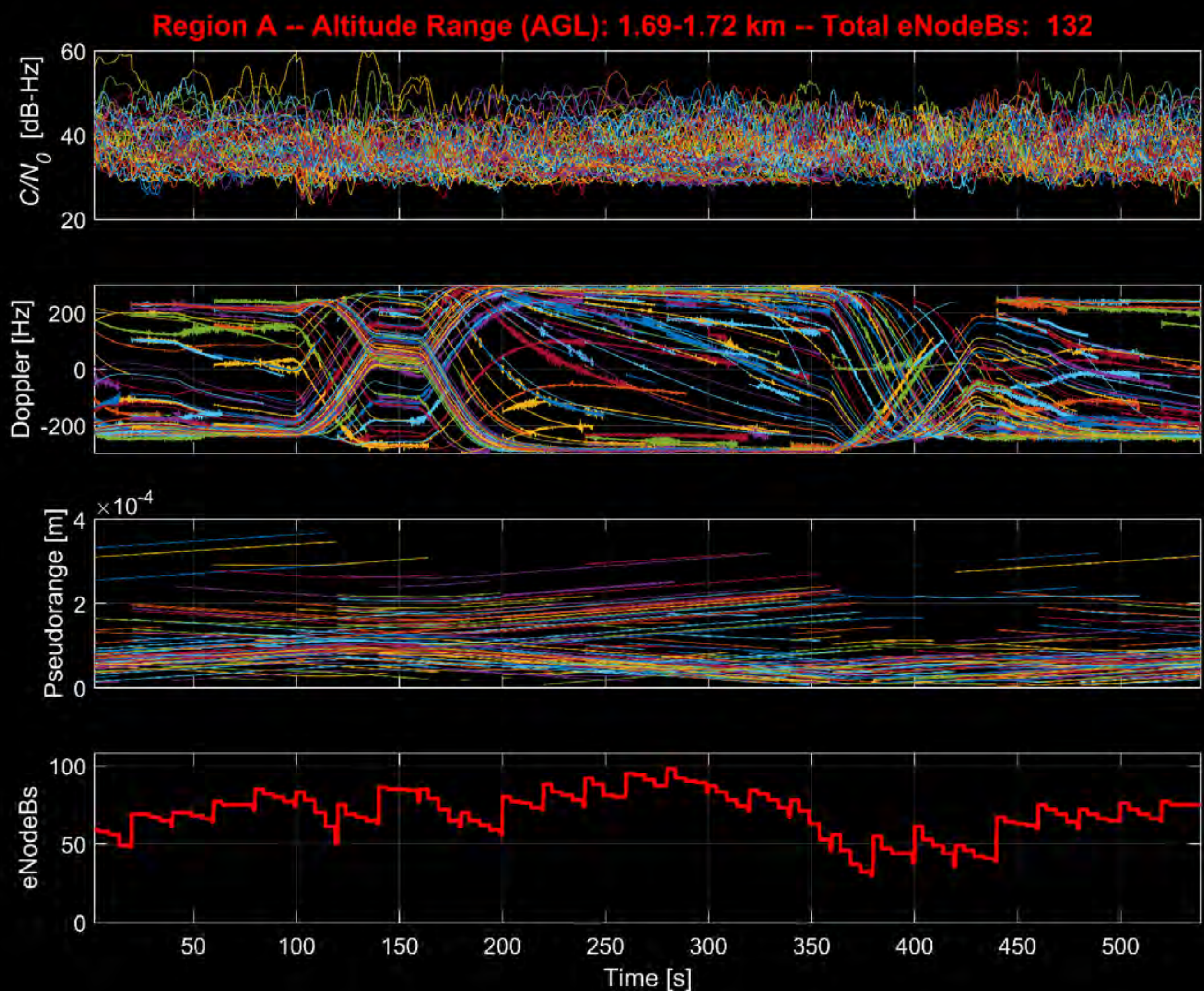
Region A -- Altitude Range (AGL): 2.3-2.32 km -- Total eNodeBs: 164
C/N0 [dB-Hz]
60
40
20
Doppler [Hz]
200
0
-200
×10-4
Pseudorange [m]
4
2
0
eNodeBs
100
50
0
100
200
300
400
500
600
Time [s]



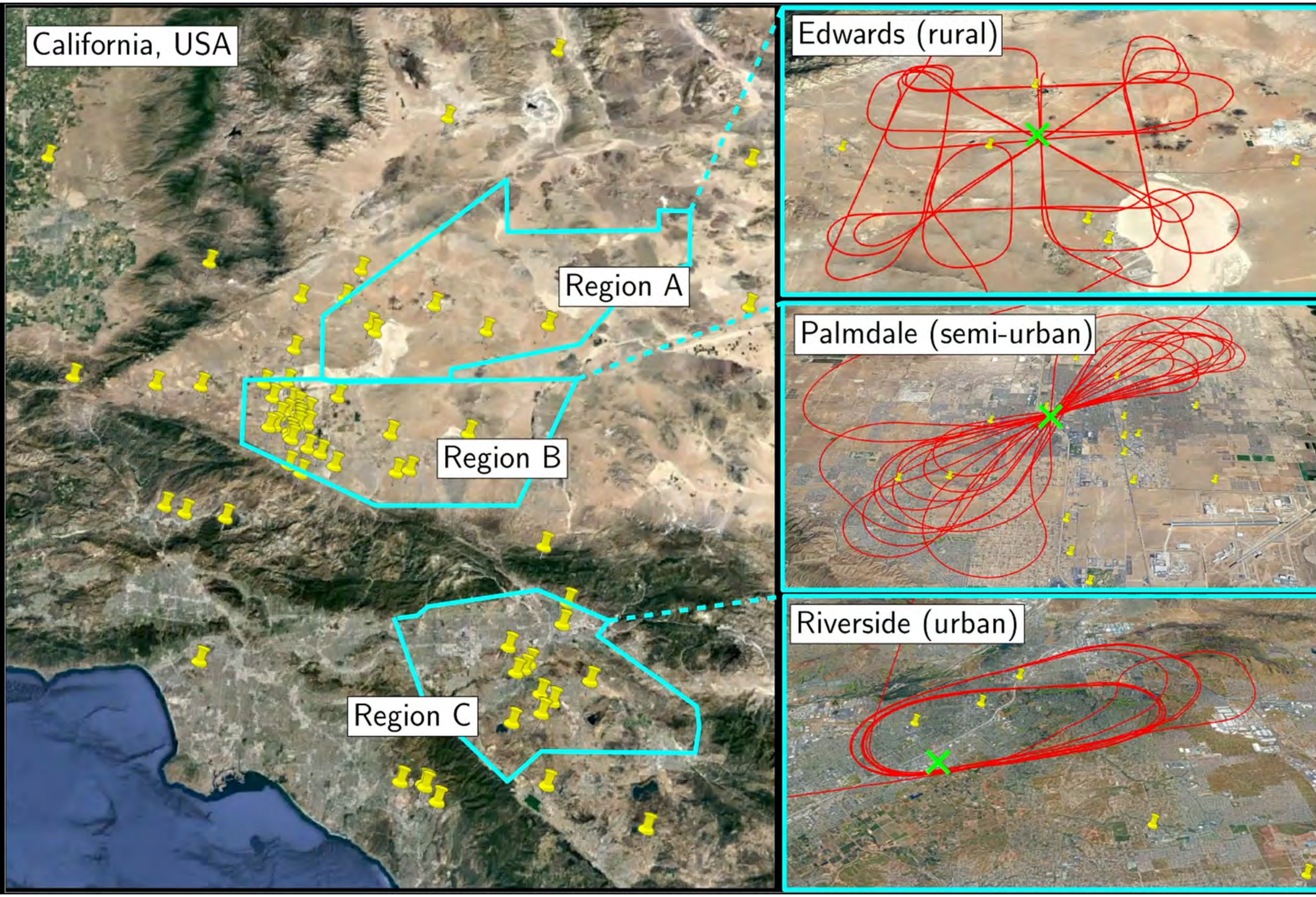
Region A -- Altitude Range (AGL): 1.85-2.01 km -- Total eNodeBs: 126
C/N0 [dB-Hz]
20
40
60
Doppler [Hz]
-200
0
200
Pseudorange [m]
×10^-4
0
2
4
eNodeBs
0
20
40
60
80
50
100
150
200
250
300
350
400
450
Time [s]



Region A -- Altitude Range (AGL): 1.08-1.86 km -- Total eNodeBs: 84
C/N0 [dB-Hz]
60
40
20
Doppler [Hz]
200
0
-200
Pseudorange [m]
×10^-5
20
10
0
eNodeBs
60
40
20
0
200
400
600
800
1000
1200
Time [s]



Region A -- Altitude Range (AGL): 1.69-1.72 km -- Total eNodeBs: 132
C/N0 [dB-Hz]
Doppler [Hz]
Pseudorange [m]
×10^-4
eNodeBs
Time [s]


