VirginiaTech
Invent the Future

Multi-Constellation GNSS Scintillation at Mid-Latitudes

Marc H. Jean, James P. Conroy and Wayne A. Scales

Bradley Department of Electrical and Computer Engineering, Virginia Tech University, Blacksburg, Virginia, USA, 24061

Outline

- Introduction & Motivation
- Background
  - Scintillation
  - GNSS
- Observations & Analysis
  - High Geomagnetic Activity
  - Low Geomagnetic Activity
- Conclusions

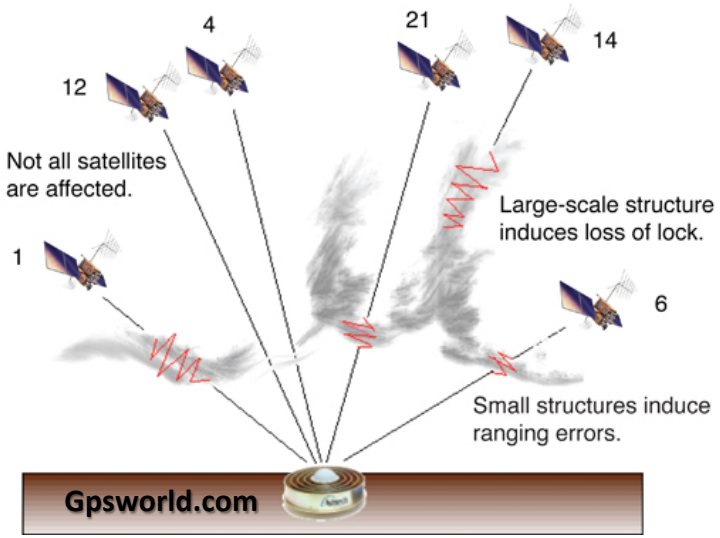
Introduction

- Ionospheric scintillation can severely degrade L band (1-2 GHz) Global Navigation Satellite Systems (GNSS) signals
- Commonly believed that mid-latitude scintillation is negligible
- Recently availability mid-latitude SuperDARN HF radar data:
  - Mid-latitude features leading to scintillations may occur more frequently than thought
  - Need to understand the source mechanisms of mid-latitude irregularities and scintillation data my provide insight
- Objectives
  - Acquire multi-constellation, multi-frequency scintillation data during geomagnetically active and quite periods to determine nature, severity & frequency of mid-latitude scintillations
  - Compare to past research done to high and low latitudes

Demonstrated the potential for severe scintillation at mid-lats

Scintillation

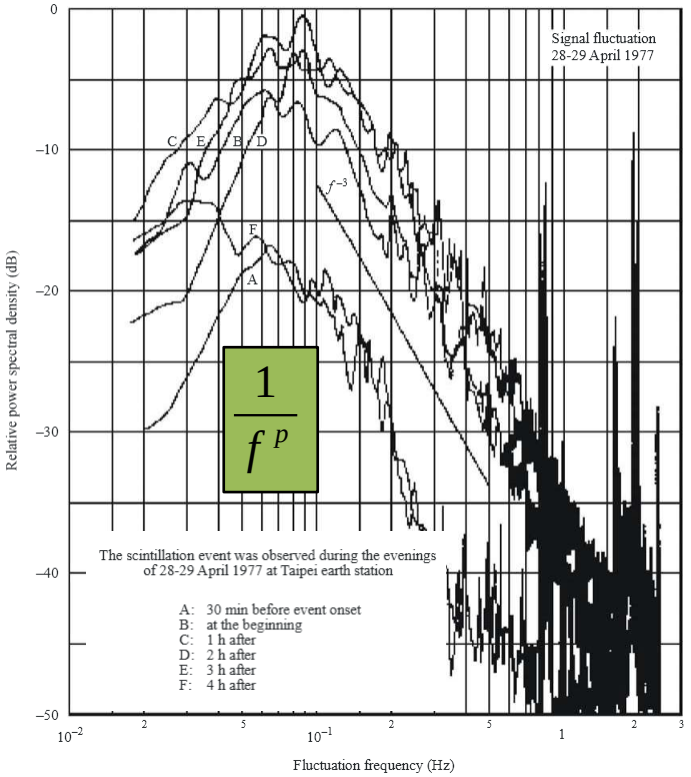
- TEC along travel path
  - Phase shift
  - Time advance
  - Phase variations along a wave front leads to interference
- Previous research suggests
  - Amp: prominent at low lats
  - Phase: prominent at high lats
- Metrics: S4, σ_ϕ,p



Channel Fluctuation Example (ITU-R P.531-12)

FIGURE 8

Power spectral density estimates for a geostationary satellite (Intelsat-IV) at 4 GHz

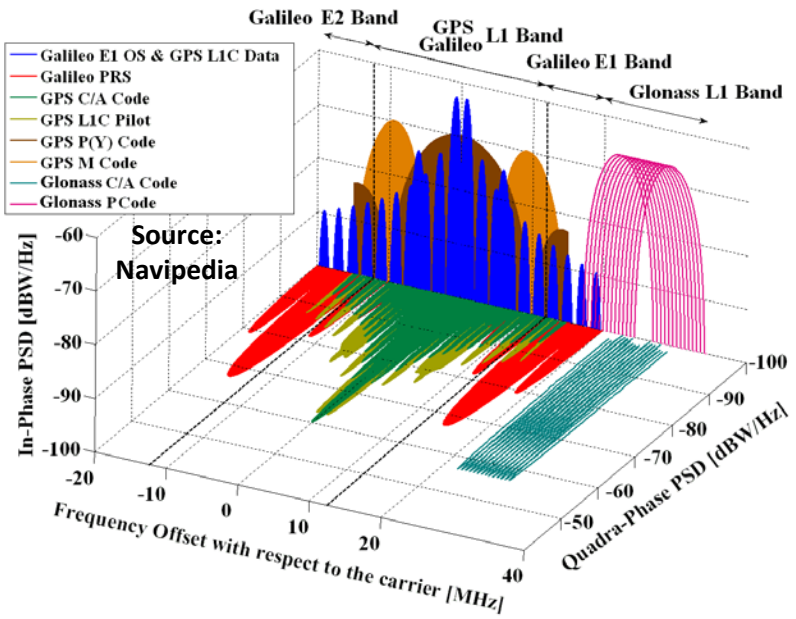


$$S_4 = \frac{\langle I^2 \rangle - \langle I \rangle^2}{\langle I \rangle^2}, \quad \sigma_\phi^2 = \langle \phi^2 \rangle - \langle \phi \rangle^2$$

