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SPECIAL ISSUE

URBAN AIR MOBILITY

SHAPING THE FUTURE OF TRANSPORTATION

Opportunity Comes Knocking

Overcoming GPS Vulnerabilities with Other Satellites' Signals

In environments where GPS signals may be unreliable or unavailable, UAVs can use "signals of opportunity" to navigate. One such method guided a drone for more than 2 kilometers with an error of only 14.8 meters after 2 minutes without any GPS.

by Zaher (Zak) M. Kassas, Joe Khalife, Mohammad Neinavaie, and Trier Mortlock, University of California, Irvine

In the next decade, a space revolution will launch tens of thousands of low-Earth orbit (LEO) satellites for broadband internet communication. The LEO satellites orbited by private companies such as SpaceX, Boeing, OneWeb and others can also be used for navigation. While relatively few of these satellites are in orbit now, the companies plan to aggregately launch extensive fleets of them in coming years.

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such as SpaceX, Boeing, OneWeb and others can also be used for navigation.

Figure 1. Experimental results with real 4G LTE signals using a non-differential opportunistic navigation framework: environmental layout of the experiment, location of the eNodeBs, ground truth and final navigation solution. *Map data: Google Earth.*

Exploiting the communications-purposed signals from these satellites for navigation offers a viable approach to the multiple challenges of urban air mobility in densely built and high-rise areas. This article describes and assesses one method for such opportunistic navigation: using innovative algorithms to extract differential carrier-phase measurements from broadband LEO satellite signals. We conduct the analysis on the Starlink constellation, which is under construction by SpaceX. The constellation will eventually consist of thousands of mass-produced small satellites in LEO, working in combination with ground transceivers. Here, we used signals from two satellites from the Orbcomm constellation, which is one of the few currently available constellations.

Opportunistic navigation exploits ambient radio signals of opportunity (SOPs)—that is, those primarily intended for another purpose—for positioning, navigation and timing (PNT). Besides LEO satellite signals, other SOPs include AM/FM radio, digital television, WiFi and cellular. Cellular in particular shows promise of a submeter-accurate navigation solution for unmanned aerial vehicles (UAVs) when carrier-phase measurements from cellular signals are used.

Cellular signals have been well studied for opportunistic navigation, and several frameworks that leverage different levels of network synchronization were developed. For example, a non-differential framework exploiting carrier-phase measurements from 4G long-term evolution (LTE) base stations (or eNodeBs) equipped with stable frequency standards achieved an 81-centimeter two-dimensional (2D) position root mean squared error (RMSE) on a UAV after approximately 3 minutes, as shown in **Figure 1.** Alternatively, a differential framework, robust against clock errors of cellular base transceiver stations (BTSs) in 3G code-division multiple access (CDMA) systems, achieved a 2D RMSE of 63 centimeter on a UAV after 3 minutes, as shown in **Figure 2.** For the complete methodology, see papers cited in the Acknowledgments.

Similarly to cellular networks and more, LEO satellites possess desirable attributes for positioning in GNSS-challenged environments:

- They are around 20 times closer to Earth than GNSS satellites, which reside in medium-Earth orbit (MEO), making