California, USA
Region A
Region B
Region C
Edwards (rural)
Palmdale (semi-urban)
Riverside (urban)

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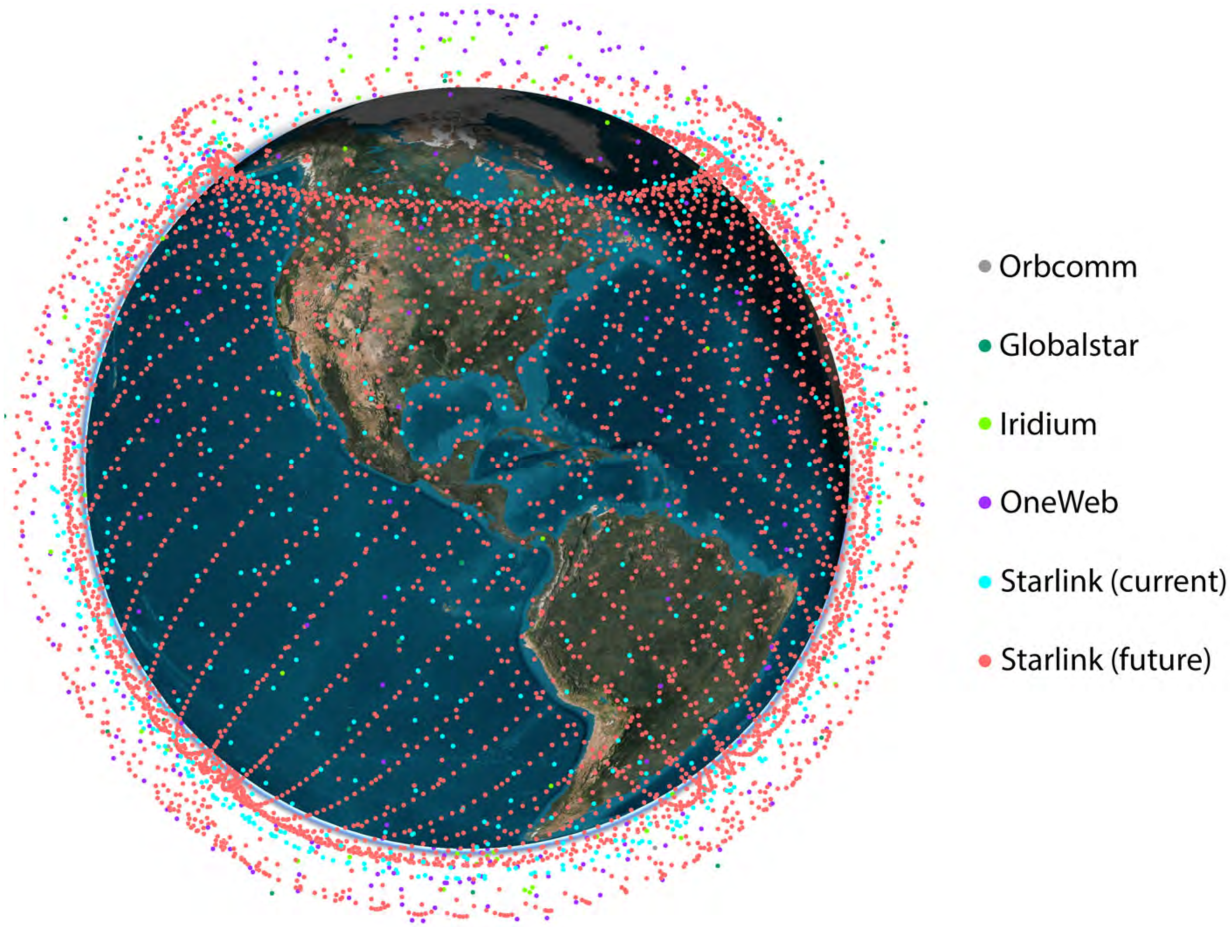
Navigation with Megaconstellation LEO Satellites

Megaconstellation LEO



Current

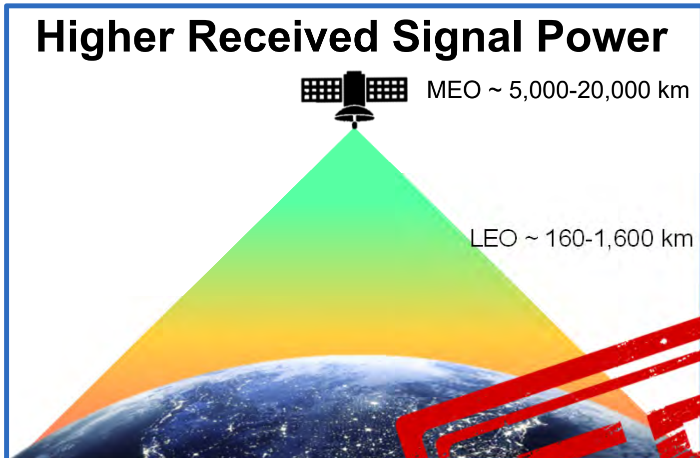
Constellation	Number
Starlink	2,300
OneWeb	288
Iridium Next	66
Globalstar	48
Orbcomm	36

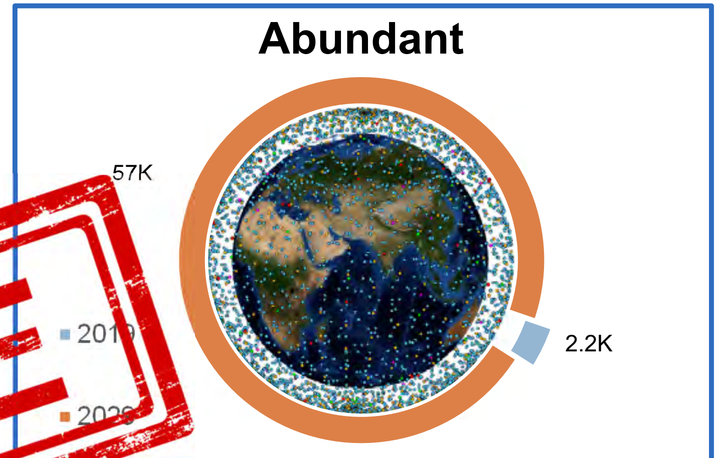
Future

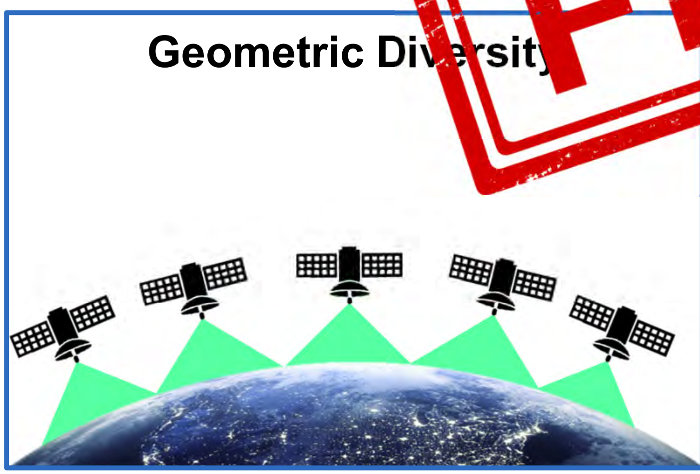
Constellation	Number
Boeing	147
OneWeb	882
Kuiper (Amazon)	3,236
Starlink	11,943
Starlink (Full)	42,000