Can severely degrade GNSS performance

GNSS Signals: Overview of Analyzed Constellations

System	Bands (GHz)	Modulation	Encoding	Chips	Chip Rate (MHz)
GPS (USA)	L1 (1.575), L2 (1.227), L5 (1.176)	BPSK, BOC, TMBOC	CDMA	1023	1.023
GLONASS (Russia)	G1 (1.598 –1.609), G2 (1.242–1.251)	BPSK	CDMA/FDMA	511	0.511
Galileo (EU)	E1 (1.575), E5a (1.176), E5b (1.207)	CBOC/BPSK, AltBOC/8-PSK	CDMA	4092-102300	1.023, 10.23



Potential impact of signal differences

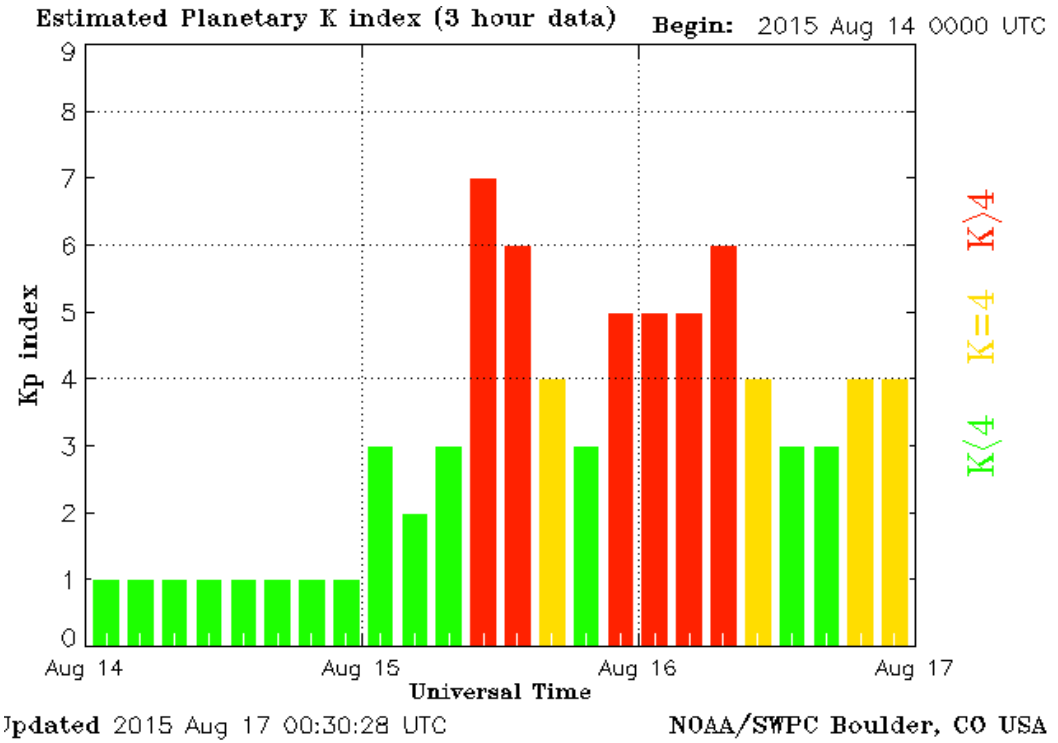
- Integration, doppler & ranging accuracy
- Increased processing options for newer constellations
- Noise bandwidth and range resolution
- Spread spectrum & interference mitigation

Ever-increasing coverage with new satellites having different signal characteristics

C. J. Hegarty and E. Chatre, "Evolution of the Global Navigation SatelliteSystem (GNSS)," in Proceedings of the IEEE, vol. 96, no. 12, Dec. 2008.
European GNSS (Galileo) Open Service Signal In Space Interface Control Document (OS SIS ICD), Issue 1.2, European Union, 2015
BeiDou Navigation Satellite System Signal-In-Space Interface Control Document , 2013.)

