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

Ad Astra: Navigation with Megaconstellation Starlink LEO Satellites

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GNSS RFI Threats to Aviation
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 radio-navigation-satellite service (RNSS) in the 1559 – 1610 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 RNSS 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. 1.101). 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 radio-navigation-satellite service and provides the list of the relevant ITU-R reference documents.

1 “Member States recognize that the safety aspects of radio-navigation 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.”
THE TRUTH IS OUT THERE
Navigation with Signals of Opportunity (SOPs)

**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

High-Altitude Aircraft Navigation with Terrestrial Cellular SOPs
What About High-Altitude Aircraft Navigation?
Signals of opportunity for Navigation In Frequency-Forbidden Environments
SNIFFER: Collected Data in California, USA

Day 1
Day 2
Day 3
Day 4

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
Region A -- Altitude Range (AGL): 2.98-3.28 km -- Total eNodeBs: 145
Region A -- Altitude Range (AGL): 1.85-2.01 km -- Total eNodeBs: 126
Region A -- Altitude Range (AGL): 1.69-1.72 km -- Total eNodeBs: 132
Navigation with Megaconstellation LEO Satellites
Megaconstellation LEO

**Current**

<table>
<thead>
<tr>
<th>Constellation</th>
<th>Number</th>
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<tbody>
<tr>
<td>Starlink</td>
<td>2,300</td>
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<tr>
<td>OneWeb</td>
<td>288</td>
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<tr>
<td>Iridium Next</td>
<td>66</td>
</tr>
<tr>
<td>Globalstar</td>
<td>48</td>
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<tr>
<td>Orbcomm</td>
<td>36</td>
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**Future**

<table>
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<th>Constellation</th>
<th>Number</th>
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<tr>
<td>Boeing</td>
<td>147</td>
</tr>
<tr>
<td>OneWeb</td>
<td>882</td>
</tr>
<tr>
<td>Kuiper (Amazon)</td>
<td>3,236</td>
</tr>
<tr>
<td>Starlink</td>
<td>11,943</td>
</tr>
<tr>
<td>Starlink (Full)</td>
<td>42,000</td>
</tr>
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</table>
LEO Satellite Signals: Opportunities

Higher Received Signal Power
- MEO ~ 5,000-20,000 km
- LEO ~ 160-1,600 km

Geometric Diversity

Abundant
- 57K
- 2.2K

Spectral Diversity
- Satellite Frequency Band
- L, S, C, X, Ku, K, Ka
LEO Satellite Signals: Challenges

Mysterious Signals

Large Ephemeris Errors

Clocks Not as Synced and Stable

Iono. & Tropo. Delays
<table>
<thead>
<tr>
<th>PNT-dedicated LEO</th>
<th>LEO-Augmented GNSS</th>
<th>Fully-Oppportunistic LEO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cassel et al., ION ITM, 2022</td>
<td>Wag et al., Remote Sensing, 2022</td>
<td>Neinavaie et al., IEEE TAES, 2022</td>
</tr>
<tr>
<td>Iannucci &amp; Humphreys., IEEE/ION PLANS, 2020</td>
<td>Oligeri et al., ACM SPWMN, 2020</td>
<td>Kassas et al., Inside GNSS, 2021</td>
</tr>
<tr>
<td>Ardito et al., ION ITM, 2019</td>
<td>Racelis et al., ION GNSS, 2019</td>
<td>Farhangian &amp; Landry, Sensors, 2020</td>
</tr>
<tr>
<td>Reid et al., NAVIGATION, 2018</td>
<td>Hsu &amp; Jan, IEEE/ION PLANS, 2014</td>
<td>Khalife et al., IEEE/ION PLANS, 2020</td>
</tr>
<tr>
<td>Meng et al., IEEE ENC, 2018</td>
<td>Joerger et al., NAVIGATION, 2010</td>
<td>Kassas et al., Inside GNSS, 2019</td>
</tr>
</tbody>
</table>
Opportunistic Positioning with Starlink LEO Satellites
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

Building an Alternative to GPS

Analyzing the position of existing low-orbit satellites could create a backup system for navigation

BY MICHELLE HAMPSHORE | 05 OCT 2021 | 3 MIN READ
### Carrier Phase Approach

<table>
<thead>
<tr>
<th>FFT Power</th>
<th>Received signal</th>
<th>Predicted Doppler</th>
<th>Carrier peaks</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>10^9</td>
<td>5</td>
<td>1</td>
</tr>
</tbody>
</table>

### Blind Approach

- Maximum at 32 μs and -2745 Hz
- CPI = 200

- | Likelihood |
- | 10^5       |
- | 10^4       |
- | 10^3       |
- | 10^2       |
- | 10^1       |
- | 10^0       |


Starlink Signal Tracking

Carrier Phase Approach

Blind Approach


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The Ohio State University
### Carrier Phase Approach

<table>
<thead>
<tr>
<th>2D-RMSE: 7.7m</th>
</tr>
</thead>
</table>


### Blind Approach

<table>
<thead>
<tr>
<th>2D-RMSE: 10m</th>
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</thead>
</table>

Starlink LEO OFDM Signals

Starlink Spectrum after DR Compensation

- OFDM Subcarriers
- Tones
- OFDM Subcarriers

5G Spectrum

IEEE TAES, 2022
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.
Opportunistic Positioning with Starlink OFDM LEO Satellites – First Results

Opportunistic Navigation with Starlink LEO Satellites

Ground Vehicle Experimental Results with Starlink+ Orbcomm + Iridium LEO

Total distance: 4.15 km
Total time: 150 s
Distance after GNSS cutoff: 1.82 km
Time after GNSS cutoff: 70 s

Position RMSE:
- GNSS-aided INS: 118.47 m
- LEO-aided INS: 18.43 m
Aerial Vehicle Simulation Results with Starlink+Orbcomm+Iridium LEO

- **Aerial vehicle’s trajectory**
- **GNSS-aided INS**
  - Position RMSE: 897.4 m
- **LEO Doppler-aided INS**
  - Position RMSE: 10.63 m
- **LEO pseudorange-aided INS**
  - Position RMSE: 7.31 m

- Total distance: 15.43 km
- Distance after GNSS cutoff: 12.28 km
- Total time: 300 s
- Time after GNSS cutoff: 240 s
LEO Satellite Tracking with Machine Learning
LEO Satellite Tracking with Carrier Phase Measurements
Experimental Results:

Localization Results

<table>
<thead>
<tr>
<th>Experiment</th>
<th>RMSE (m)</th>
<th>Final Error (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IMU Only</td>
<td>105.9</td>
<td>235.5</td>
</tr>
<tr>
<td>IMU+LEO</td>
<td>6.0</td>
<td>8.2</td>
</tr>
</tbody>
</table>

Total Time: 100 s
Time after cutoff: 30 s
Total Distance: 2,888 m
Distance after cutoff: 869 m
Opportunistic Differential Navigation with Starlink LEO Satellites
Aerial Vehicle Simulation Results with Carrier Phase Differential Starlink LEO

- LEO SVs’ trajectories (44 SVs)
- True UAV trajectory
- Estimated UAV trajectory using CD-LEO

(a) Map of LEO satellites positioning
(b) Simulated trajectory over Irvine, California
(c) Close-up of base receiver location
(d) Total trajectory: 15.1 km
   2-D position RMSE: 32.4 cm
(e) Maximum 2-D position error: 73.6 cm
Acknowledgements