Navigation with Multi-Constellation LEO Satellite Signals of Opportunity: Starlink, OneWeb, Orbcomm, and Iridium

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Abstract—This paper summarizes current state-of-the-art navigation results with multi-constellation low Earth orbit (LEO) satellite signals of opportunity. Experimental results with four LEO satellite constellations are presented: Starlink, OneWeb, Orbcomm, and Iridium. Two receiver designs are presented: (R1) a cognitive opportunistic navigation approach, which utilizes minimal, publicly available prior knowledge about the LEO satellite signal structure and (R2) a blind approach, which assumes no prior knowledge of the signals. Stationary positioning and mobile ground vehicle navigation results are presented. For the ground vehicle, results with two frameworks are presented: (N1) a LEO-aided inertial navigation system (INS) simultaneous tracking and navigation (STAN) and (N2) a LEO-aided differential STAN. The results reveal the tremendous promise of exploiting multi-constellation LEO satellite signals of opportunity for navigation. For positioning: (i) with R1, starting with an initial estimate about 179 km away, by exploiting signals from 6 Starlink, 1 Orbcomm, and 4 Iridium, a final two-dimensional (2-D) position error of 6.5 m was achieved and (ii) with R2, starting with an initial estimate about 3,600 km away, by exploiting signals from 4 Starlink, 2 OneWeb, 1 Orbcomm, and 1 Iridium, a final 2-D position error of 5.1 m was achieved. For navigation, a ground vehicle was equipped with an industrial-grade inertial measurement unit (IMU) and an altimeter. (i) With R1 and N1, the vehicle traversed 4.15 km in 150 seconds (GNSS signals were only available for the first 2.33 km). By exploiting signals from 3 Starlink, 2 Orbcomm, and 1 Iridium, the 3-D position root mean squared error (RMSE) and final 3-D error were 18.4 m and 27.1 m, respectively. The GNSS-aided INS position RMSE and final 3-D error were 118.5 m and 472.7 m, respectively. (ii) With R2 and N2, the vehicle traversed 1.03 km in 110 seconds (GNSS signals were only available for the first 0.11 km). By exploiting signals from 4 Starlink, 1 OneWeb, 2 Orbcomm, and 1 Iridium, the 3-D position RMSE and final 3-D error were 9.5 m and 4.4 m, respectively. The GNSS-aided INS position RMSE and final 3-D error were 205 m and 525 m, respectively.

Index Terms—Positioning, navigation, signals of opportunity, Doppler tracking, low Earth orbit satellite, Starlink, OneWeb.

I. INTRODUCTION

We are witnessing a renewed space race. From technology giants, to startups, to governments, everyone is claiming stake in launching their own LEO constellation. These constellations promise to transform our daily lives, offering broadband connectivity anywhere on Earth [1], and will benefit scientific inquiry in fields such as remote sensing [2], [3]. However, not all such constellations are created equal. So-called meg-constellations comprising tens of thousands of satellites are on their way to become a reality, with SpaceX’s Starlink being the clear frontrunner with their plan to deploy nearly 12,000 LEO satellites. These constellations will be welcomed by current constellations inhabiting LEO, and collectively they could usher a new era for positioning, navigation, and timing (PNT) [4]–[8]. The promise of utilizing LEO satellites for PNT has been the subject of extensive recent studies [9]–[18]. These studies can be categorized into three groups. The first considers providing a standalone navigation solution by launching PNT-dedicated LEO constellations or transmitting PNT signals from existing LEO constellations [19]–[26]. The second considers augmenting global navigation satellite systems (GNSS) with LEO constellations [27]–[33]. The third exploits LEO signals from any constellation in an opportunistic fashion [34]–[41]. LEO satellites possess desirable attributes for PNT [42], [43]: (i) they are around twenty times closer to the Earth compared to GNSS satellites, which reside in medium Earth orbit (MEO), which could yield significantly higher carrier-to-noise ratio; (ii) they are becoming abundant as tens of thousands of broadband Internet satellites are expected to be deployed into LEO; and (iii) they transmit in different frequency bands and are placed in varying orbits, making LEO satellite signals diverse in frequency and direction.

