PRIVATE GROUP COURSE

Course 338: Ionospheric Effects, Monitoring, and Mitigation Techniques (1.8 CEUs)

Dr. Jade Morton

DAY 1	DAY 2	DAY 3
• Lecture 1: Introduction to ionospheric effects (R1: p879-894; R2) • 1. Fundamental properties of ionosphere impacting satellite navigation • 1.1. Ionosphere electron density profiles • 1.2. Ionospheric refractive index: Appleton-Hartree equation and linear expansions • 1.2.1. Plasma frequency and electron gyrofrequency • 1.2.2. Refractive index for L band signals • 1.2.3. Carrier refractive index vs code refractive index • 1.2.4. Comparison between ionosphere and troposphere refractive index • 2. Ionospheric refraction effects in GNSS measurements: code delay, carrier advance, and total electron content (TEC) • 3. TEC broadcast models for single-frequency receivers • 3.1. Klobuchar model • 3.2. BDGIM • 3.3. NeQuick G • 3.4. Performance comparison of broadcast models • 4. TEC estimation using dual-frequency receiver measurements • 4.1. General approach • 4.2. Code multipath and noise estimation • 4.3. Differential code bias (DCB) estimation • 5. TEC estimation using multi-frequency receiver measurements • 6. TEC estimation using single-frequency receiver measurements	• Lecture 3: Ionospheric Scintillation – Concepts, theory, modeling, and monitoring (R1: p906-914; R4; R5) • 1. Distinctions between refraction and diffraction effects • 2. Scintillation theory: phase screen models • 3. GNSS signal scintillation indicators • 3.1. Amplitude scintillation index • 3.2. Phase scintillation index • 3.3. Frequency scintillation index • 3.4. Decorrelation time • 3.5. Rate of TEC index • 4. Scintillation model for GPS-like signals transmitted from LEO satellites • 4.1. Phase screen model adaption for LEO satellite signals • 4.2. Simulated scintillation effects on LEO satellite-transmitted GPS-like signals at L1, L2, and L5 bands • 5. Scintillation model for VHF, UHF, L, C, and S band signals transmitted from LEO satellites • 5.1. Phase screen model adaption for LEO satellite signals at VHF, UHF, L, C, and S bands • 5.2. Simulated scintillation effects on LEO satellite-transmitted signals at VHF, UHF, L, C, and S bands. • 5.3. Scintillation observations of real VHF and L band signals transmitted from LEO satellites	• Lecture 5: Recent advances in ionospheric effects monitoring and forecasting (R12: p971-994; R13; R14; R15; R16) • 1. GNSS radio occultation • 1.1. Fundamentals of radio occultation (RO) • 1.2. GNSS-RO TEC retrieval • 1.2.1. Dual-frequency retrieval • 1.2.2. Single frequency retrieval • 1.3. Electron density retrieval • 1.4. RO measurement error sources • 1.5. Scintillation observations using GNSS-RO measurements • 1.6. Case studies using COSMIC-2 • 2. GNSS reflectometry • 2.1. Fundamentals of GNSS-reflectometry (GNSS-R) • 2.2. Scintillation observations through delay-Doppler maps • 2.3. Carrier phase-based GNSS-R range measurements • 2.4. Ionospheric TEC retrieval through coherent carrier phase measurements • 2.5. Real GNSS-R ionospheric TEC and scintillation retrieval using low cost CubeSats measurements • 3. Ionospheric effects on signals transmitted from LEO satellites • 3.1. Controlled ionospheric disturbance experiments • 3.2. Ionospheric effects frequency dependence • 3.3. Ionospheric orbit dependence • 4. Machine learning (ML) for ionospheric disturbance detection, classification, and forecasting. • 4.1. Similarities and difference among ionospheric disturbances, satellite oscillator anomalies, and radio frequency interference • 4.2. ML architecture and feature engineering for event detection/classificaiton • 4.3. ML for global TEC forecasting • 4.4. ML for ionospheric disturbance prediction
• Lecture 2: Ionospheric effects correction method (R1: p894-906; R3) • 1. Vertical TEC (VTEC) and mapping function • 2. IGS VTEC products • 3. Network-based VTEC mapping methods • 3.1. Triangular tile method • 3.2. Spherical harmonics basis function method • 3.3. Tomography-based method • 3.4. Other network-based TEC mapping methods • 4. TEC estimation using low-cost receivers • 5. TEC estimation using cell phone measurements • 6. Higher-order ionospheric errors • 6.1. Estimation method • 6.2. Higher-order error impact on position solution accuracy	• Lecture 4: Ionospheric scintillation effects and mitigation techniques (R1: p914 - 928; R6, R7,R8, R9, R10, R11) • 1. Scintillation effects • 1.1. Scintillation effects on carrier phase measurements • 1.2. Scintillation effects on position solution accuracy and availability • 1.3. High latitude scintillation • 1.4. Equatorial scintillation • 1.5. Mid-latitude scintillation • 1.6. Scintillation climatology • 2. Scintillation signal tracking algorithms: architecture, implementations, and performance assessment • 2.1. Ionospheric scintillation monitoring (ISM) receivers: conventional architecture, implementation, and measurements • 2.2. Challenges of scintillation signals on carrier tracking • 2.3. Semi-open loop tracking • 2.4. Open loop tracking • 2.5. State-based GNSS carrier tracking • 2.6. Optimized inter-carrier aiding algorithm • 2.7. Vector processing	See reverse side for reference materials

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We will provide you with information about your training options and happily address all your questions.