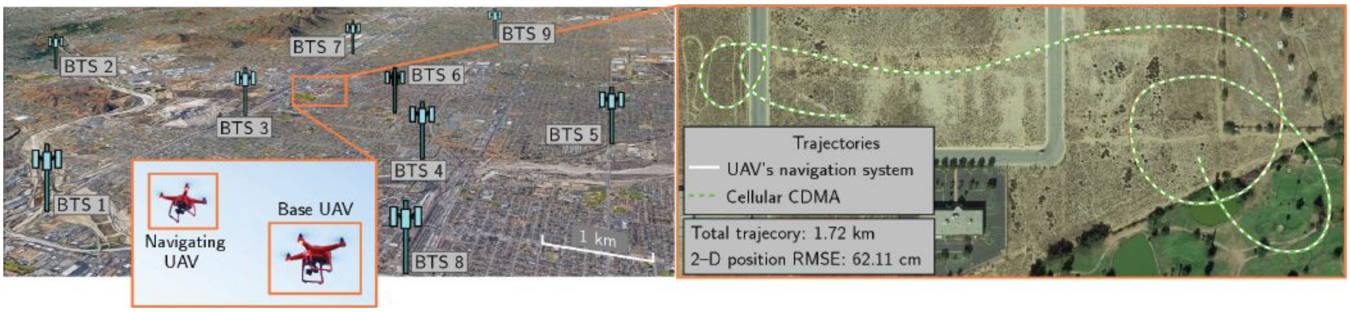

Figure 2. Experimental results with real 3G CDMA signals using a differential framework: environmental layout of the experiment, location of the BTSs, ground truth and final navigation solution. *Map data: Google Earth.*

their received signal power between 24 to 34 dBs higher than GNSS signals;

- They will become very abundant in the next decade;
- Each broadband provider will deploy its satellites in unique constellations, transmitting at different frequency bands, making LEO satellite signals diverse in frequency and direction.

The Keplerian elements parameterizing the orbits of these LEO satellites are made publicly available by the North American Aerospace Defense Command (NORAD) and are updated daily in the two-line element (TLE) files. Using TLEs and orbit determination algorithms such as SGP4, the positions and velocities of these satellites can be known, albeit not precisely. In addition, some of these broadband LEO satellites, such as those from Orbcomm, are equipped with GPS receivers; they broadcast GPS solution to terrestrial receivers.

Here we consider the problem of navigating exclusively with LEO satellite signals in environments where GNSS signals are unavailable or untrustworthy. Several challenges must be overcome. First, there are no publicly available receivers that can produce navigation observables from LEO satellite signals. Second, existing navigation frameworks do not apply in a straightforward fashion to megaconstellation LEO satellites, due to the unique error sources associated with them. Third, the achievable navigation performance with megaconstellation LEO satellites is not fully characterized; that is, described according to defined parameters such as accuracy, integrity, continuity and availability.

We make four contributions that aim to address the second and third challenges above:

- We developed a carrier-phase differential (CD) LEO navigation framework for real broadband LEO satellite signals and an efficient method for resolving carrier-phase integer ambiguities in a batch solver. This article does not include the rather complex mathematics underlying this method; see the paper cited in the Acknowledgments.
- We derived the probability density functions (pdfs) of megaconstellation LEO satellites' azimuth and elevation angles. These pdfs are essential tools to efficiently study the performance of LEO satellite-based navigation.
- We characterized the performance of the CD-LEO framework using the derived pdfs by analyzing the position dilution of precision (PDOP) of megaconstellation LEO satellites, the measurement residuals due to ephemeris errors, and the measurement residuals due to integer ambiguity estimation errors as a function of the system design parameters: more precisely, the differential baseline and the batch size. This enabled design of system parameters to guarantee a desired performance.
- We present experimental results showing a UAV localizing itself with real LEO satellite signals using differential carrier-phase measurements to an acceptable level of accuracy.

FRAMEWORK

The high precision level of carrier-phase measurements enables a sub-meter navigation solution, as has been demonstrated in GNSS and cellular SOPs. However, this

RADIO FREQUENCY TERMS

CARRIER-PHASE MEASUREMENTS

A measure of the range between a satellite and a receiver expressed in units of cycles of continuous radio-frequency waveform that "carries" the GPS pseudorandom noise-ranging codes and the navigation messages. This measurement can be made with very high precision (of the order of millimeters), but the whole number of cycles between satellite and receiver is not measurable. The underlying carrier of a satellite signal can be recovered and its phase measured at regular intervals by the receiver once it locks onto the signal. *See insidegnss.com/generating-carrier-phase-measurements.*

INTEGER AMBIGUITY

The (unknown) integer number of frequency cycles between satellite and receiver. This can be determined by various techniques of integer ambiguity resolution.

DOUBLE-DIFFERENCE

In carrier-phase processing applications, some positioning errors can be removed by differencing (comparing) observations between two receivers, that of the base and that of the rover.