However, exploiting LEO satellite signals for PNT purposes in an opportunistic fashion comes with challenges [44], as these constellations are owned by private operators that typi-
cally do not disclose crucial information about the satellites’:
(i) ephemerides, (ii) clock synchronization and stability, and
(iii) signal specifications.

To address the first challenge, several approaches have been
proposed, including differential navigation utilizing known
base receiver(s) [45]–[47], simultaneous tracking and naviga-
tion (STAN) [48], and analytical/machine-learning satellite
orbit tracking [49]–[52]. Approaches to address the second
challenge have been offered in [53]–[55]. To address the third
challenge, the paradigm of cognitive opportunistic navigation
[56], which estimates the minimally known LEO satellite
signals in a blind fashion has been showing tremendous
promise [57].

This paper summarizes recent progress with exploiting
multi-constellation LEO satellites for PNT. The focus of the
paper is to present the navigation solution achieved with
real LEO signals of opportunity on stationary and mobile
platforms in a standalone and a differential fashion. To the
authors’ knowledge, these results represent the most accurate
positioning and navigation results reported in the literature
with multi-constellation LEO signals of opportunity.

Experimental results with four LEO constellations are pre-
sented: Starlink, OneWeb, Orbcomm, and Iridium. Two re-
ciever design approaches are presented:

- **R1**: a cognitive opportunistic navigation approach, which
  utilizes minimal, publicly available prior knowledge
  about the LEO satellite signal structure
- **R2**: a blind approach, which assumes no prior knowledge
  of the signals

Stationary positioning and mobile ground vehicle navigation
results are presented. For the ground vehicle, results with two
frameworks are presented:

- **N1**: a LEO-aided inertial navigation system (INS) simul-
taneous tracking and navigation (STAN)
- **N2**: a LEO-aided differential STAN (DSTAN).

For positioning: (i) with R1, starting with an initial estimate
about 179 km away, by exploiting signals from 6 Starlink,
1 Orbcomm, and 4 Iridium, a final two-dimensional (2-D)
position error of 6.5 m was achieved and (ii) with R2, starting
with an initial estimate about 3,600 km away, by exploiting
signals from 4 Starlink, 2 OneWeb, 1 Orbcomm, and 1
Iridium, a final 2-D position error of 5.1 m was achieved. For
navigation, a ground vehicle was equipped with an industrial-
grade inertial measurement unit (IMU) and an altimeter. (i)
With R1 and N1, the vehicle traversed 4.15 km in 150 seconds
(GNSS signals were only available for the first 2.33 km).
By exploiting signals from 3 Starlink, 2 Orbcomm, and 1
Iridium, the 3-D position root mean squared error (RMSE)
and final 3-D error were 18.4 m and 27.1 m, respectively. The
GNSS-aided INS position RMSE and final 3-D error were
9.5 m and 4.4 m, respectively. The GNSS-aided INS position RMSE
and final 3-D error were 205 m and 525 m, respectively.
The results presented in this paper reveal the tremendous
promise of exploiting multi-constellation LEO satellite signals
of opportunity for navigation.

The paper is organized as follows. Section II overviews
the LEO constellations considered in this paper. Section III
presents experimental results with the cognitive opportunis-
tic navigation receiver with Starlink, Orbcomm, and Iridium
NEXT on a stationary receiver and a mobile ground vehicle
navigating via the LEO-aided STAN framework. Section IV
presents experimental results with the opportunistic naviga-
tion receiver with Starlink, OneWeb, Orbcomm, and Iridium
NEXT on a stationary receiver and a mobile ground vehicle
navigating via the LEO-aided DSTAN framework. Section V
gives concluding remarks.

