GNSS-based Satellite Formation Flying Simulation and Applications to Ionospheric Remote Sensing

YuXiang (Phillip) Peng, Wayne Scales, Thom R. Edwards

Center for Space Science and Engineering Research, Bradley Department of Electrical and Computer Engineering, Virginia Tech, USA

1. Background and Motivation

▪ Satellite formation flight has been applied in many space science missions (e.g. MMS[1], GRACE[2], SWARM[3], etc.). Specifically, CubeSat formation flying concepts offer multidimensional observation flexibility and scalability for future cost-effective mission designs.

▪ As the most popular modern technology of positioning, navigation, and timing, Global Navigation Satellite Systems (GNSS) are commonly utilized in absolute and relative navigation for satellite formation flying.

▪ Given the ionospheric propagation impacts on GNSS signals, GNSS are widely applied to ionospheric remote sensing, including space-based (e.g. radio occultation) as well as ground-based measurements, such as total electron content (TEC) and scintillation.

▪ The robustness of satellite formation flight missions depend on the performance of the Guidance, Navigation and Control (GNC) system. A platform to test the functionality of all the hardware and software systems is needed to demonstrate the feasibility of these missions before they launch. To effectively develop and validate GNC algorithms, assess onboard GNSS receiver(s) performance and emulate various mission scenarios, hardware-in-the-loop (HIL) simulation is needed for designing GPS-based spacecraft formation flying missions.

2. Objective of the Work

▪ Develop a GNSS-based HIL simulation testbed for CubeSat formation flight (a chief & a deputy satellite) with ionospheric remote sensing capability.

▪ Design ionospheric tomography scenarios (e.g. Equatorial Spread F or plasma bubbles) using GPS-based satellite formation flying, and demonstrate the mission concept by running real-time HIL simulations.

▪ Explore the possibilities to apply this technique to more ionospheric phenomena, such as mid-latitude trough, storm-enhanced density (SED), sub-auroral polarization stream (SAPS), etc.