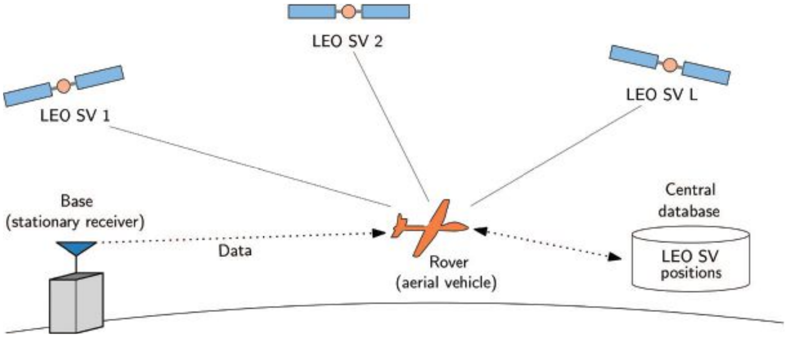

Figure 3. Base/rover CD-LEO framework. The base receiver can be either stationary or mobile, such as a high-flying aerial vehicle.

precision comes at the cost of added ambiguities that need to be resolved. To address this challenge for LEO satellites, consider a receiver onboard a "rover" on Earth making carrier-phase measurements to broadband LEO satellites, and a "base" station in the vicinity of the rover making carrier-phase measurements to the same LEO satellites. One can form the double-difference carrier-phase measurements from base and rover measurements and solve for the rover's position as well as for the resulting integer ambiguities. **Figure 3** illustrates the base/rover CD-LEO framework.

Without any position priors, the rover cannot perform real-time positioning and must wait until there is enough change in satellite geometry and solve a batch least-squares to estimate its position and the integer ambiguities. To optimally resolve the integer ambiguities, an integer least-squares (ILS) estimator can be employed. However, the complexity of the ILS grows exponentially with the number of ambiguities.

With the proposed LEO constellations, hundreds of satellites are expected to be visible at any point in time and almost anywhere on Earth, making the ILS approach impractical. To address this issue, we propose an integer ambiguity resolution algorithm that approaches the performance of the ILS but with a fraction of its complexity. Once the ambiguities are resolved, the rover can perform real-time positioning.

Aside from integer ambiguities, another major source of error that has to be considered in the CD-LEO framework is the error in the satellite positions obtained from the TLE files. These errors can be on the order of kilometers as the orbit is propagated way beyond the epoch at which the TLE file was generated. Blindly using the satellite positions obtained from the TLE files introduces significant errors in the measurement residuals.

Figure 4. Base/rover experimental setup of the CD-LEO framework.

Although double-difference carrier-phase measurements will cancel out most of these errors, significant errors will remain if the base and the rover are too far apart. These errors are too large to ignore if an accurate navigation solution is desired. We characterize this error and its statistics as a function of the differential baseline, from which the baseline can be designed to guarantee a desirable performance.

The performance of the proposed integer ambiguity resolution algorithm and the magnitude of the CD-LEO measurement residuals due to ephemeris errors heavily depend on the satellite-to-receiver geometry, which is captured by the satellites' azimuth and elevation angles. Subsequently, it is of paramount importance to characterize the distribution of these angles for LEO megaconstellations. This enables several efficient and insightful performance analyses, and facilitates performance-driven framework design; that is, design-system parameters to meet desired performance requirements.

CD-LEO

The framework consists of a rover and a base receiver in an environment comprising L visible LEO space vehicles (SVs). See again **Figure 3.** The base receiver (B) is assumed to have knowledge of its own position state, such as a stationary receiver deployed at a surveyed location, or a high-flying UAV with access to GNSS. The rover (R) does not have knowledge of its position. The base communicates its own position and carrier-phase observables with the rover. The LEO SVs' positions are known through the TLE files and orbit determination software, or by decoding the transmitted ephemerides, if any.

Our objective is to estimate the rover's position using double-difference carrier-phase measurements. Such measurements have inherent ambiguities that must be resolved. A total of (L–1) measurements are obtained from L visible satellites, with one unknown ambiguity associated with each double-difference measurement. Using only one set of carrier-phase measurements with no *a priori* knowledge on the rover position results in an underdetermined system:

(L+2) unknowns (3 position states and (L–1) ambiguities) with only (L–1) measurements.