### II. OVERVIEW OF LEO CONSTELLATIONS

Table I compares the four LEO constellations considered
in this paper. The number of satellites specified in the table
represent the current number, as of the writing of this paper.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Starlink</th>
<th>OneWeb</th>
<th>Orbcomm</th>
<th>Iridium</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandwidth</td>
<td>240 MHz</td>
<td>230 MHz</td>
<td>4.8 kHz</td>
<td>31.5 kHz</td>
</tr>
<tr>
<td>Beacon length</td>
<td>4/3 ms</td>
<td>10 ms</td>
<td>1 s</td>
<td>90 ms</td>
</tr>
<tr>
<td>Number of satellites</td>
<td>3,660</td>
<td>542</td>
<td>36</td>
<td>66</td>
</tr>
<tr>
<td>Modulation</td>
<td>OFDM</td>
<td>OFDM</td>
<td>SD-QPSK</td>
<td>DE-QPSK</td>
</tr>
<tr>
<td>Frequency band</td>
<td>Ku, Ka</td>
<td>Ku</td>
<td>VHF</td>
<td>L</td>
</tr>
<tr>
<td>Downlink</td>
<td>10.7–12.7 GHz</td>
<td>137 MHz</td>
<td>1.616–1.626 GHz</td>
<td></td>
</tr>
<tr>
<td>Number of channels</td>
<td>8</td>
<td>8</td>
<td>2</td>
<td>240</td>
</tr>
<tr>
<td>Number of beams</td>
<td>≈ 48</td>
<td>16</td>
<td>N/A</td>
<td>48</td>
</tr>
<tr>
<td>Altitude</td>
<td>550 km</td>
<td>1,200 km</td>
<td>750 km</td>
<td>780 km</td>
</tr>
</tbody>
</table>

### III. NAVIGATION WITH STARLINK, ORBCOMM, AND IRIDIUM NEXT LEO SATELLITES: A COGNITIVE OPPORTUNISTIC NAVIGATION APPROACH

This section presents multi-constellation navigation results
exploiting Starlink, Orbcomm, and Iridium NEXT LEO satel-
lites with R1 and N1.

#### A. Stationary Positioning

Signals from a total of 11 LEO satellites (6 Starlink, 1
Orbcomm, and 4 Iridium NEXT) were recorded on top of
a parking structure at the University of California, Irvine,
CA, USA. The receiver presented in [58] was used to process
Orbcomm and Iridium NEXT signals, from which it produced
Doppler navigation observables. The receiver presented in [59]
was used to process Starlink signals, from which it produced
carrier phase observables. It is worth mentioning that not all
satellites were visible simultaneously, and the signals were
recorded as satellites passed overhead. The hardware setup is
described in [58], [59]. Fig. 1 illustrates the skyplot of the
LEO satellites.
The navigation observables were processed through an extended Kalman filter, which estimated the receiver’s 2-D position (the receiver’s height was known). The EKF was initialized 179 km away from the true receiver position. The EKF’s final position estimate converged to within 6.5 m. Fig. 2 illustrates the LEO satellite trajectories, initial estimate and ground truth receiver position, and final estimate along with the $99^{th}$ percentile estimation error ellipse.

**B. Mobile Navigation via LEO-Aided STAN**

A ground vehicle was equipped with a Septentrio AsteRx-I V integrated GNSS-INS system with an industrial-grade IMU and an altimeter, from which the ground truth was derived. The hardware setup is described in [48]. The vehicle was driven on the CA-55 freeway next to Irvine, California, USA, for 4.15 km in 150 seconds. During the experiment, signals from 6 LEO satellites (3 Starlink, 2 Orbcomm, and 1 Iridium NEXT) were recorded. The skyplot of satellites’ trajectory during the experiment are shown in Fig. 3. The receiver presented in [60] was used to process Orbcomm signals, from which it produced carrier phase navigation observables. The receiver presented in [58] was used to process Iridium NEXT signals, from which it produced Doppler navigation observables. The receiver presented in [61] was used to process Starlink signals, from which it produced Doppler navigation observables. The vehicle navigated via the LEO-aided STAN framework described in [48].

GNSS signals were available for the first 80 seconds of the experiment but were fictitiously cut off for the last 70 seconds, during which the vehicle traveled 1.82 km. The GNSS-INS navigation solution drifted to a final 3-D position error of 472.7 m and a 3-D position RMSE of 118.5 m over the true trajectory. The STAN LEO-aided INS yielded a final 3-D position error of 27.1 m and a 3-D position RMSE of 18.4 m. Fig. 4 summarizes the experimental results. For details about the data processing, EKF formulation, and additional results and analyses, the reader is referred to [48].
IV. NAVIGATION WITH STARLINK, ONEWEB, ORBCOMM, AND IRIDIUM NEXT LEO SATELLITES: A BLIND NAVIGATION APPROACH

This section presents multi-constellation navigation results exploiting Starlink, OneWeb, Orbcomm, and Iridium NEXT LEO satellites with R2 and N2.