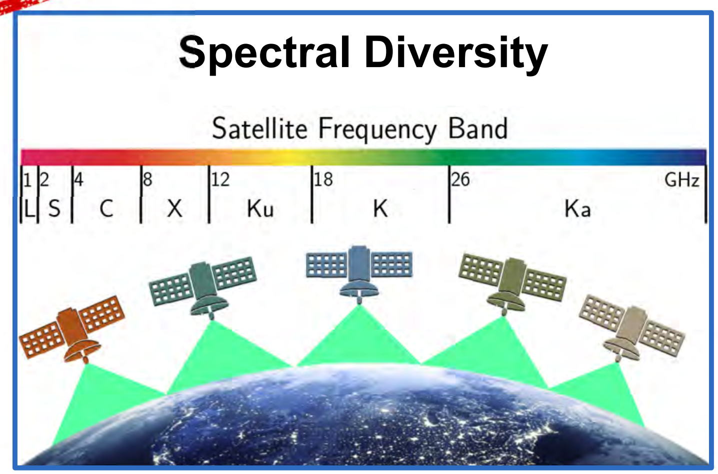
LEO Satellite Signals: Opportunities

The Ohio State University





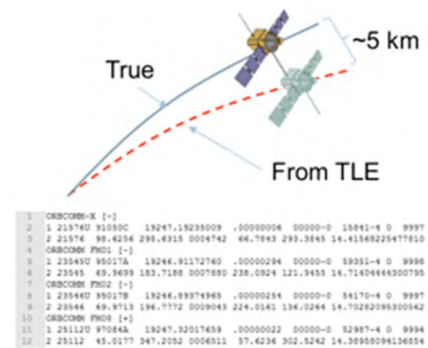




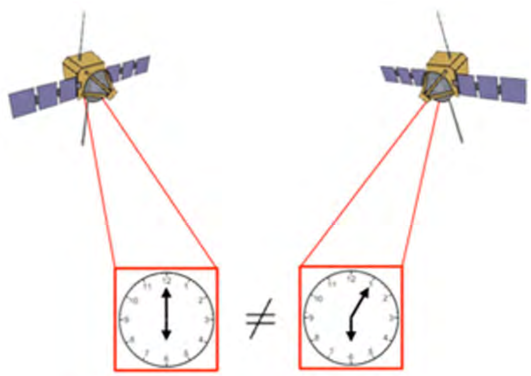
LEO Satellite Signals: Challenges

Mysterious Signals

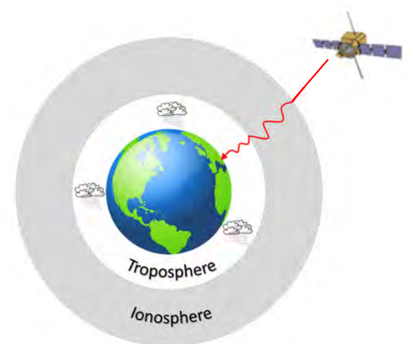
Large Ephemeris Errors



Clocks Not as Synced and Stable



Iono. & Tropo. Delays



LEO-Based PNT Solutions

PNT-dedicated LEO	LEO-Augmented GNSS	Fully-Opportunistic LEO
Cassel et al., ION ITM, 2022	*Wag et al., Remote Sensing, 2022*	*Neinavaie et al., IEEE TAES, 2022*
Ji et al., Sensors, 2021	*Li et al., GPS Solutions, 2022*	*Psiaki, NAVIGATION, Journal of the Institute of Navigation, 2021*
Iannucci & Humphreys., IEEE/ION PLANS, 2020	*Oligeri et al., ACM SPWMN, 2020*	*Kassas et al., Inside GNSS, 2021*
Ardito et al., ION ITM, 2019	*Racelis et al., ION GNSS, 2019*	*Farhangian & Landry, Sensors, 2020*
Reid et al., NAVIGATION, 2018	*Hsu & Jan, IEEE/ION PLANS, 2014*	*Khalife et al., IEEE/ION PLANS, 2020*
Meng et al., IEEE ENC, 2018	*Joerger et al., NAVIGATION, 2010*	*Kassas et al., Inside GNSS, 2019*

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Opportunistic Positioning with Starlink LEO Satellites

Science

Scientists create their own GPS by spying on internet satellites

Technique could one day improve location tracking for geologists and biologists

27 SEP 2021 · 4:05 PM · BY ADAM MANN

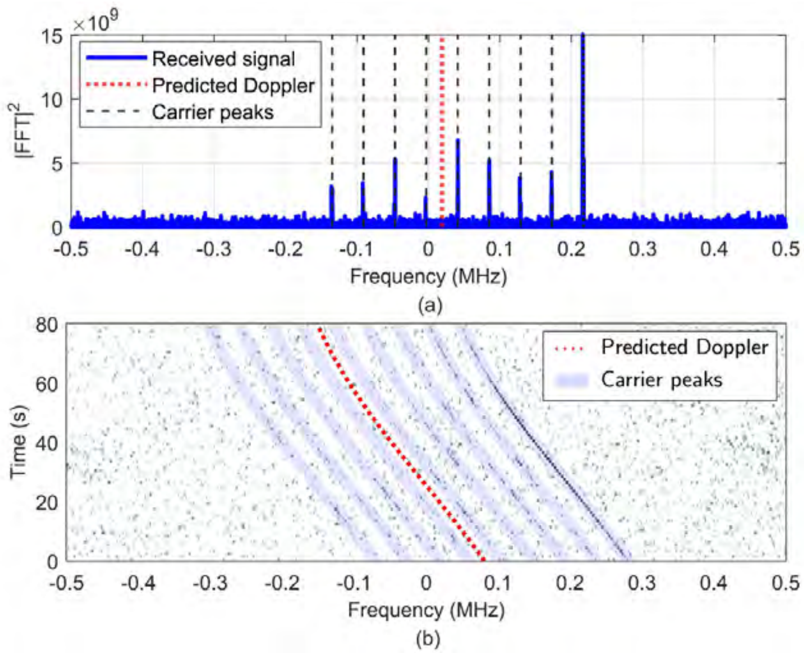
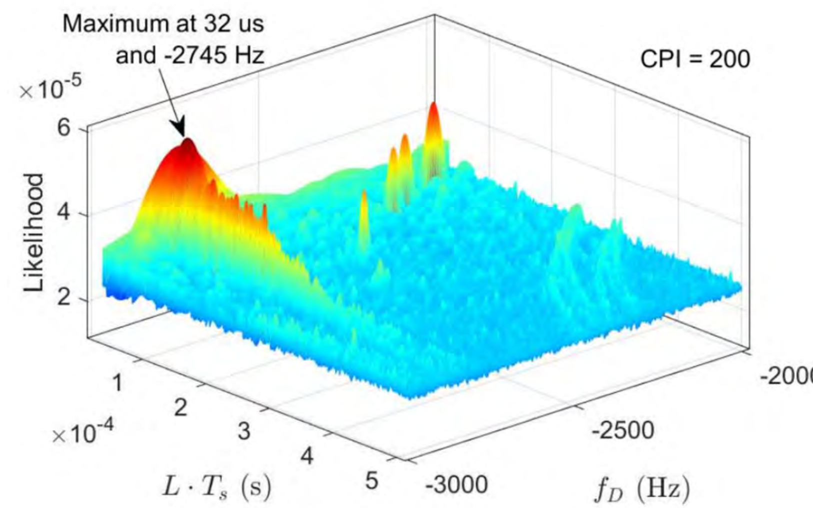
Type to search

NEWS | TELECOMMUNICATIONS

Building an Alternative to GPS › Analyzing the position of exisiting low-orbit satellites could create a backup system for navigation

BY MICHELLE HAMPSON | 05 OCT 2021 | 3 MIN READ

Starlink Signal Acquisition

Carrier Phase Approach	Blind Approach
	
Khalife, Neinavaie, & Kassas (2022). The first carrier phase tracking and positioning results with Starlink LEO satellite signals, *IEEE Transactions on Aerospace and Electronic Systems*.	Neinavaie, Khalife, & Kassas (2022). Acquisition, Doppler tracking, and positioning with Starlink LEO satellites: first results, *IEEE Transactions on Aerospace and Electronic Systems*.

Starlink Signal Tracking

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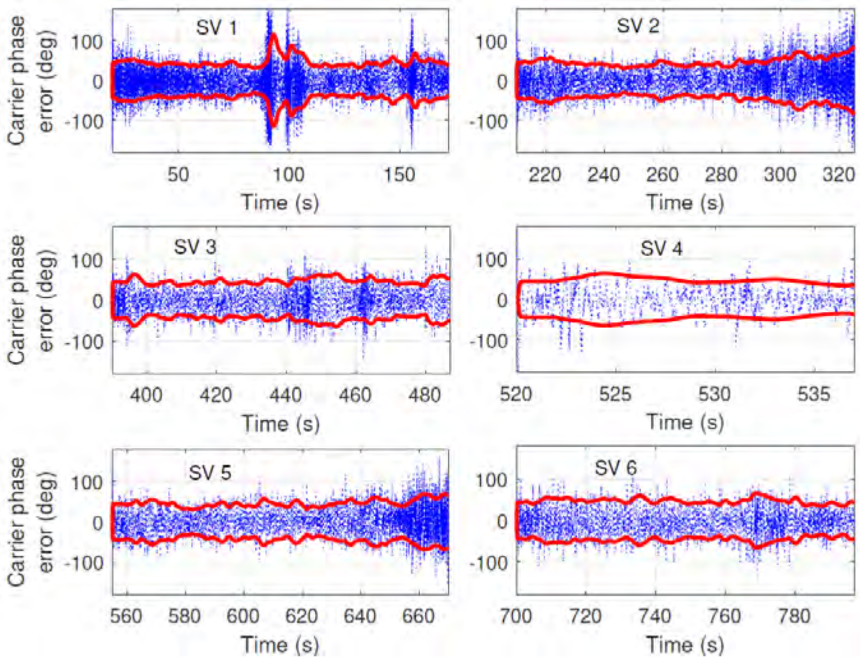
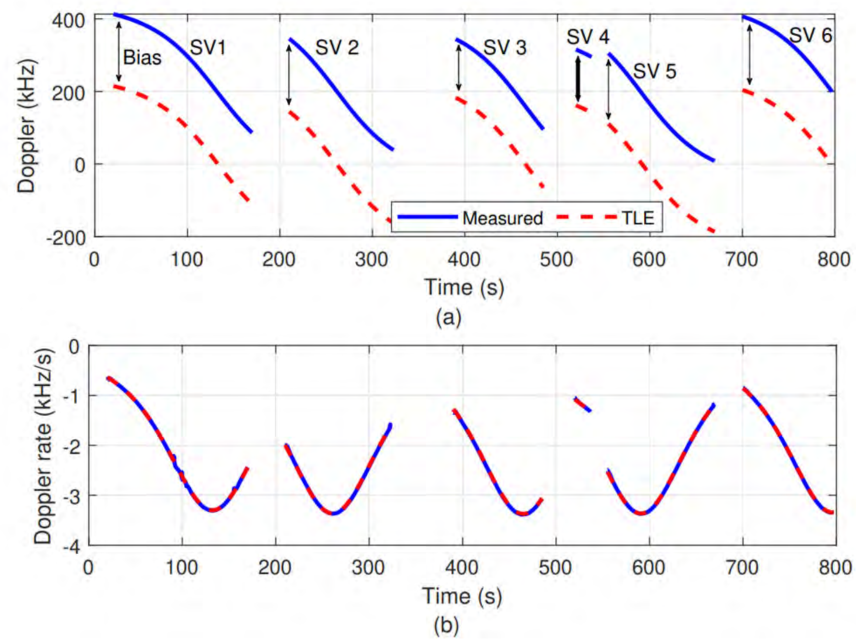
Carrier Phase Approach