Therefore, when no *a priori* information on the position of the rover is known, a batch-weighted nonlinear least-squares (B-WNLS) over a window of K time-steps is employed to solve for the rover's position and ambiguities. The rover could either remain stationary or move during the batch window. Subsequently, the rover uses measurements collected at different times in a batch estimator, resulting in an overdetermined system.

The total number of measurements will be K×(L–1) in the batch window. If the rover remains stationary, the total number of unknowns will remain L+2. Otherwise, the number of unknowns becomes 3K+L–1 (3 position states at each time-step and (L–1) ambiguities). The dimensions of the unknown parameters and the measurement vector set a necessary condition on K and L to obtain a solution. Once an estimate of the ambiguities is obtained, the rover position can be estimated in real time using a point-solution weighted nonlinear least-squares (PS-WNLS) estimator. Both the B-WNLS and PS-WNLS estimate the rover's position from LEO double-difference carrier-phase measurements, described next.

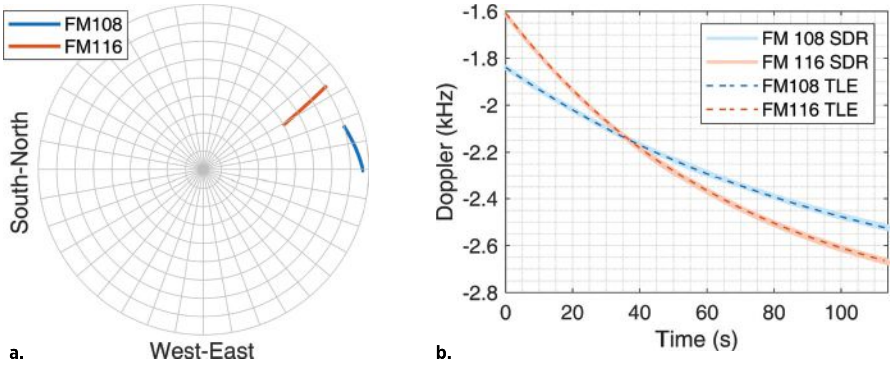

Figure 5. (a) Sky plot of the geometry of the two Orbcomm SVs during the experiment. (b) The measured Doppler frequencies using the proprietary SDR and the expected Doppler calculated from the TLE for both Orbcomm SVs.

REDUCED-SIZED INTEGER ALGORITHM

When the proposed LEO constellations are fully deployed, hundreds of LEO satellites will be visible from almost anywhere on Earth. In fact, hundreds of Starlink LEO SVs will be visible almost anywhere on Earth for an elevation mask of 5 degrees once the constellation is full deployed. Dozens of satellites will still be visible for even higher elevation masks. For example, 60 Starlink LEO SVs will be visible over Irvine, California, for a 25-degree elevation mask. For such a number of satellites, it is impractical to solve the ILS, as its complexity grows exponentially with the number of integer ambiguities.

We propose an integer ambiguity resolution algorithm, referred to as reduced-size ILS, which approaches the performance of the Least-squares Ambiguity Decorrelation Adjustment (LAMBDA) method, but with a significantly smaller fraction of the LAMBDA method's complexity. The reduced-size ILS relies on the tradeoff between complexity and performance. That is, for every integer, a test is formulated to determine whether the Integer Rounding method, which has negligible complexity, is a good estimate of the corresponding integer, or whether the integer must be estimated using an ILS.

EXPERIMENT SETUP

The experiment's rover was a DJI Matrice 600 UAV equipped with an Ettus E312 universal software radio peripheral (USRP), a high-end VHF antenna and a small consumer-grade GPS antenna to discipline the onboard oscillator. The base was a stationary receiver equipped with an Ettus E312 USRP, a custom-made VHF antenna and a small consumer-grade GPS antenna to discipline the onboard oscillator. The receivers were tuned to a 137 MHz carrier frequency with 2.4 MHz sampling bandwidth, which covers the 137–138 MHz band allocated to Orbcomm SVs. Samples of the received signals were stored for off-line post-processing using a software-defined radio (SDR).