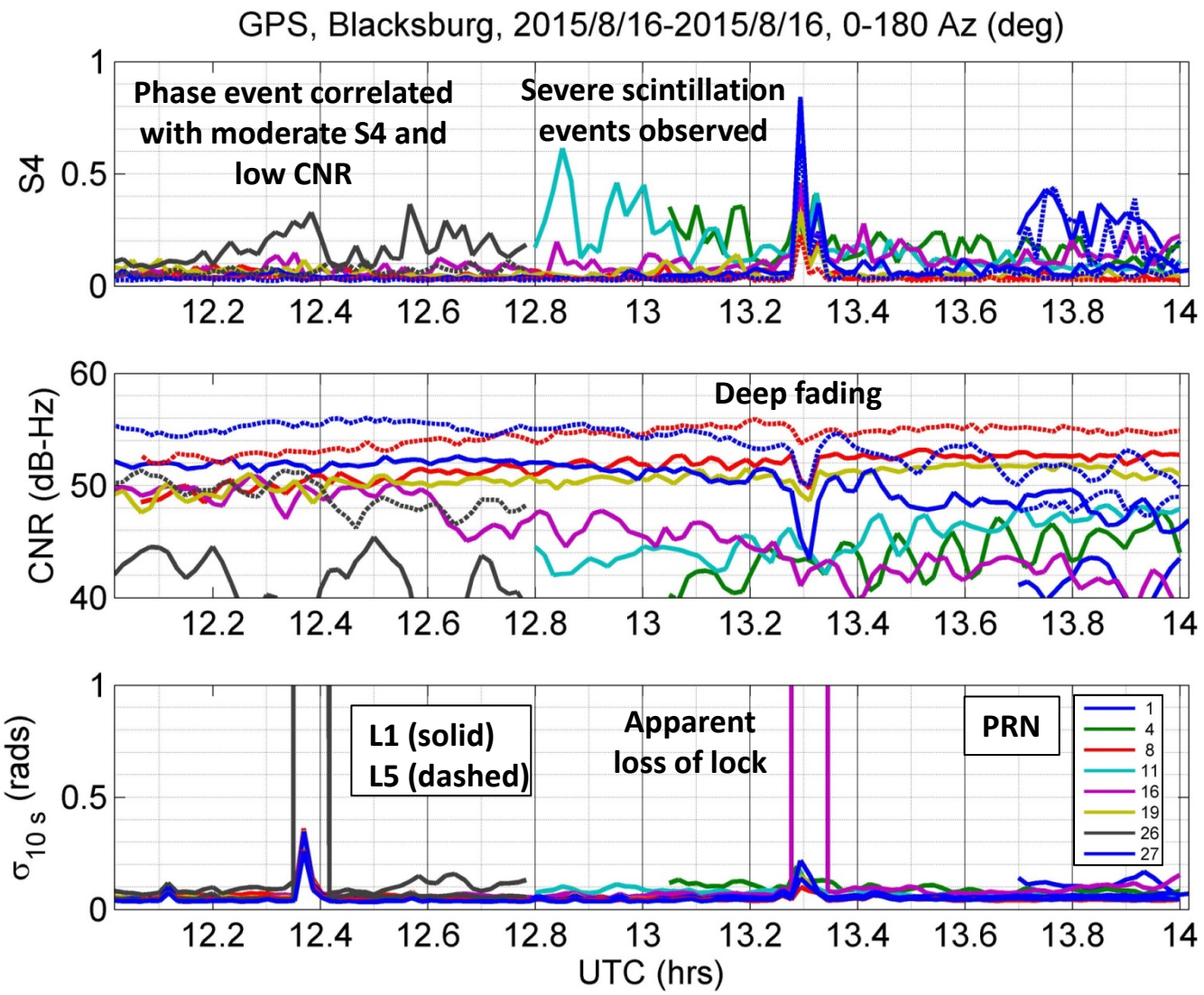
Data Acquisition & Processing

- Novatel GP6-Station receiver
  - Blacksburg, VA (37.2° N, 80.4° W)
  - 50 Hz, 6th order high pass
  - Elevations >10 deg
- Data acquired
  - GPS (L1CA, L2C, L5)
  - GLONASS (L1CA, L2C)
  - GALILEO (L1BC, E5a, E5b)
- Analysis periods
  - Storm: 8/16/15
  - Quiet: 8/4/16-8/15/16
- SuperDARN HF radar
  - Blackstone, VA (37.0804° N, 77.9972° W)
  - Measured E and F region back scatter



Amplitude scintillation up 0.9 observed during storm

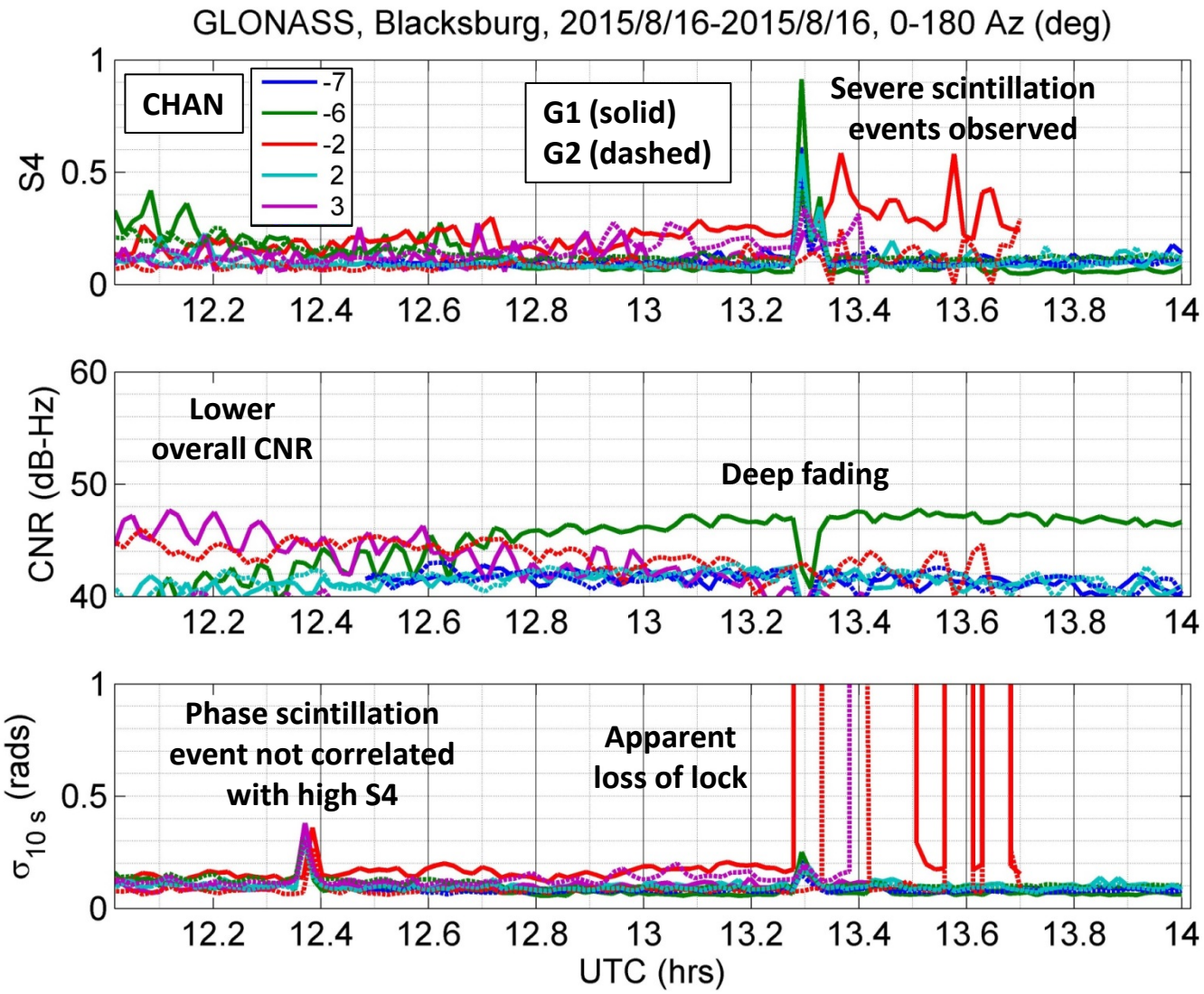
Results & Analysis: 8/16/2015 (GPS)