Khalife, Neinavaie, & Kassas (2022). The first carrier phase tracking and positioning results with Starlink LEO satellite signals, *IEEE Transactions on Aerospace and Electronic Systems*.

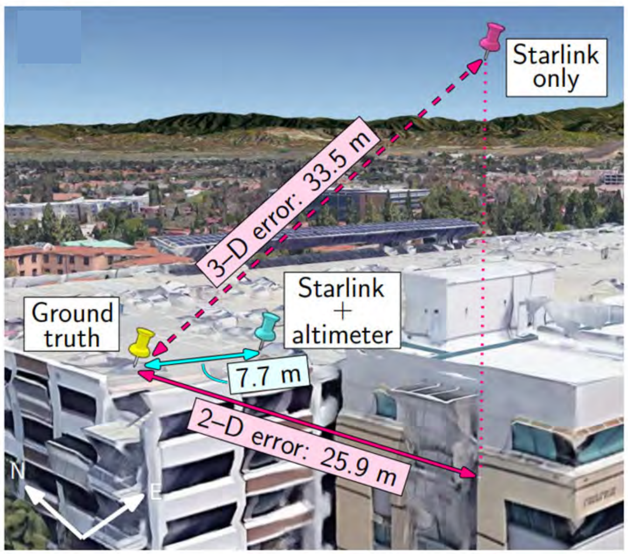
Blind Approach



Neinavaie, Khalife, & Kassas (2022). Acquisition, Doppler tracking, and positioning with Starlink LEO satellites: first results, *IEEE Transactions on Aerospace and Electronic Systems*.

Carrier Phase Approach

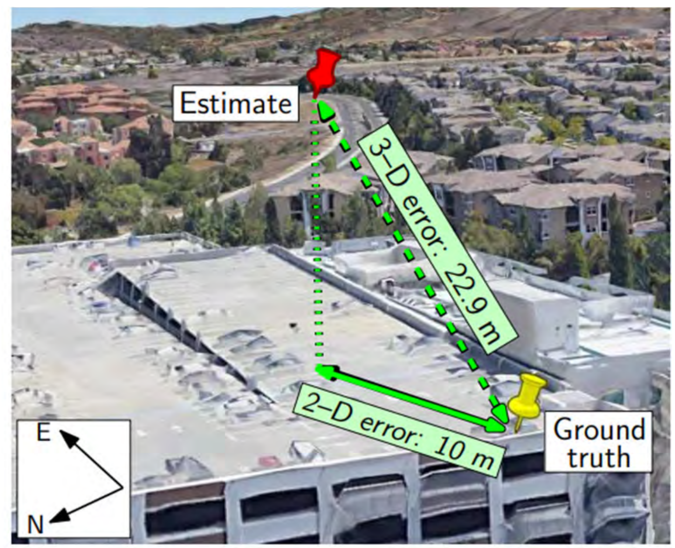
2D-RMSE: 7.7m



J. Khalife, M. Neinavaie, & Z. Kassas (2022). The first carrier phase tracking and positioning results with Starlink LEO satellite signals, *IEEE Transactions on Aerospace and Electronic Systems*.

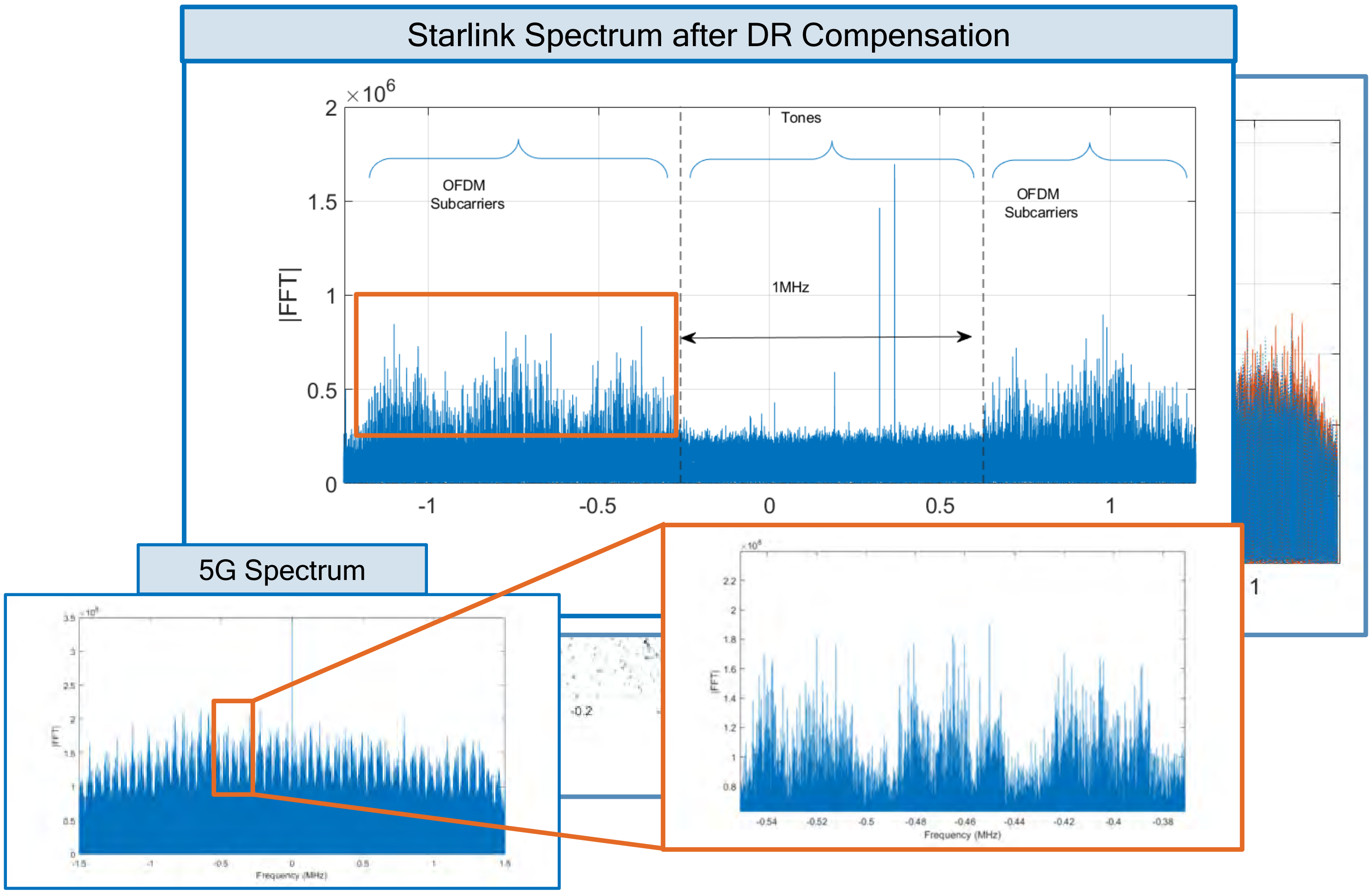
Blind Approach

2D-RMSE: 10m



M. Neinavaie, J. Khalife, & Z. Kassas (2022). Acquisition, Doppler tracking, and positioning with Starlink LEO satellites: first results, *IEEE Transactions on Aerospace and Electronic Systems*.

