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GNSS-based Hardware-in-the-loop Simulation of Spacecraft Formation Flight: An Incubator for Future Multi-scale Space Weather Studies

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Conventional space weather observation techniques (e.g. ground-based remote sensing, single satellite probes, and sounding rockets) have helped us to study our geo-space environment by collecting decades of valuable scientific information. However, the existing measurement methods are still limited at certain levels of temporal and spatial resolution. Recently, several missions apply the concept of satellite constellation to increase the measurement quantity. For example, the COSMIC mission and the company, Spire Global, Inc., use small satellites or Cube-Sats to probe and retrieve atmospheric properties (e.g. plasma density, scintillation, temperature) based on the atmospheric radio occultation technique. However, the exact location, size, and full structure of ionospheric irregularities are often not accurate enough using these approaches. Today, there is a need for more flexible, agile, and cost-efficient observation techniques to further understand various multi-scale space weather problems (e.g. ionospheric irregularities and turbulence). Spacecraft formation flying, an emerging space mission concept, can be applied to design new missions to meet future multi-scale observational requirements. Several distributed smaller probes can form a team to produce more robust, flexible, sustainable, low-cost observation capability.

The geometry of satellite formation fleet can be accurately determined using multi-constellation, multi-frequency global navigation satellite systems (GNSS). The Virginia Tech Formation Flying Testbed (VTFFTB), a GNSS-based hardware-in-the-loop simulation testbed has recently been developed to simulate closed-loop, real-time spacecraft formation flight at low Earth orbits (LEO) [1,2,3]. A group of 2 or 3 satellites, with each carrying a GNSS receiver, are simulated in scenarios with some basic ionospheric impacts on GPS and Galileo. Besides precise absolute and relative navigation, each onboard GNSS receiver can be used to measure the ionosphere. Total electron density (TEC) and GNSS scintillation index (e.g. S4) are detected. TEC is used to determine localized electron density between each pair of LEO satellite (with GNSS receiver), which is advantageous to sense or monitor the ionospheric irregularities along or nearby the trajectory of the satellite fleet.

Four new applications are incubated on the VTFFTB. First, the electron density in the vicinity of the satellite fleet can be measured without using any in-situ sensor. Second, the global and microscale morphology (e.g., location, size and structure) of ionospheric irregularities can be better observed. Third, different types of ionospheric irregularities in different regions can be measured by customizing several most favorable formation configurations of the LEO satellite formation fleet. For example, the appropriate relative separations, orbit types, formation modes, and measurement algorithms can all be designed, evaluated, and optimized by running HIL simulations on the VTFFTB. Last but not the least, the VTFFTB can also serve as a HIL testbed to study the impact of space weather models on GNSS-related technologies. More GNSS-related applications using the VTFFTB will be further discussed as well.

References

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