The LEO carrier-phase measurements were produced at a rate of 4.8 kHz and were downsampled to 10 Hz. The base's position was surveyed on Google Earth, and the UAV trajectory was taken from its onboard navigation system, which uses GNSS (GPS and GLONASS), an inertial measurement unit and other sensors. The hovering horizontal precision of the UAV is reported to be 1.5 meters by DJI. The experimental setup is shown in **Figure 4**. The UAV traversed a total trajectory of 2.28 kilometers in 120 seconds.

Over the course of the experiment, the receivers onboard the base and the UAV were listening to two Orbcomm SVs: FM 108 and FM 116. The SVs transmit their positions as estimated by their onboard GPS receivers. These positions were decoded and used as ground truth. A position estimate of FM 108 and FM 116 was also obtained from TLE files and SGP4 software. The satellites were simultaneously visible for 2 minutes. See **Figure 5.**

Figure 6(a) shows the SV trajectories. Because only two satellites were visible at a time, which is the case with many of the current LEO constellations, an extended Kalman filter (EKF) was used to estimate the three-dimensional position and velocity of the UAV from single-difference measurements. To demonstrate the potential of the CD-LEO navigation framework, two frameworks were implemented for comparison: a modified version of the CD-LEO framework, and a non-differential framework that employs carrier-phase LEO measurements from the UAV's receiver only.

CD-LEO EXPERIMENT

Single-difference measurements provide more information on the SV-to-receiver geometry than double-difference measurements. But this comes at the cost of an additional state to be estimated: the common clock bias. To this end, the UAV's position and velocity states were estimated along with the common clock bias and the constant ambiguity. Note that the constant ambiguity was lumped into the constant clock bias.

The UAV's position and velocity were assumed to evolve according to a nearly constant velocity model, and the common clock state was assumed to evolve according to the standard model of double integrator driven by noise. A prior for the UAV position and velocity was obtained from the UAV's onboard system and was used to initialize the EKF. After initialization, the EKF was using single-difference Orbcomm LEO SV measurements to estimate the states of the UAV.

To study the effect of ephemeris errors on the navigation solution, two EKFs were implemented: one that uses the Orbcomm LEO SV positions estimated by the SVs' on-board GPS receiver. and one that uses the Orbcomm LEO SV positions estimated from TLE files. The estimated trajectories are shown in **Figure 6(b)** and **Figure 6(c).** The 3D position root mean squared errors (RMSEs) and final errors for both EKFs are shown in **Table 1.**

NON-DIFFERENTIAL LEO EXPERIMENT

To demonstrate the importance of the CD-LEO framework, a non-differential LEO framework is implemented. To this end, the UAV's position and velocity are estimated in an EKF using the non-differential measurements. In this case, two clock biases must be estimated capturing the difference between the receiver's clock bias and each of the Orbcomm LEO SVs' bias. The same dynamics models and initialization method employed in the previous section were used in the non-differential framework. Similarly, two EKFs were implemented, and the estimated trajectories are shown in **Figure 6(b)** and **Figure 6(c).** The 3D position RMSEs and final errors for both EKFs are shown in **Table 1.**