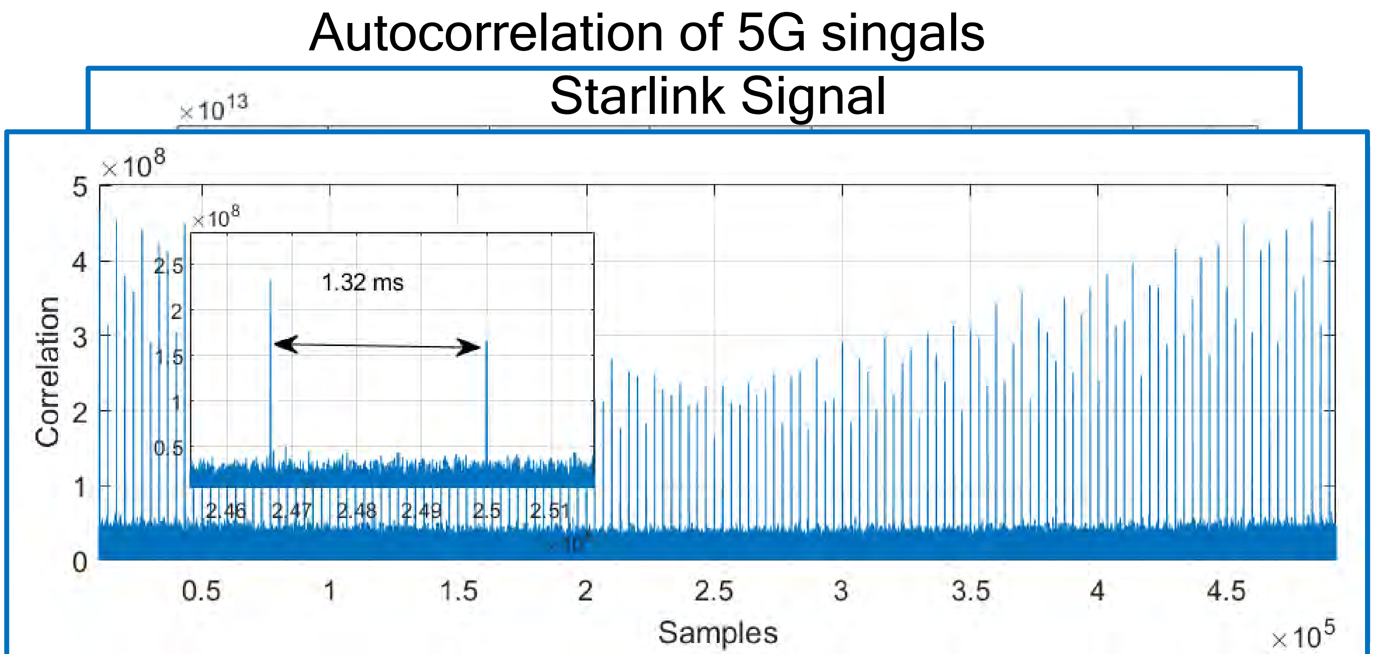
Starlink LEO OFDM Signals



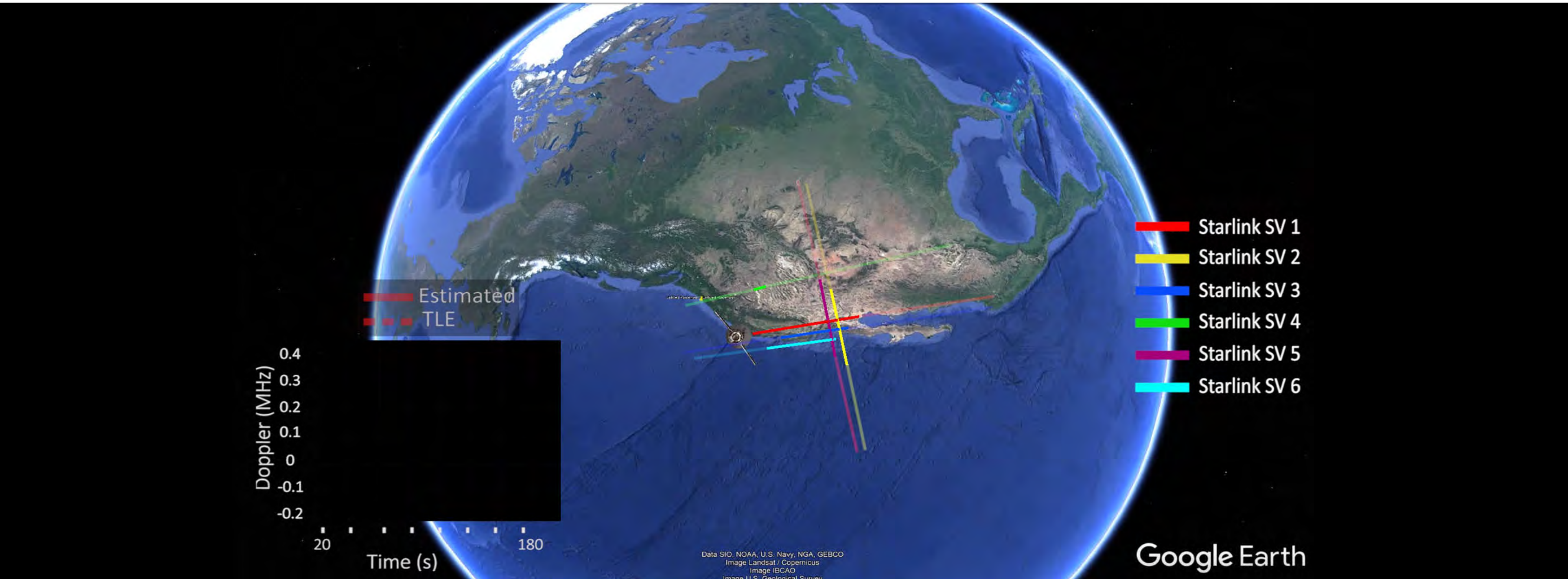
Frame Length of a Starlink Signal

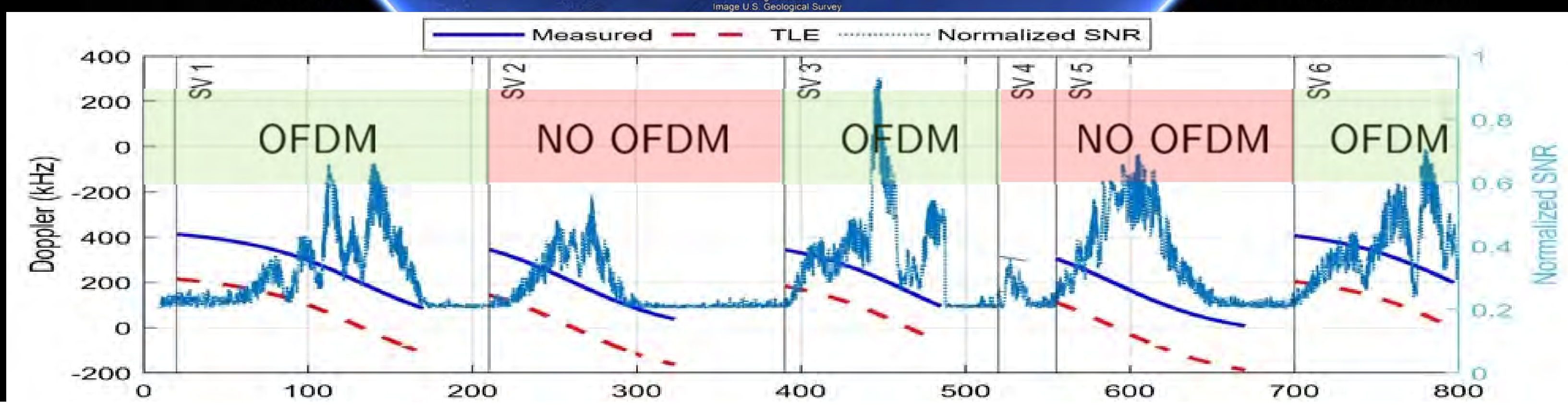
The Ohio State University

What is the frame length of a Starlink OFDM-like signal?