3. Overview of Virginia Tech Formation Flying Testbed

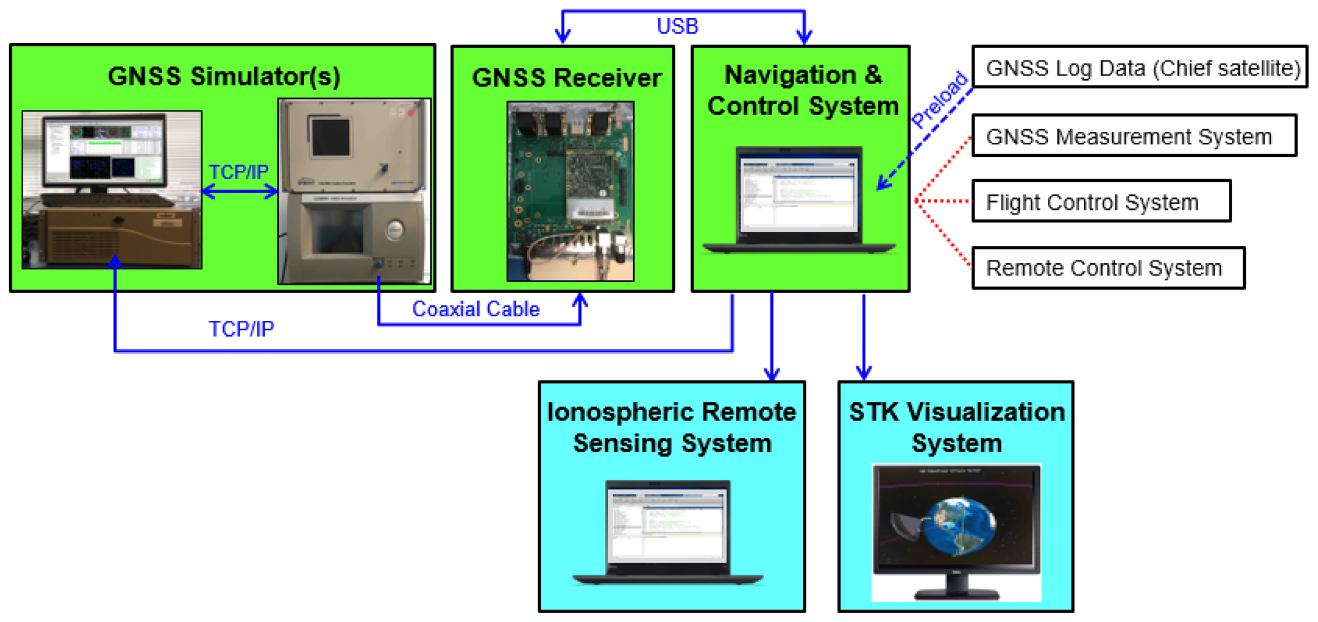

Figure 1. System configuration of the VTFFTB

▪ The Virginia Tech Formation Flying Testbed (VTFFTB), a GNSS-based HIL simulation testbed for spacecraft formation flight, mainly consists of GPS and Galileo RF hardware signal simulators, multi-constellation multi-frequency GNSS receivers, a navigation & control system, an STK visualization system, and an ionospheric remote sensing system.

4. Software Algorithms and Design Methodology

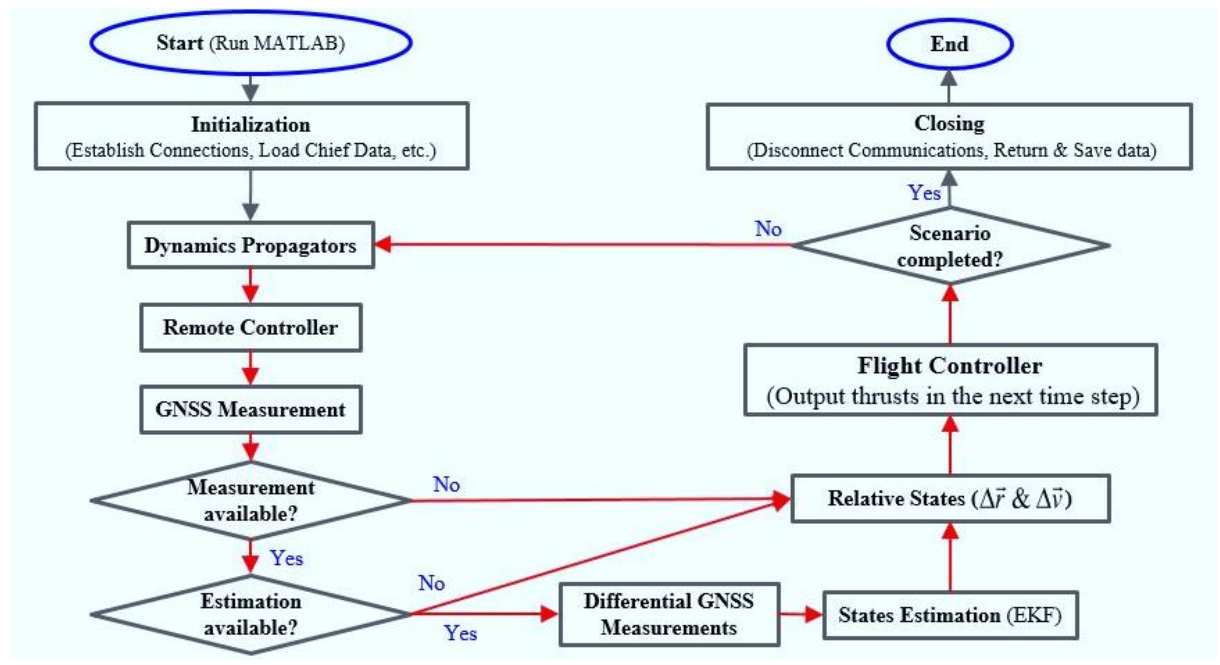

Figure 2. Algorithm flowchart of the navigation & control system

➢ **Measurement model**: Single-differential carrier phase[4]
➢ **Estimation model:** Extended Kalman Filter (EKF)[5]
➢ **Control technique:** State Dependent Riccati Equation (SDRE) based on the Hill-Clohessy-Wiltshire model of relative motion[6]