Phase event correlated with moderate S4 and low CNR

Severe scintillation correlated with deep fading & apparent loss of lock

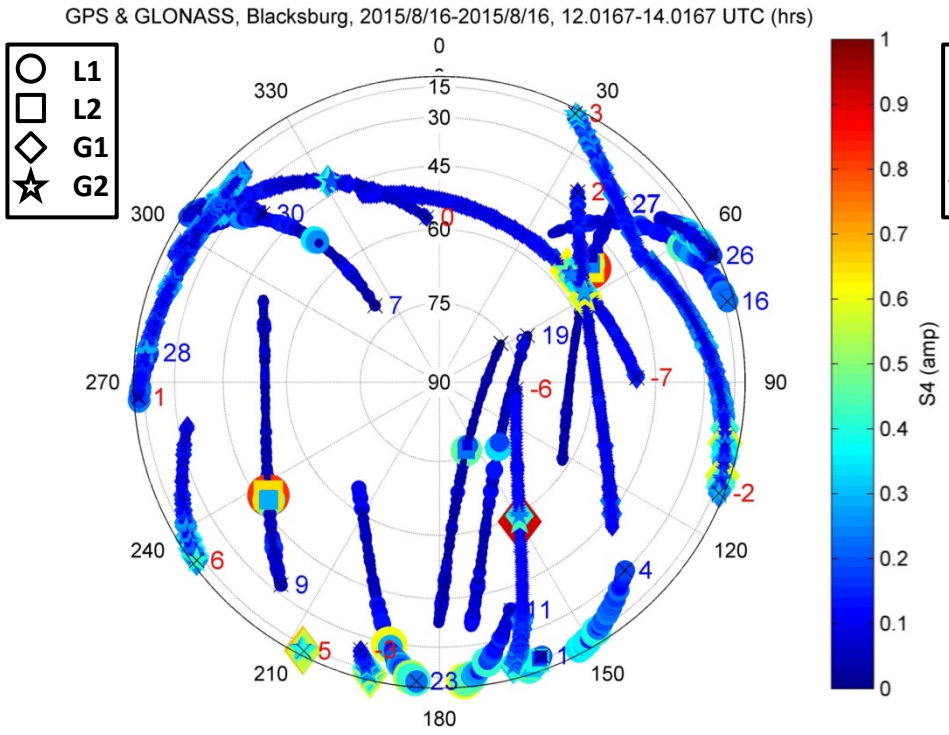
Results & Analysis: 8/16/2015 (GLONASS)

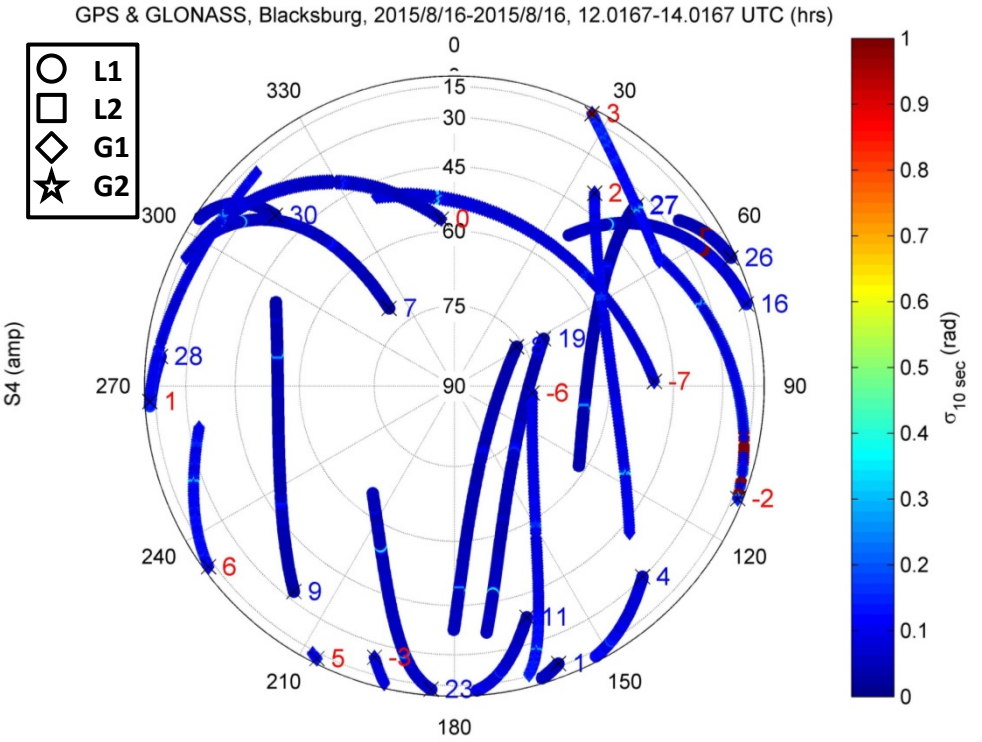


Phase event correlated with low CNR but low S4

Severe scintillation correlated with deep fading & apparent loss of lock

Results & Analysis: 8/16/2015 (GPS & GLONASS)





Modest phase scintillation

Severe scintillation events highly distributed

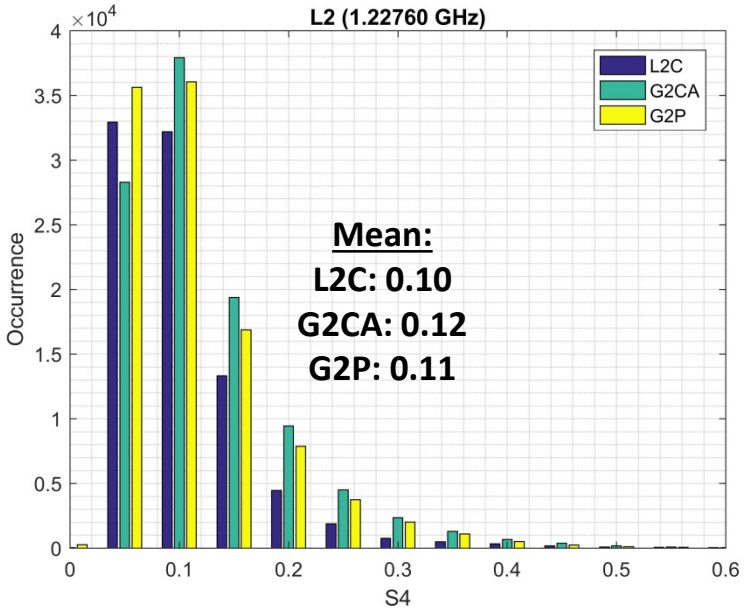
Results & Analysis: 8/16/2015 (GPS & GLONASS)