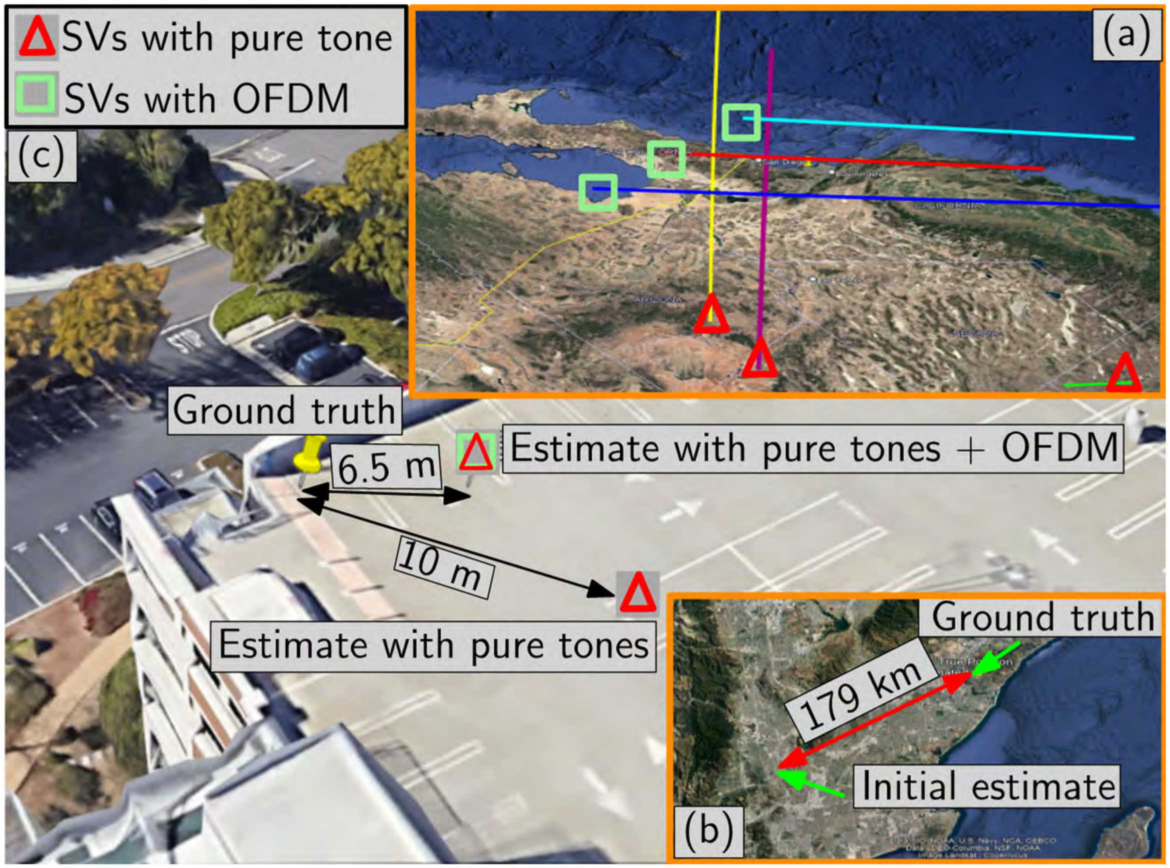


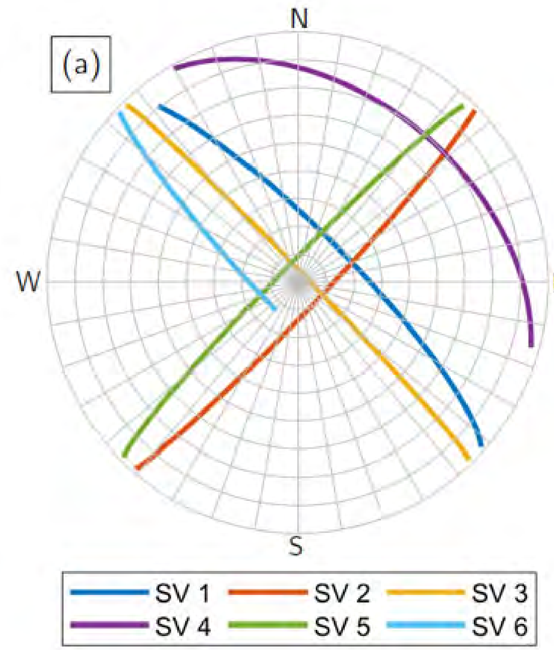
By correlating the Starlink signal, its period is found to be 1.32 ms


Starlink SV 1
Starlink SV 2
Starlink SV 3
Starlink SV 4
Starlink SV 5
Starlink SV 6
Estimated
TLE
Doppler (MHz)
0.4
0.3
0.2
0.1
0
-0.1
-0.2
20
180
Time (s)
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image Landsat / Copernicus
Image IBCAO
Image U.S. Geological Survey
Google Earth


Measured
TLE
Normalized SNR
SV 1
SV 2
SV 3
SV 4
SV 5
SV 6
OFDM
NO OFDM
OFDM
NO OFDM
OFDM
Doppler (kHz)
Normalized SNR
400
200
0
-200
400
200
0
-200
0
100
200
300
400
500
600
700
800
1
0.8
0.6
0.4
0.2
0

Opportunistic Positioning with Starlink OFDM LEO Satellites – First Results





M. Neinavaie and Z. Kassas (2022). Unveiling beamforming strategies of Starlink LEO satellites. *ION GNSS+ Conference,* Denver, CO.

The Ohio State University

Opportunistic Navigation with Starlink LEO Satellites

Navigation with Starlink Megaconstellations

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Kassas, et al. (2021). Enter LEO on the GNSS Stage: navigation with Starlink satellites. *Inside GNSS Magazine*, pp. 42-51 (**Cover article**).

IEEE TRANSACTIONS ON AEROSPACE AND ELECTRONIC SYSTEMS

JUNE 2022 VOLUME 58 NUMBER 3 IEARAX (ISSN 0018-9251)

(Contents Continued on Page 1497)

IEEE

Neinavaie, Khalife, & Kassas, “Acquisition, Doppler tracking, and positioning with Starlink LEO satellites: first results.” *IEEE Transactions on Aerospace and Electronic Systems* **(Most downloaded paper Jul. – Oct., 2022).**

Ground Vehicle Experimental Results with Starlink+ Orbcomm + Iridium LEO

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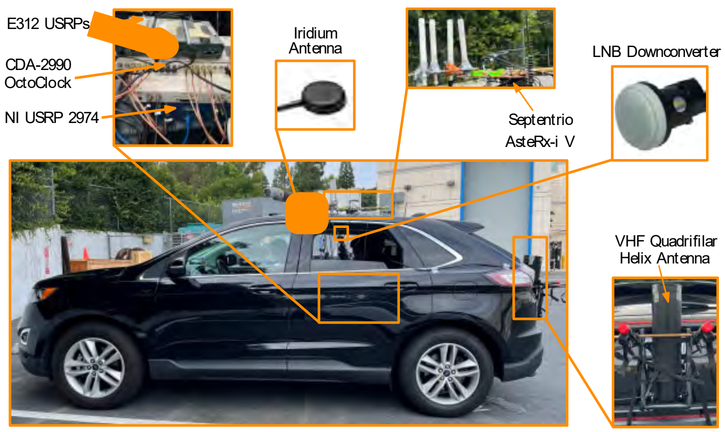
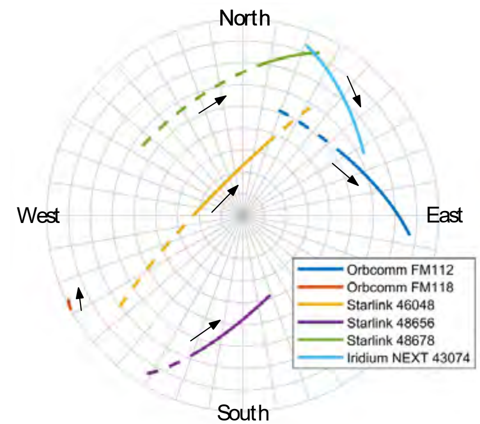
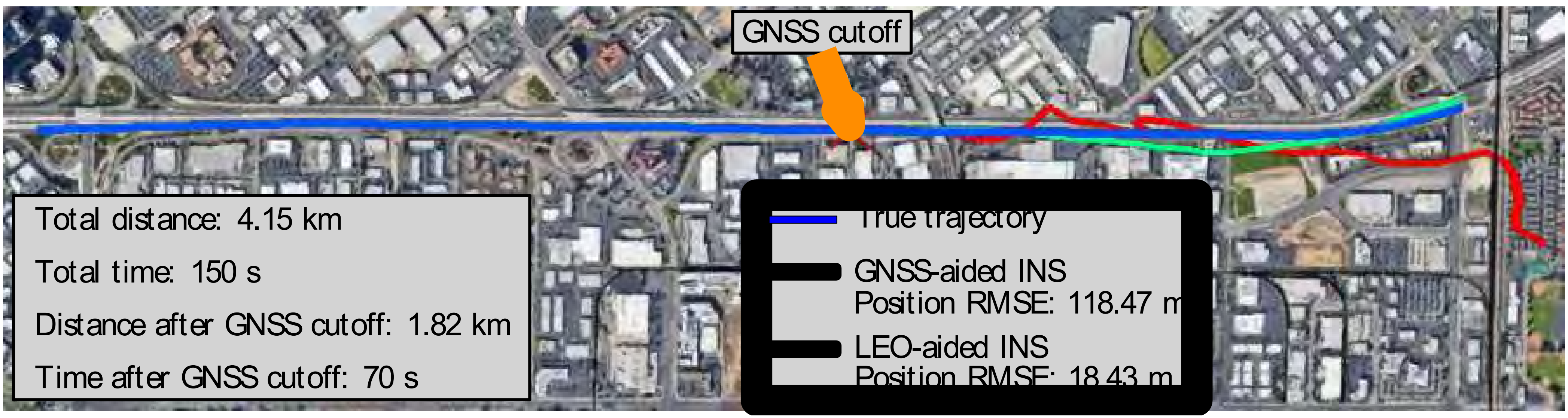