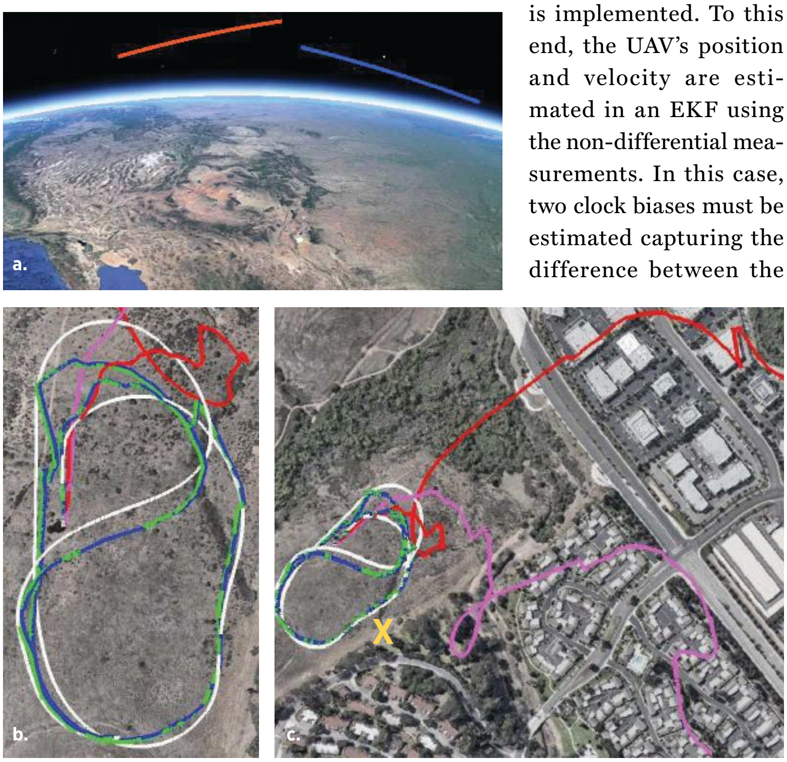

Figure 6. a: LEO SV paths. b–c: True (white) and estimated (blue: CD-LEO with SV positions from GPS; green: CD-LEO with SV positions from TLE; magenta: non-differential LEO with SV positions from GPS; red: non-differential LEO with SV positions from TLE) UAV paths. X=base. *Map data: Google Earth*

DISCUSSION

The residuals in the non-differential carrier-phase measurements are on the order of kilometers, which explains the unacceptably large RMSEs of the non-differential framework. While using the SV positions transmitted by the Orbcomm SVs reduces RMSEs, the errors remain unacceptably large in that framework due to other unmodeled errors. Such errors cancel out in the CD-LEO framework, giving acceptable performance for SV positions from either GPS or TLE.

The accuracy of these results is unprecedented, considering that only two LEO SVs were used, no other sensors were fused into the navigation, and these LEO SVs are not intended for navigation and are exploited opportunistically. The double-difference residual due to ephemeris errors was calculated and was found to be on the order of centimeters, showing the robustness of the CD-LEO framework against ephemeris errors.

SIMULATION RESULTS: A FUTURE GLIMPSE

This section details simulation results of a fixed-wing UAV navigating with signals from the proposed Starlink LEO SV megaconstellation under the CD-LEO framework. The UAV, representing the rover, flew a total trajectory of 15.1 kilometers in 300 seconds. The simulated UAV compares in performance to a small private plane with a cruise speed of roughly 50 meters/second. Its trajectory, shown in white in **Figure 7(b)**, consisted of a straight segment, followed by a figure-eight pattern and then a final straight segment. The UAV flew at a constant altitude of 2.5 kilometers, while executing the rolling and yawing maneuvers. The distance between a stationary base and the UAV ranged between 3.826 kilometers and 2.489 kilometers. The elevation angle mask was set to 15 degrees in both receivers. The UAV and base station both received signals from 44 simulated LEO SVs, whose trajectories appear in blue in **Figure 7(a)**. To simulate ephemeris errors, the true anomaly of each satellite was randomly shifted such that the satellite position errors were distributed between 75