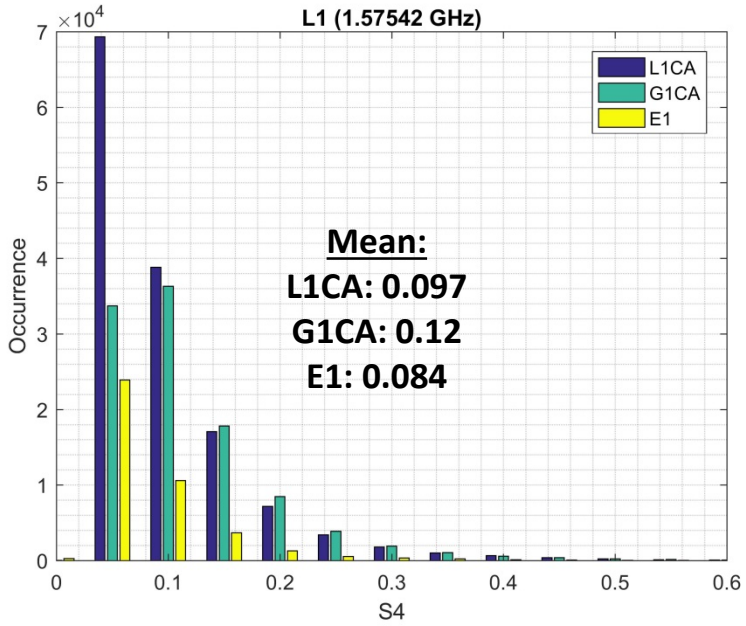
Sat Type	PRN	Band	Max S4	Max Phase φ (rads)	Az. (deg)	El. (deg)
GPS	9	L1	0.81	0.35	236	47
GPS	9	L5	0.65	0.26	236	47
GPS	27	L1	0.84	0.35	52	51
GPS	27	L5	0.64	0.26	52	51
GLONASS	14	G1	0.61	0.37	48	56
GLONASS	14	G2	0.46	0.28	48	56
GLONASS	17	G1	0.91	0.37	150	58
GLONASS	17	G2	0.42	0.30	150	58
Galileo	19	E1	0.39	0.35	214	14
Galileo	19	E5A	0.55	0.26	211	9
Galileo	19	E5B	0.56	0.27	211	9

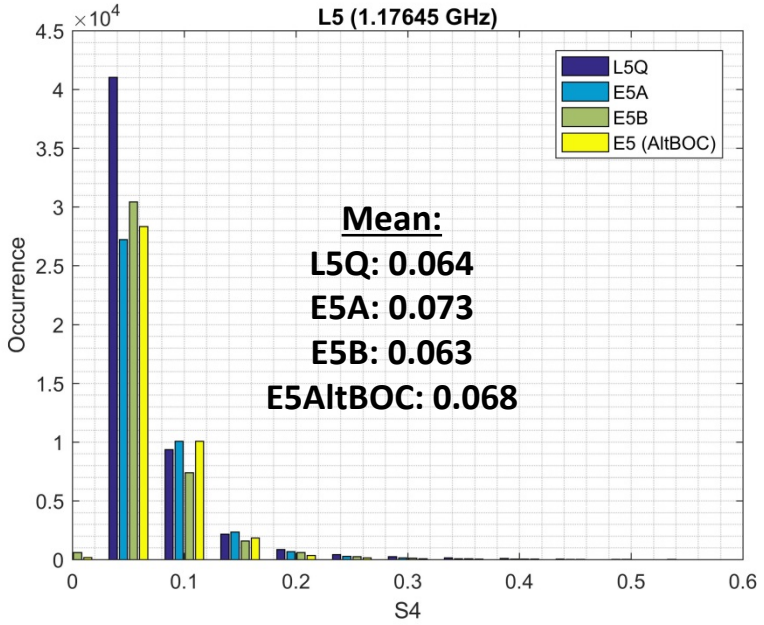
E5ab phase scintillation less severe than E1; S4 for L5<L1, G2<G1

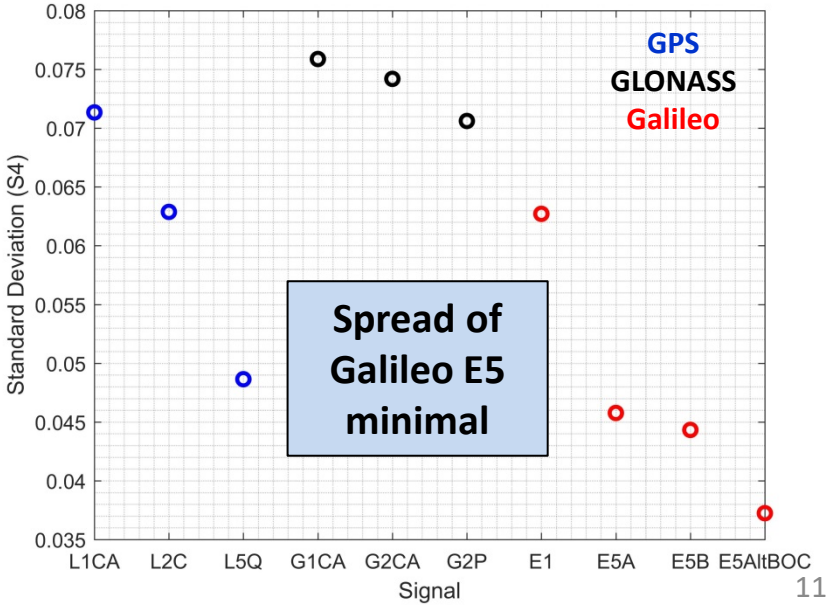
S4 values up to 0.91 with simultaneous change for satellites

Results & Analysis: Blacksburg, VA, 8/4/16-8/15/16 (El 10 deg>)