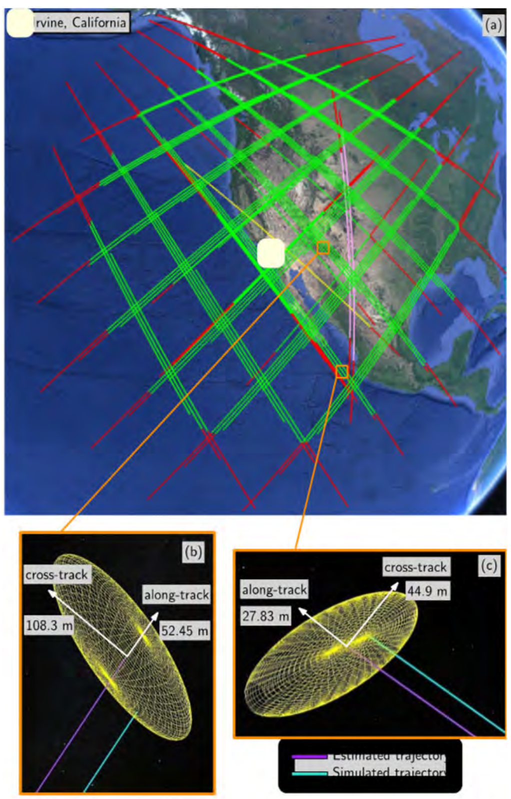




Aerial Vehicle Simulation Results with Starlink+Orbcomm+Iridium LEO

74 Starlink

2 Orbcomm   1 Iridium NEXT



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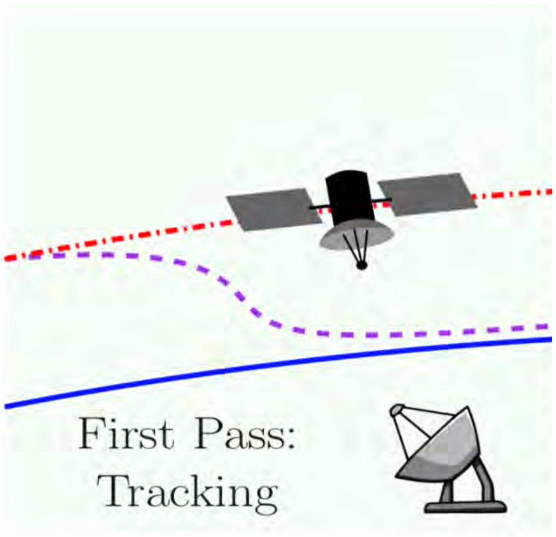
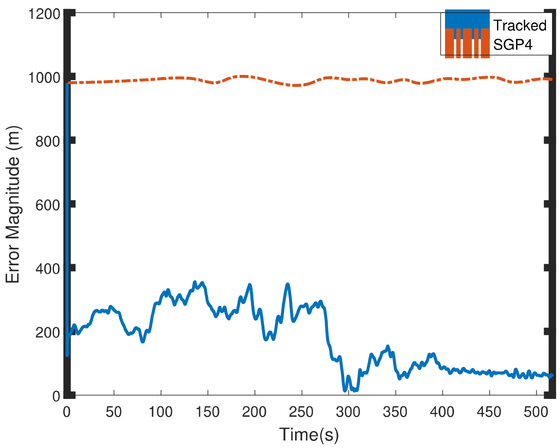
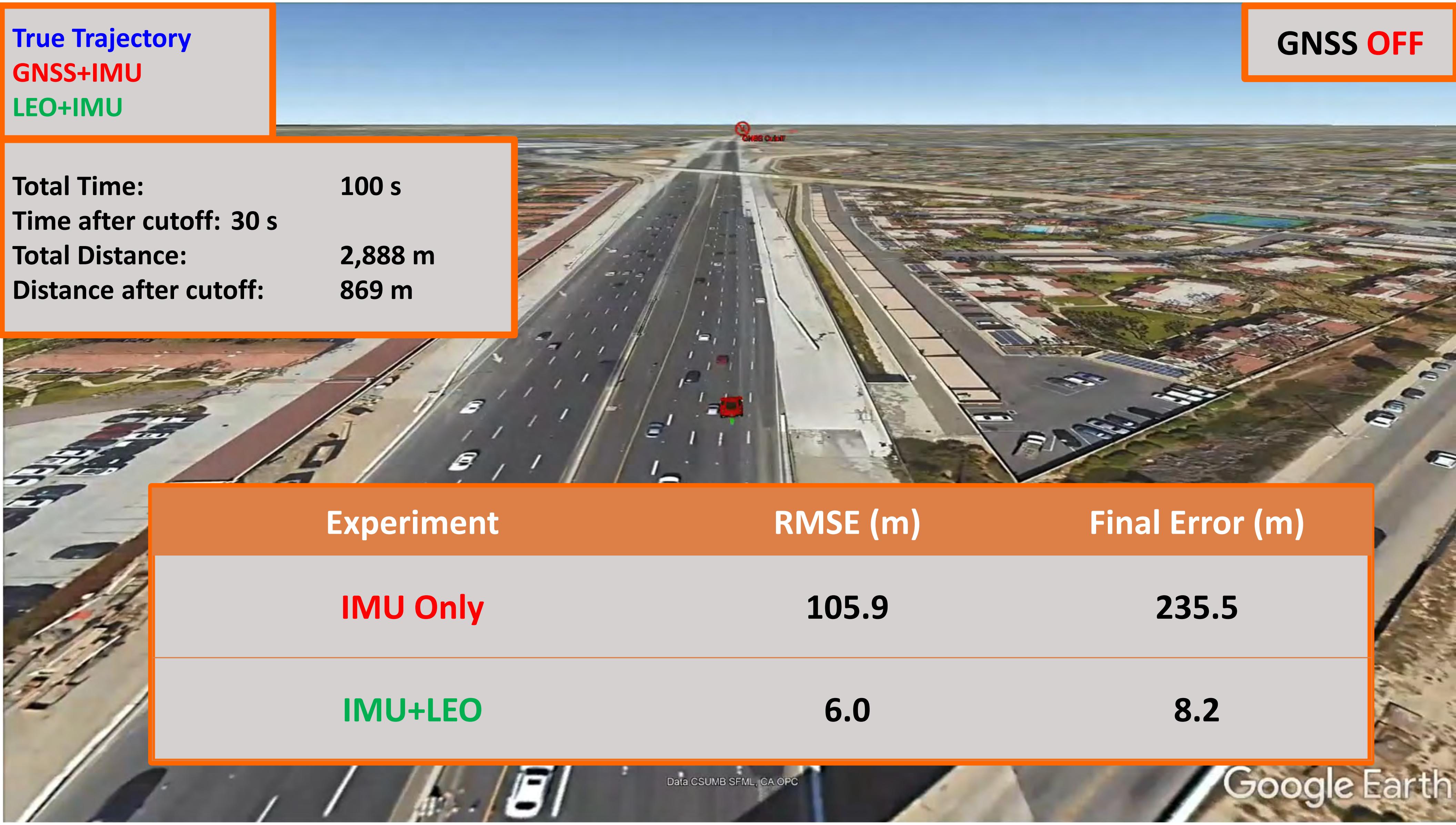
LEO Satellite Tracking with Machine Learning