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Lecture Reference Materials:

R1. Morton, Y., Z. Yang, B. Breitsch, H. Borne, C. Rino, Chapter 31: Ionospheric Effects, Monitoring, and Mitigation Techniques, in Position, Navigation, and Timing Technologies in the 21st Century, edt. Y. J. Morton, F. van Diggelen, J. J., Spilker, B. Parkinson, Wiley-IEEE Press, 2020.

R2. Evans, M., B. Breitsch, J. Morton, Ionospheric TEC estimations using singal-frequency wideband low elevation GNSS signals, Proc. ION GNSS+, 2024.

R3. Morton, Y., F. van Graas, Q. Zhou, J. Herdtner, Assessment of the higher order ionosphere error on position solutions, Navigation, J. Institute of Navigation, 56(3), 185-193, Fall 2009.

R4. Morton. Y. J., D. Xu, Y. Jiao, Ionospheric scintillation effects on signals transmitted from LEO satellites, Proc. ION GNSS+, DOI: 10.33012/2022.18341, 2022.

R5. Sun, A., Y. J. Morton, C. Rino, J. Lee, Ionospheric scintillation effects across multiple carrier frequency bands transmitted from LEO satellites, submitted to AFRL for public release approval, 2024.

R6. Xu D., Y. Morton, Semi-open loop estimation of GPS carrier phase variations during deep amplitude fading of equatorial ionospheric scintillation, IEEE Trans. Aero. Elec. Sys., DOI: 10.1109/TAES.2017.2764778, PP(99), 2017.

R7. Van Graas, F., Soloviev, A., de Haag, M. U., & Gunawardena, S. Closed-loop sequential signal processing and open-loop batch processing approaches for GNSS receiver design. IEEE Journal of Selected Topics in Signal Processing, 3(4), 571-586, 2009.

R8. Yang, R., Y. Morton, K. Ling, E. Poh, Generalized GNSS signal carrier tracking in challenging environments: part II - optimization and implementation, IEEE Trans. Aero. Elec. Sys., 53(4):1798-1811, DOI:10.1109/TAES.2017.2674198, 2017.

R9. Yang, R., D. Xu, Y. Morton, Generalized multi-frequency GPS carrier tracking architecture: design and performance analysis, IEEE Trans. Aero. Elec. Sys., DOI: 10.1109/TAES.2019.2948535, 2019.

R10. Lashley, M., S. Martin, J. Sennott, Chapter 16: Vector Processing, in Position, Navigation, and Timing Technologies in the 21st Century, edt. Y. J. Morton, F. van Diggelen, J. J., Spilker, B. Parkinson, Wiley-IEEE Press, 2020.

R11. Morton, Y., R. Yang, B. Breitsch, Chapter 15: GNSS Receiver Signal Tracking, in Position, Navigation, and Timing Technologies in the 21st Century, edt. Y. J. Morton, F. van Diggelen, J. J., Spilker, B. Parkinson, Wiley-IEEE Press, 2020.

R12. Mannucci, A., J., W. Williamson, Chapter 33: GNSS Radio Occultation, in Position, Navigation, and Timing Technologies in the 21st Century, edt. Y. J. Morton, F. van Diggelen, J. J., Spilker, B. Parkinson, Wiley-IEEE Press, 2020.

R13. Wang, Y., Y. J. Morton, Ionospheric total electron content and disturbance observations from space borne coherent GNSS-R measurements, IEEE Trans. Geosci. Remote Sensing, DOI: 10.1109/TGRS.2021.3093328, 2021.

R14. Morton, Y. J., H. Bourne, S. Taylor, C. Yang, M. Naudeau, A controlled experiment of ionospheric effects on VHF signals transmitted from a NOAA weather satellite. Proc. ION GNSS+, 2024.

R15. Wu, K., Y. J. Morton, S. T. Dittmann, H. Chang, GNSS Signal Disturbance Detection and Classification Based on LEO Satellite Measurements, Proc. ION ITM, 2024.

R16. Liu, Y., Z. Yang, Y. J. Morton, R. Li, Spatiotemporal deep learning network for high-latitude ionospheric phase scintillation forecasting, Navigation, J. of ION, 70(4), 2023.

R17. Liu, L., Y. J. Morton, Y. Liu, ML Prediction of Global Ionospheric TEC Maps, Space Weather, DOI:10.1029/2022SW003135, 2022.

R18. Liu, L., Y. J. Morton, Y. Liu, Machine learning prediction of storm-time high latitude ionospheric irregularities from GNSS-derived ROTI maps, Geophy. Res. Lett., DOI: 10.1029/2021GL095561, 2021.