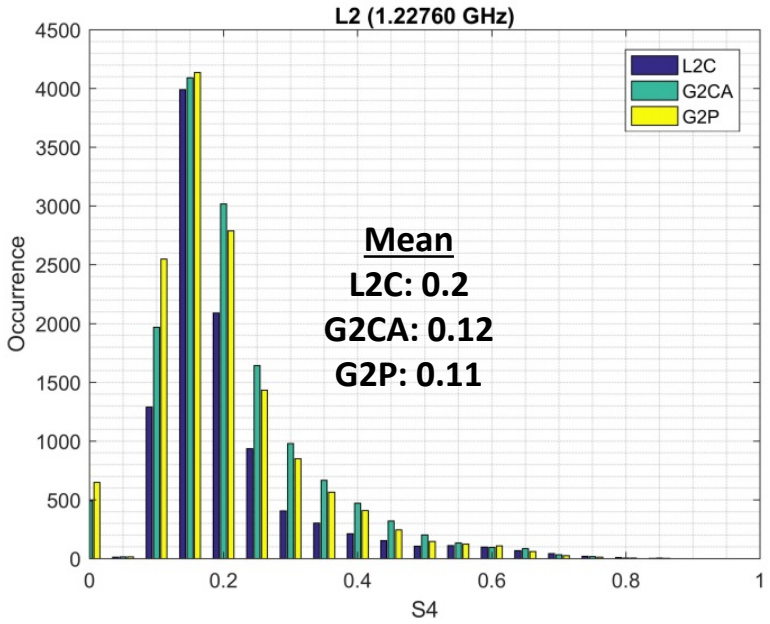


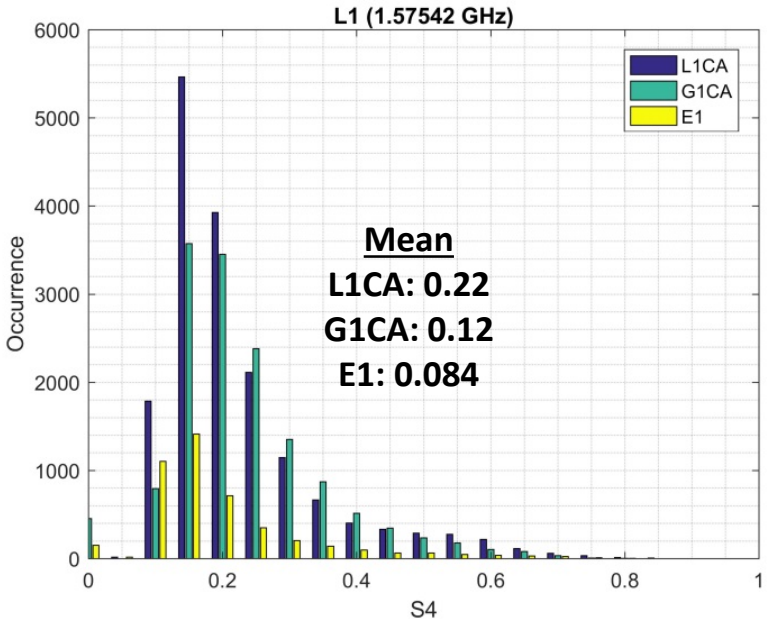


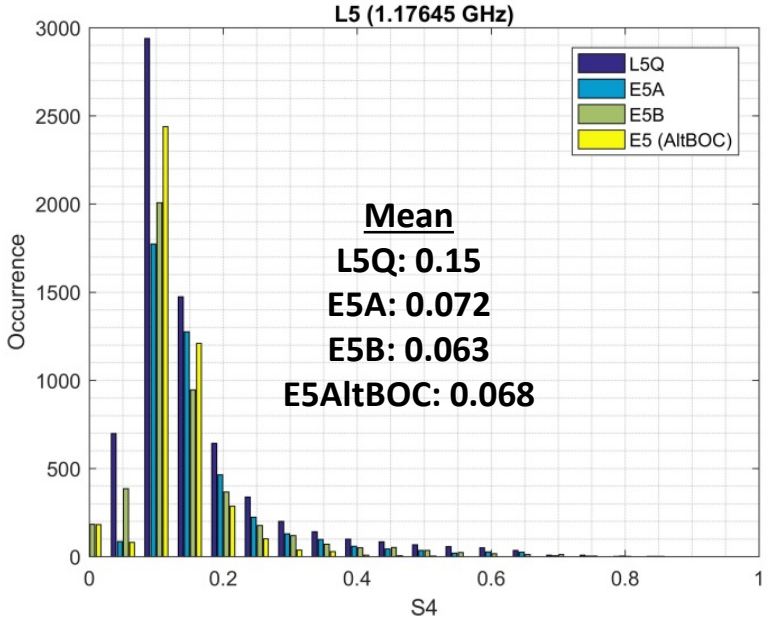


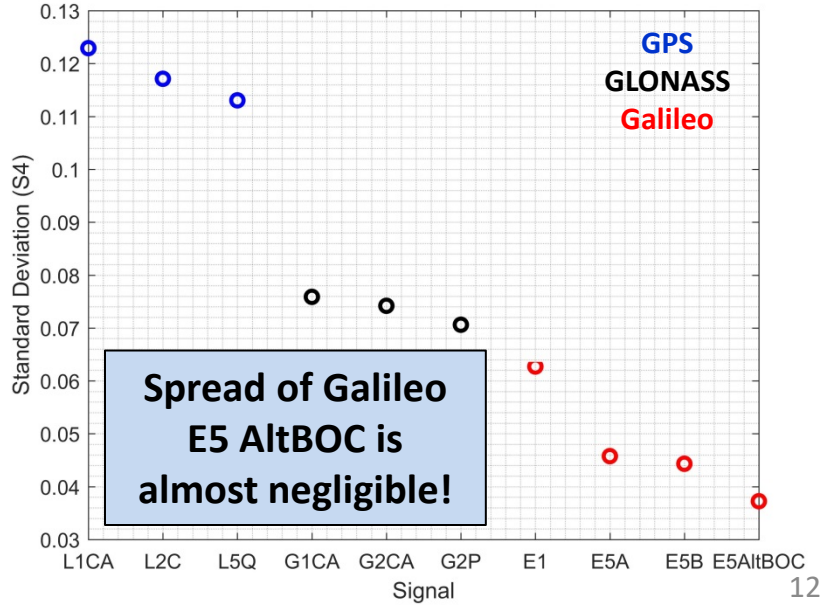


Results & Analysis: Blacksburg, VA, 8/4/16-8/15/16 (El 10 deg<)