LEO Satellite Tracking with Carrier Phase Measurements





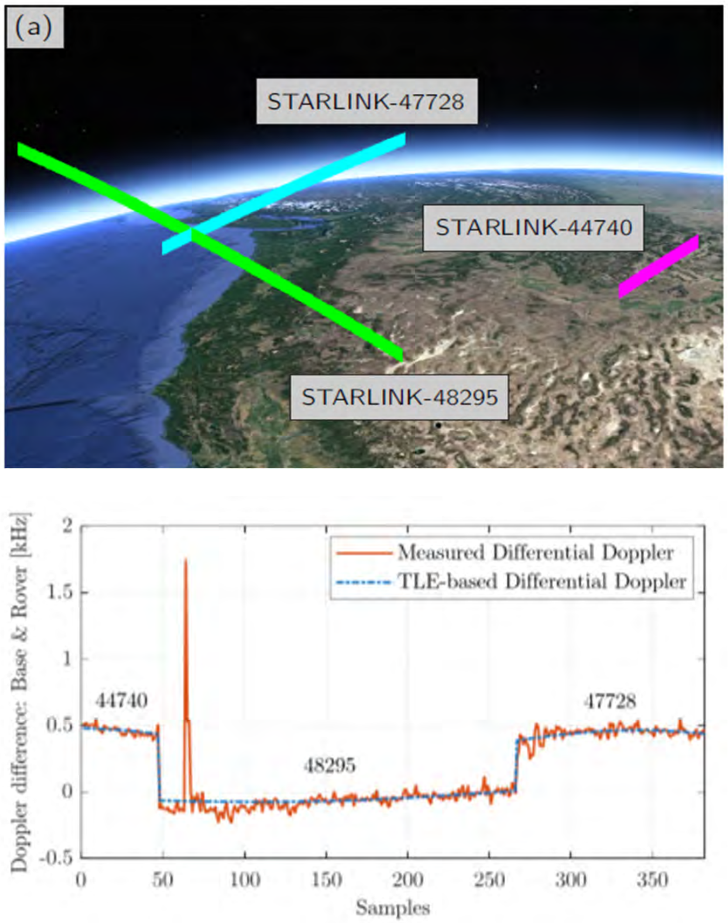


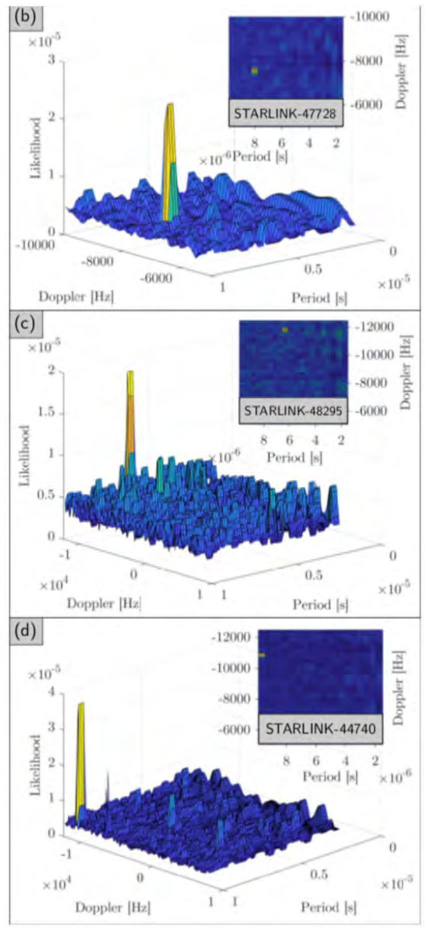
Experiment	RMSE (m)	Final Error (m)
IMU Only	105.9	235.5
IMU+LEO	6.0	8.2

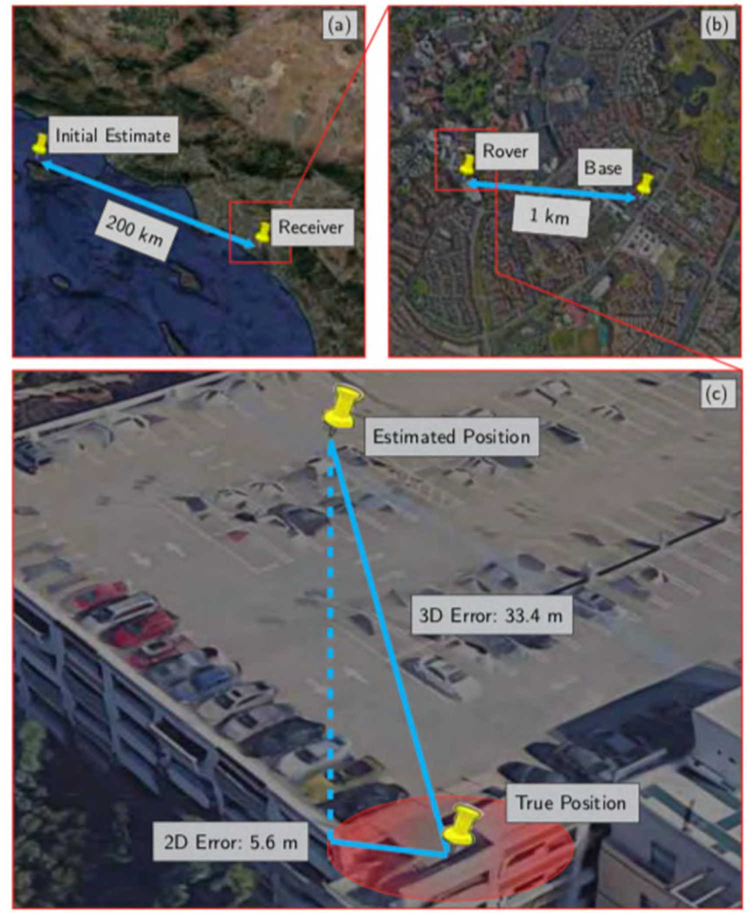
Opportunistic Differential Navigation with Starlink LEO Satellites

The Ohio State University

Differential Doppler Positioning with Starlink LEO Satellies

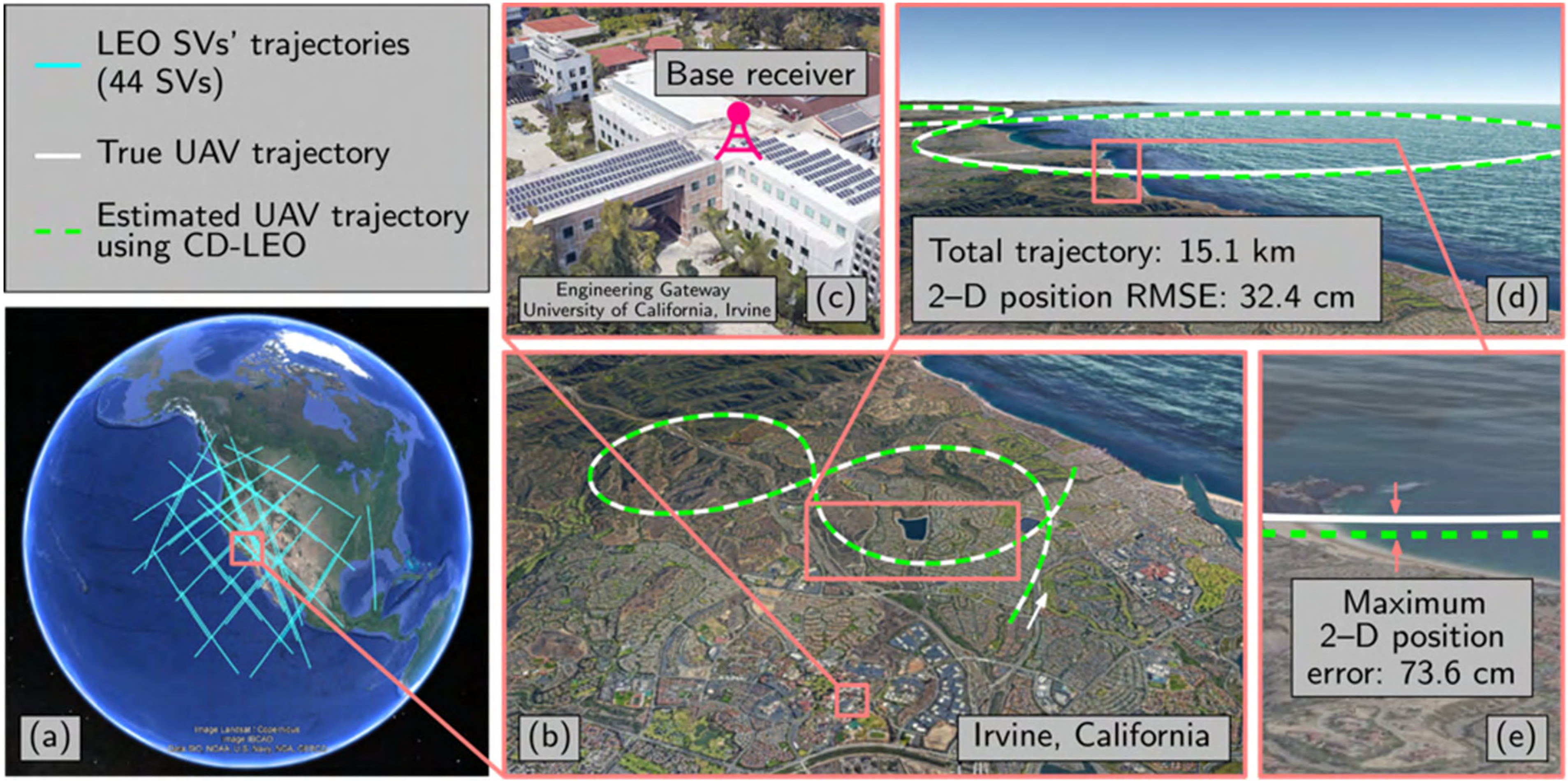






Neinavaie, Shadram, Kozhaya, & Kassas (2022). First results of differential Doppler positioning with unknown Starlink satellite signals. *IEEE Aerospace Conference*, pp. 1-14.

Aerial Vehicle Simulation Results with Carrier Phase Differential Starlink LEO



Acknowledgements

Office of Naval Research
ONR
Science & Technology

Air Force Office of Scientific Research
United States Air Force

Edwards
Air Force Base

NIST
National Institute of
Standards and Technology

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Department of Transportation
United States of America

Sandia
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Laboratories