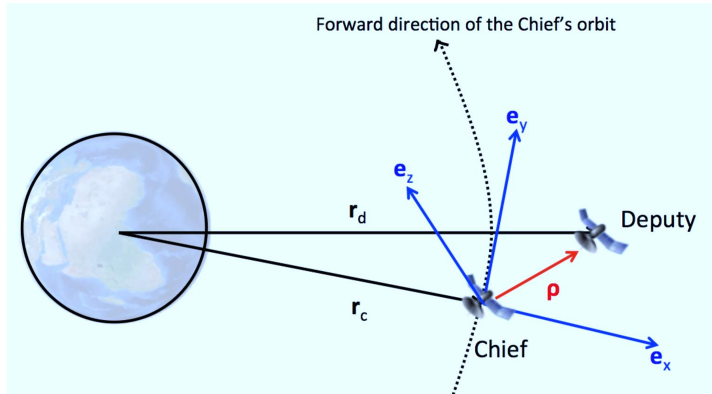

Figure 3. Body-frame (LVLH) of satellite formation flying: $\mathbf{e}_x$ (radial), $\mathbf{e}_y$ (in-track/along-track) and $\mathbf{e}_z$ (cross-track)

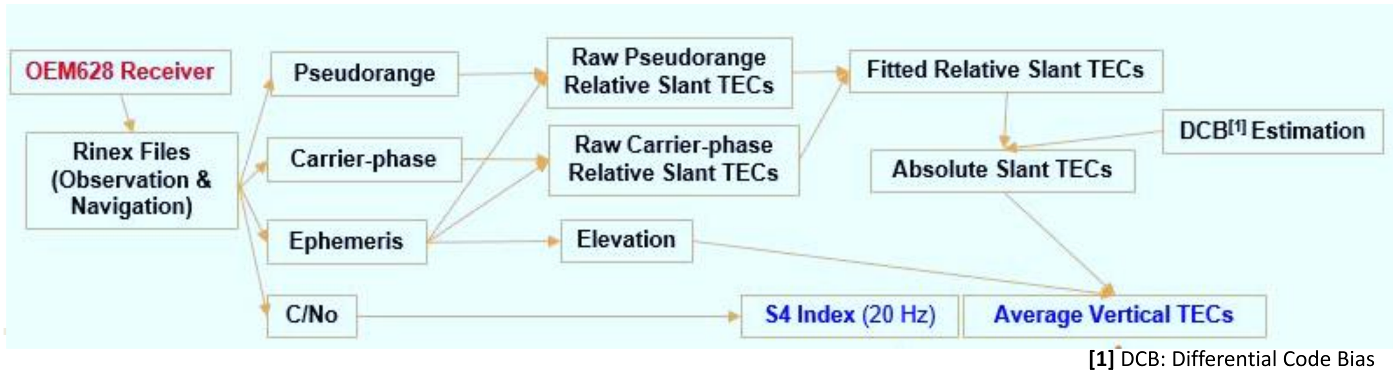

Figure 4. Algorithm flowchart of the ionospheric remote sensing system

5. Validation of Real-time Formation Flight Simulation

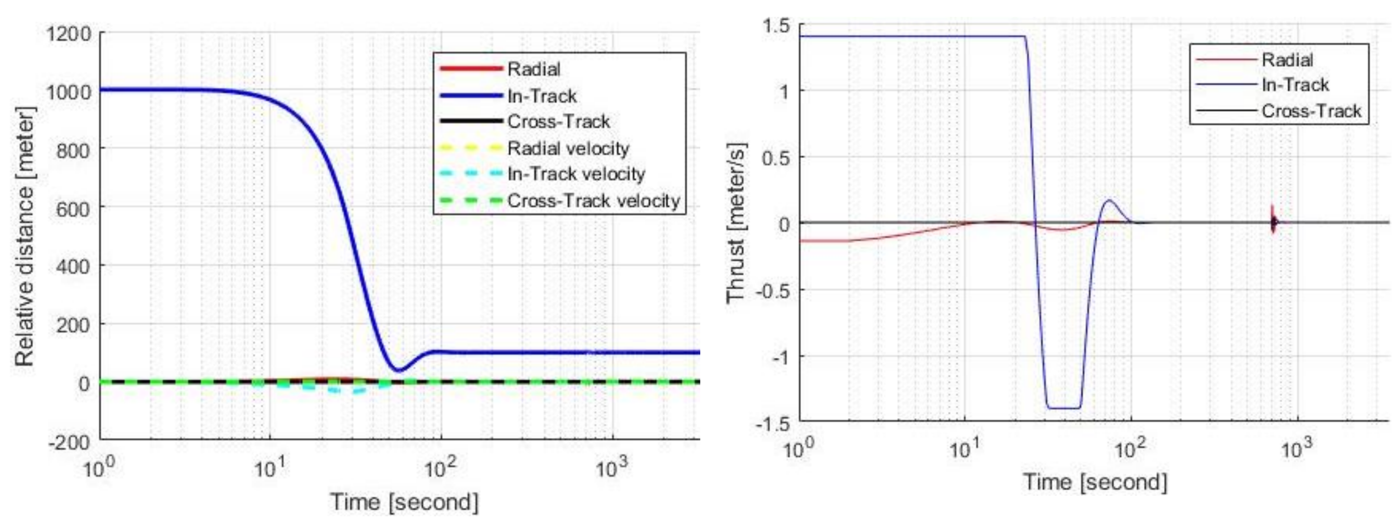

Figure 5. HIL simulation results (Left: relative orbit history; Right: thrust history)

▪ A reference scenario of two Low Earth Orbit (LEO) satellites was simulated successfully with the initial in-track offset of 1000-m and the targeted along-track separation of 100-m. Both software and HIL simulations were performed and analyzed for this 1-hour reference scenario, and the overall results are consistent with the reference simulation results[7]. This demonstrated the feasibility and performance of using VTFFTB for GPS-based real-time spacecraft formation flying simulation.

6. Ionospheric Remote Sensing Demonstration

■ **Scenario Design**

➢ An ionospheric bubble is modelled by setting the user defined vertical TEC profile (using the TIE-GCM model[8]) and amplitude scintillation grid in the VTFFTB. The irregularity region ranges 290 km – 350 km vertically, 20:00 LT to 21:00 LT longitudinally, and 0° to 10° S latitudinally (Above the Jicamarca Radio Observatory in Peru). **[Epoch:** 2016.03.21 01:00:00 UTC]

➢ Low inclination
➢ Small-eccentricity
➢ Varying LEO altitude
➢ Equatorial region monitoring