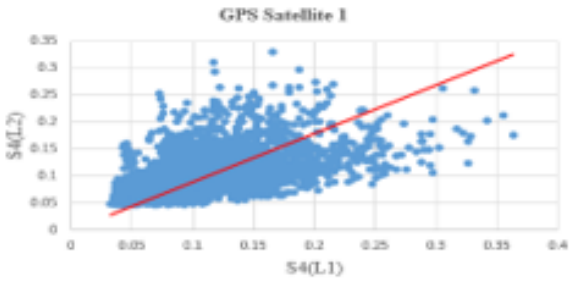




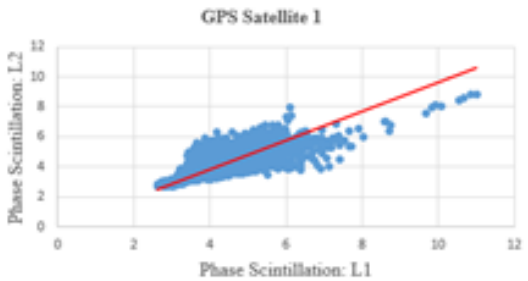




Results & Analysis: Blacksburg, VA, 8/4/16-8/15/16 (correlation)

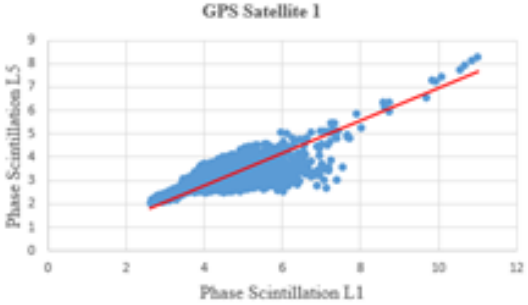


(L1 vs. L2) R = 0.8949

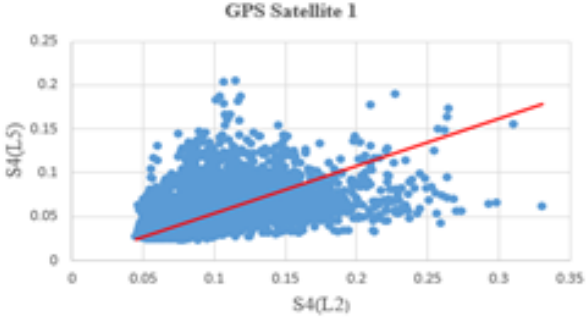


(L1 vs. L2) R = 0.9645

(L1 vs. L5) R = 0.5107



(L1 vs. L5) R = 0.6959



(L2 vs. L5) R = 0.5416

(L2 vs. L5) R = 0.7143

GPS Amp:

- **L1 vs. L2; R = 0.89**
- **L1 vs. L5 R = 0.51**
- **L2 vs. L5 R = 0.54**

GPS Phase:

- **L1 vs. L2; R = 0.96**
- **L1 vs. L5; R = 0.69**
- **L2 vs. L5; R = 0.71**

GLONASS Amp:

- **G1 vs. G2; R = 0.85**

GLONASS Phase:

- **G1 vs. G2; R = 0.80**

Galileo Amp:

- **E1 vs. E5A; R = 0.72**
- **E1 vs. E5B; R = 0.64**
- **E5A vs. E5B; R = 0.84**

Galileo Phase:

- **E1 vs. E5A; R = 0.87**
- **E1 vs. E5B; R = 0.79**
- **E5A vs. E5B; R = 0.90**

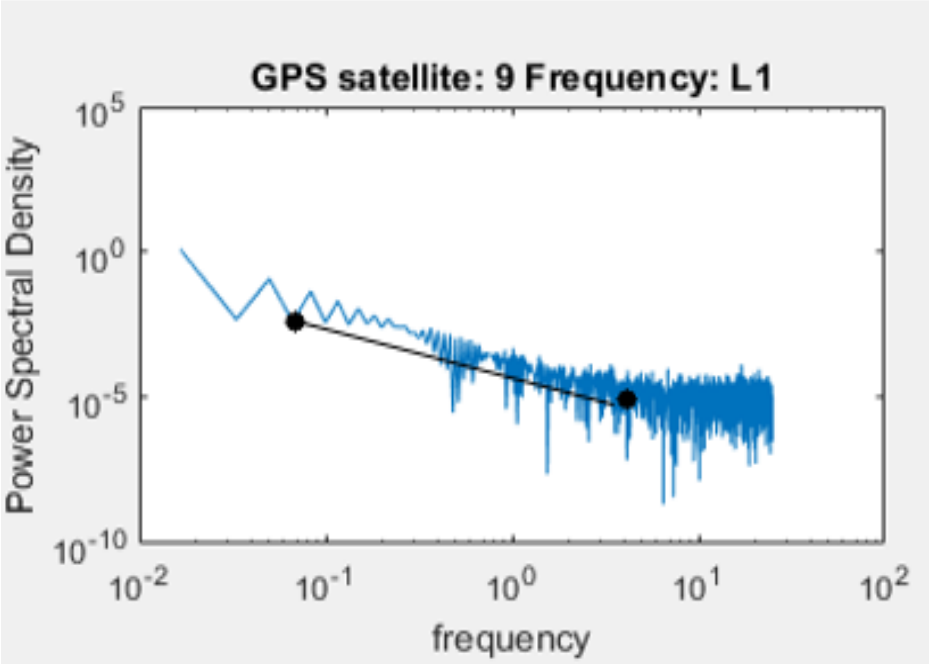
Bands 1 and 2 amplitude and phase scintillation reasonably well correlated; not as well correlated with band 5

Conclusions & Future Work

- High S4 observed at mid-latitudes
  - Relatively rare
  - Resulted in apparent loss of receiver lock
- S4 may be more prominent at mid-latitudes than phase scintillation
- During quiet conditions
  - L5 slightly outperform L1 and L2
  - L1/G1 scintillation highly correlated with L2/G2
  - E5B scintillated less than E1 and E5A, but has a high correlation to E5A
  - Average of spectral index $p<2$; indicates modest scintillation
- Newer, more advanced signals utilized by Galileo
  - Lower scintillation mean and standard deviation than GPS and GLONASS
  - Galileo E6AltBOC had excellent performance under high multipath conditions
- Future work
  - Develop deeper understanding and determine how to interpret and/or utilize the apparent resistance of Galileo signals to scintillation
  -