A. Stationary Positioning

Signals from a total of 8 LEO satellites (4 Starlink, 2 OneWeb, 1 Orbcomm, and 1 Iridium NEXT) were recorded on top of the ElectroScience Laboratory (ESL) at The Ohio State University, Columbus, OH, USA. The receiver presented in [57] was used to process all LEO signals, from which it produced Doppler navigation observables. It is worth mentioning that not all satellites were visible simultaneously, and the signals were recorded as satellites passed overhead. The hardware setup is described in [57]. Fig. 1 illustrates the skyplot of the LEO satellites.

The Doppler navigation observables were processed through a nonlinear least-squares (NLS) estimator, which estimated the receiver’s 3–D position. The NLS was initialized in Irvine, CA, USA, about 3,600 km away from the true receiver position. The NLS’s final position estimate converged to within a 2–D error of 5.1 m. Fig. 6 illustrates the LEO satellite trajectories, initial estimate, ground truth receiver position, and final estimate. For additional details about the data processing, NLS formulation, and additional results and analyses, the reader is referred to [57].

B. Mobile Navigation via LEO-Aided DSTAN

A ground vehicle was equipped with a Septentrio AsteRx SBi3 Pro+ integrated GNSS-INS system with an industrial-grade IMU and an altimeter, from which the ground truth was derived. A differential base station with a known position was set up on top of ESL at The Ohio State University campus, about 2.2 km away from the rover (ground vehicle). The ground vehicle traversed a trajectory of 1.03 km in 110 seconds. During the experiment, signals from 8 LEO satellites (4 Starlink, 1 OneWeb, 2 Orbcomm, and 1 Iridium NEXT) were recorded.
were recorded. The receiver presented in [57] was used to process signals collected by the base station and the rover, from which it produced Doppler navigation observables. The vehicle navigated via the DSTAN framework described in [47].

GNSS signals were available for the first 7 seconds of the experiment but were fictitiously cut off for the last 103 seconds, during which the vehicle traveled 0.92 km. The GNSS-INS navigation solution drifted to a final 3-D position error of 525 m and a 3-D position RMSE of 205 m over the true trajectory. The DSTAN LEO-aided INS yielded a final 3-D position error of 4.4 m and a 3-D position RMSE of 9.5 m. Fig. 7 summarizes the experimental results.

<table>
<thead>
<tr>
<th>Distance (km)</th>
<th>Time (s)</th>
<th>Total</th>
<th>No GNSS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.03</td>
<td>110</td>
<td>1.03</td>
<td>0.92</td>
</tr>
</tbody>
</table>

![Figure 7](image)

**Fig. 7.** Navigation results with 1 OneWeb, 4 Starlink, 1 Iridium NEXT, and 2 Orbcomm LEO satellites: ground truth trajectory (blue), GNSS-aided INS (red), and DSTAN LEO-aided INS (green).

V. CONCLUSION

This paper summarized the current state-of-the-art with exploiting multi-constellation LEO satellite signals of opportunity for positioning and navigation. Exploiting 6 Starlink, 1 Orbcomm, and 4 Iridium via a cognitive opportunistic navigation receiver is shown to yield a stationary 2-D position error of 6.5 m, starting with an initial estimate about 179 km away. With signals from 3 Starlink, 2 Orbcomm, and 1 Iridium NEXT, a ground vehicle equipped with an industrial-grade IMU traveling for 4.15 km in 150 s (the last 1.82 km in 70 s of which without GNSS) could achieve a 3-D position RMSE of 18.4 m via the LEO-aided STAN framework. Exploiting 4 Starlink, 2 OneWeb, 1 Orbcomm, and 1 Iridium via a blind navigation receiver is shown to yield a stationary 2-D position error of 5.1 m, starting with an initial estimate about 3,600 km away. With signals from 4 Starlink, 1 OneWeb, 2 Orbcomm, and 1 Iridium, a ground vehicle equipped with an industrial-grade IMU traveling for 1.03 km in 110 s (the last 0.92 km in 103 s of which without GNSS) could achieve a 3-D position RMSE of 9.5 m via the LEO-aided DSTAN framework.

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REFERENCES