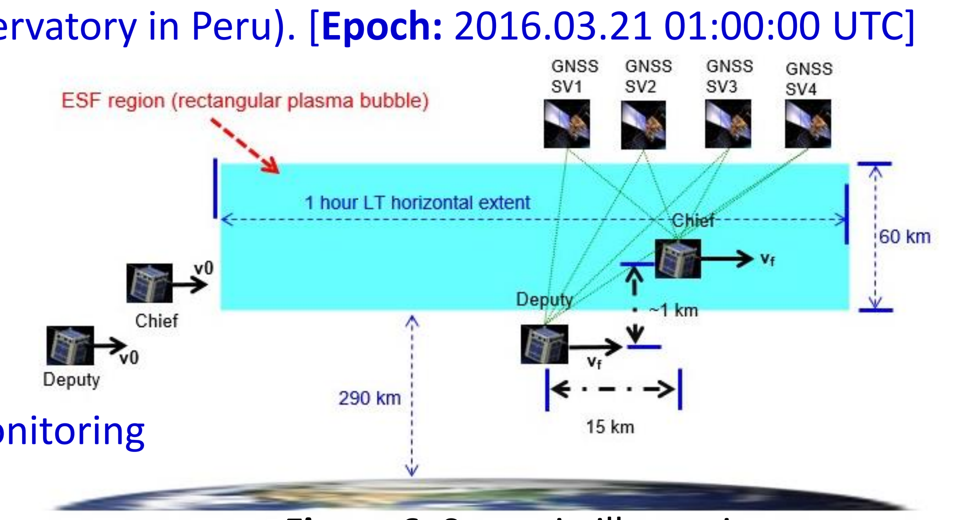

Figure 6. Scenario illustration

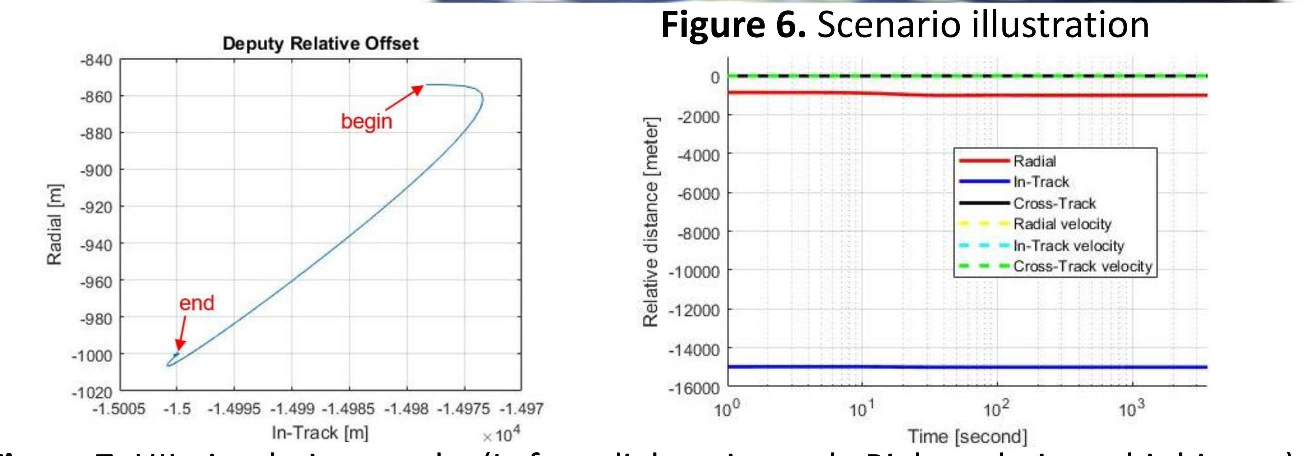

Figure 7. HIL simulation results (Left: radial v.s. in-track; Right: relative orbit history)

■ **Measurement Results**

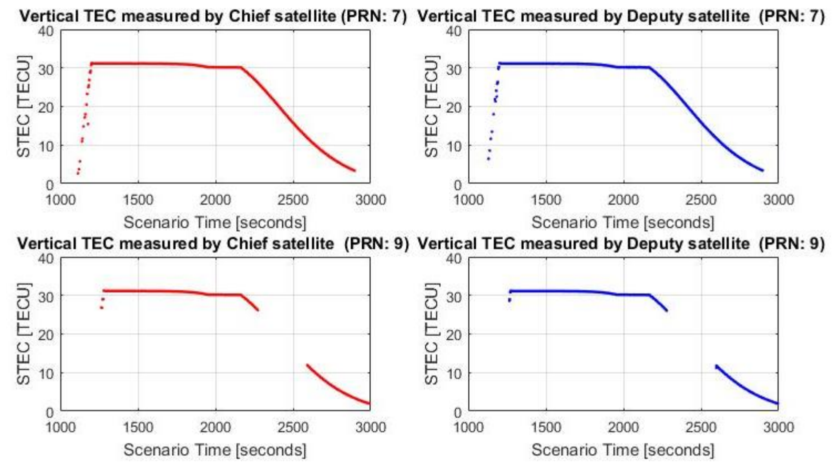

Figure 8. Vertical TEC measured by the chief (left) and deputy (right) relative to SV#7 (up) and SV#9 (down).