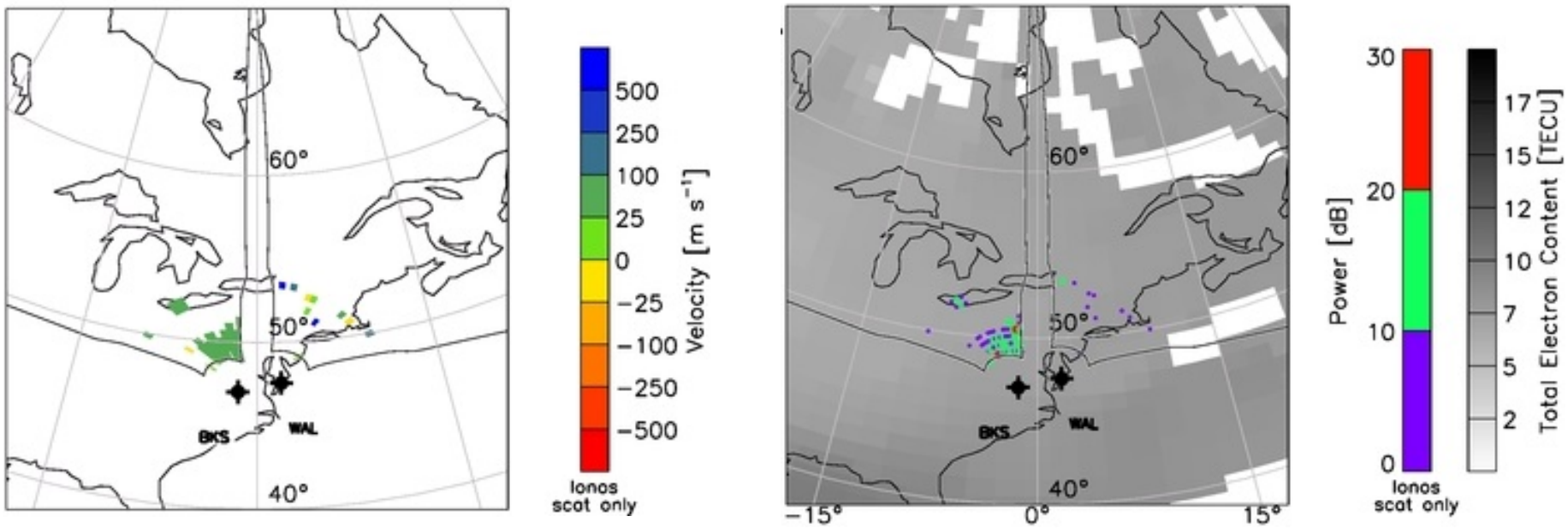
Results & Analysis: Blacksburg, VA, 8/4/16-8/15/16 (spectral slope)

- Linear data fit from Fresnel frequency to noise floor, used to estimate means spectral index *p*
  - GPS: 1.92
  - GLONASS: 1.65
  - Galileo: 1.57
- Average Fresnel frequency for GPS data: 0.0966 Hz; drift velocity on the order of 50 m/s



Suggests that under quiet conditions, the mid-latitude Ionosphere is composed of slow-moving plasma creating minimal turbulence

Results & Analysis: 8/16/2015 (SuperDARN)



Data processed over 5 minute interval

Slow-moving features classified as Ionospheric plasma backscatter located in approximately the same location and time as the scintillation events

May provide some estimate of the spatial location and extent of features which resulted in mid-latitude scintillation event; additional spatial correlation work needed

References

[1] I.-R. R. P.531-12, *Ionospheric propagation data and prediction methods required for the design of satellite services and systems*. International Telecommunications Union, 2013.

[2] S.-B. A. S. I. W. Group, "How irregularities in electron density perturb satellite navigation systems [online]," *Available: http://gpsworld.com/*, 2012, April.

[3] H. J. Strangeways, Y. H. Ho, M. H. O. Aquino, Z. G. Elmas, H. A. Marques, J. F. G. Monico, and H. A. Silva, "On determining spectral parameters, tracking jitter, and gps positioning improvement by scintillation mitigation," *Radio Science*, vol. 46, pp. 1–14, Dec 2011.

[4] Y. Jiao and Y. T. Morton, "Comparison of the effect of high-latitude and equatorial ionospheric scintillation on gps signals during the maximum of solar cycle 24," *Radio Science*, vol. 50, pp. 886–903, Sept 2015.

[5] I. F. Grant, J. W. MacDougall, J. M. Ruohoniemi, W. A. Bristow, G. J. Sofko, J. A. Koehler, D. Danskin, and D. Andre, "Comparison of plasma flow velocities determined by the ionosonde doppler drift technique, superdarn radars, and patch motion," *Radio Science*, vol. 30, pp. 1537–1549, Sept 1995.

[6] A. Eltrass, W. A. Scales, P. J. Erickson, J. M. Ruohoniemi, and J. B. H. Baker, "Investigation of the role of plasma wave cascading processes in the formation

of midlatitude irregularities utilizing gps and radar observations," *Radio Science*, vol. 51, pp. 836–851, June 2016.

[7] C. J. Hegarty and E. Chatre, "Evolution of the global navigation satellitesystem (gnss)," *Proceedings of the IEEE*, vol. 96, pp. 1902–1917, Dec 2008.

[8] S. Delay, C. S.Carrano, K. M. Groves, and P. H. Doherty, ""keynote - a statistical analysis of gps l1, l2, and l5 tracking performance during ionospheric scintillation, in *Proceedings of the ION 2015 Pacific PNT Meeting, Honolulu, Hawaii, April 2015, pp. 1-9.*, 2015.

[9] N. Hlubek, J. Berdermann, V. Wilken, S. Gewies, and N. Jakowski, "Scintillations of the gps, glonass, and galileo signals at equatorial latitude," in *J. Space Weather Space Climate., 4, A22.*, 2014.

[10] K. Borre, D. Akos, N. Bertelson, P. Rinder, and S. H. Jensen, *A Software-Defined GPS and Galileo Receiver: A Single-Frequency Approach*. Birkhauser, 2007.

[11] A. J. V. Dierendonck, J. Klobuchar, and Q. Hua, "Ionospheric scintillation monitoring using commercial single frequency c/a code receivers," in *Proceedings of the 6th International Technical Meeting of the Satellite Division of The Institute of Navigation*, (Salt Lake City, UT), pp. 1333–1342, September 1993.