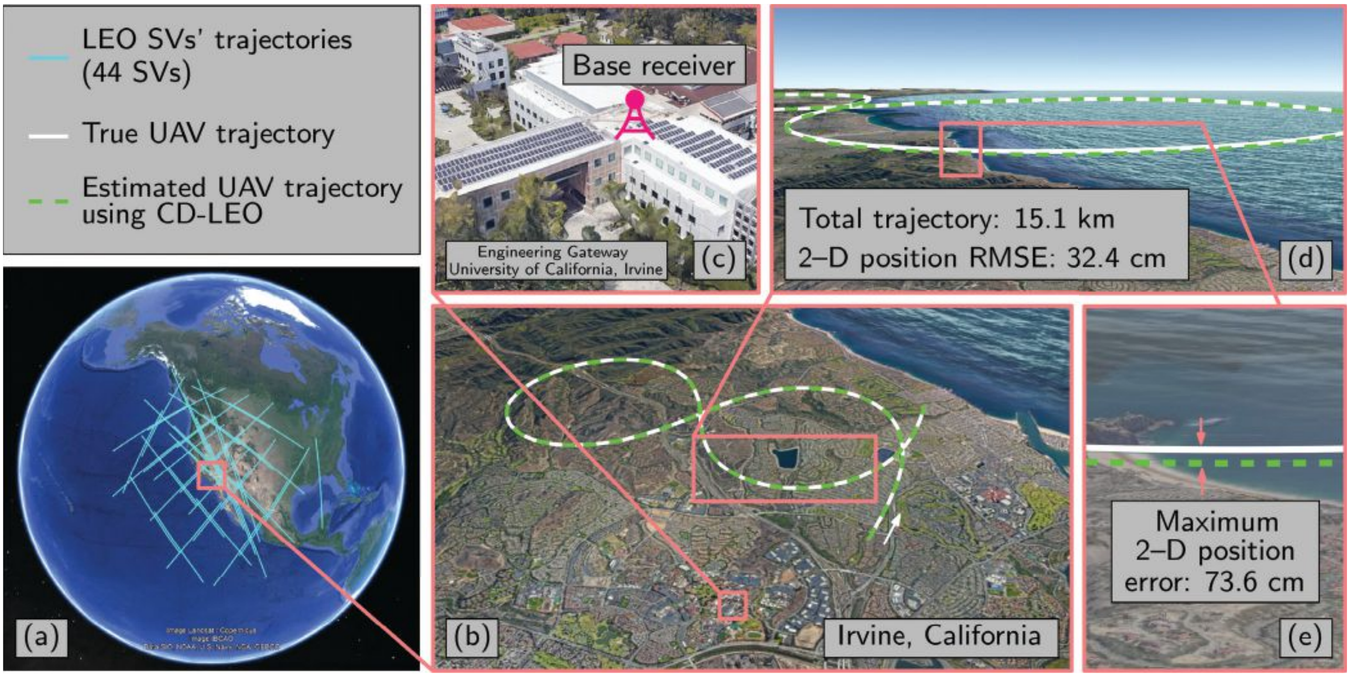

Figure 7. Simulation of UAV and base receiving signals from 44 simulated LEO SVs.

meters and 3.5 kilometers. It was assumed that the UAV had access to GNSS for the first 50 seconds, during which the B-WNLS is solved. After 50 seconds, the UAV solves for its 3D position using CD-LEO measurements and the integer ambiguities estimates obtained by solving the B-WNLS. The total 3D position RMSE was 2.2 meters and the total 2D RMSE was 32.4 centimeters. The simulation layout and the true and estimated UAV trajectories are shown in **Figure 7**. Note that similar to GNSS, the vertical uncertainty in the CD-LEO framework is larger than the horizontal uncertainty due to less geometric diversity in the vertical direction.

CONCLUSION

A differential framework for opportunistic navigation with carrier-phase measurements from megaconstellation LEO satellites offers promise for UAV navigation in GNSS-challenged zones. A computationally efficient integer ambiguity resolution algorithm reduces the size of the ILS problem. Simulation using the Starlink constellation as a specific example showed a 60 percent reduction in the size of the ILS problem while maintaining optimality. A UAV navigated for 2.28 kilometers exclusively using signals from only two Orbcomm LEO SVs via the proposed framework, with an unprecedented position RMSE of 14.8 meters over a period of 2 minutes. Simulation results show submeter-accurate navigation is attainable using the CD-LEO framework with future LEO megaconstellations.

Framework	SV position source	RMSE	Final error
CD-LEO	GPS	14.8 m	3.9 m
CD-LEO	TLE	15.0 m	4.8 m
Non-differential	GPS	338.6 m	590.4 m
Non-differential	TLE	405.4 m	759.5 m

Table 1. Experimental results RMSEs and final errors.

ACKNOWLEDGMENTS

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For accounts of the methodology, see these conference papers: IEEE/ION/PLANS 2020, "Navigation with Differential Carrier-Phase Measurements from Megaconstellation LEO Satellites," at www.ion.org/publications/browse.cfm. Figure 1 is from K. Shamaei and Z. Kassas, "Sub-meter accurate UAV navigation and cycle slip detection with LTE carrier phase measurements," ION GNSS+ 2019. Figure 2 is from J. Khalife, S. Bhattacharya, and Z. Kassas, "Centimeter-accurate UAV navigation with cellular signals," ION GNSS+ 2018. ■