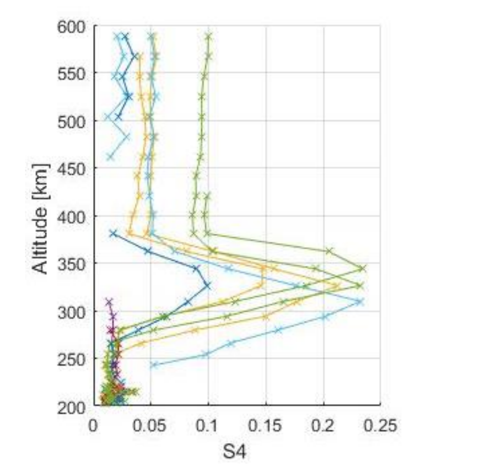

Figure 10. Vertical GPS L1 chief satellite S4 measurements

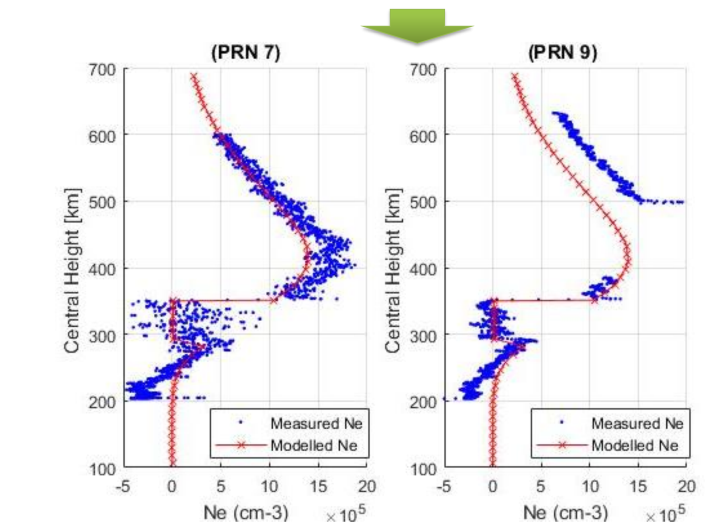

Figure 9. Retrieved electron density versus height using SV#7 (left) and SV#9 (right).

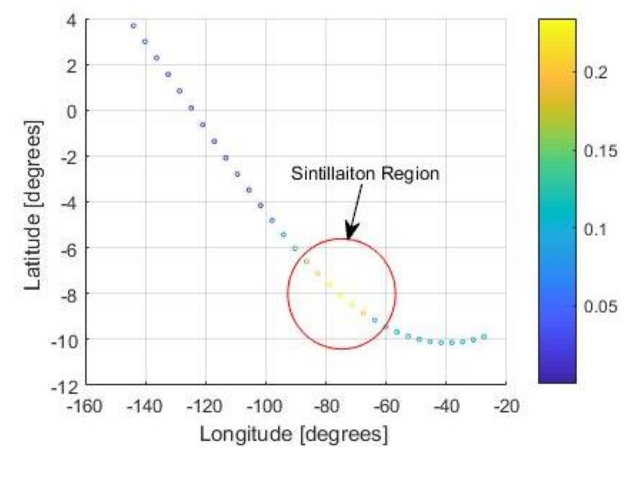

Figure 11. Horizontal GPS L1 chief satellite S4 measurements

7. Summary

▪ The VTFFTB has recently been successfully developed and validated by benchmarking with past closed-loop real-time reference results.

▪ A scenario of GPS-based satellite formation flying missions for ionospheric remote sensing has been proposed, demonstrated, and validated on the VTFFTB by running HIL simulation. Vertical electron density profiles can be retrieved and tomography of the modelled ionospheric irregularities can be studied.

▪ Although some limitations exist in modelling/simulating specific ionospheric phenomena in the current configuration, a number of important applications can be further developed.

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Contact: Yuxiang (Phillip) Peng, M.S.
Organization: Center for Space Science and Engineering Research at Virginia Tech, USA
Email: yuxiang7@vt.edu
LinkedIn: https://www.linkedin.com/in/yuxiang-peng-50a9979a/

References:

1. The MMS mission website. Available at: https://mms.gsfc.nasa.gov/
2. The GRACE mission website. Available at: http://www.csr.utexas.edu/grace/
3. The SWARM mission website. Available at: http://www.esa.int/Our_Activities/Observing_the_Earth/Swarm
4. Busse, F.D., How, J.P., Simpson, J. Demonstration of adaptive extended Kalman filter for low earth orbit formation estimation using CDGPS. J. Inst. Navigation 50 (2), 79–93, 2003.
5. Yaakov, B.S., Li, X. R., Thiagalingam, K., "Estimation with applications to tracking and navigation." New York: Johh Wiley and Sons, 2001.
6. Cloutier, J.R. State-dependent Riccati equation techniques: an overview, in: Presented at the American Control Conference, pp. 923–936, 1997.
7. Park, J.-I., Park, H.-E., Park, S.-Y., Choi, K.-H., Hardware-in-the-loop simulations of GPS-based navigation and control for satellite formation flying, Advances in Space Research, Vol. 46, No. 11, pp. 1451–1465, 2010.
8. The TIE-GCM model website. Available at: https://ccmc.gsfc.nasa.gov/models/modelinfo.php?model=TIE-GCM