PNT-Reliant Industries

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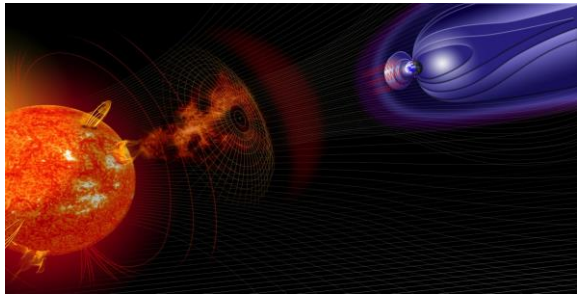
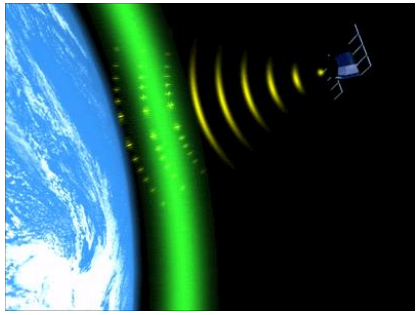
Positioning, Navigation and Timing

- PNT is critical to defense, agriculture, transportation, marine, surveying and emerging industry applications
- Timing applications include financial services and mobile networks
- Currently approx $200B annual GNSS revenue (devices and services)
- Growing added-value markets for road and consumer solutions (>50% of global GNSS revenue)

Vulnerability
Space weather impact on PNT applications?





Space weather:
solar-terrestrial interaction, solar flares, solar radio bursts, geomagnetic storms

GNSS observations:
RF propagation effects, range errors, scintillation effects, signal disruptions

Service providers and users:
risk and reliability

Positioning, Navigation and Timing: GNSS

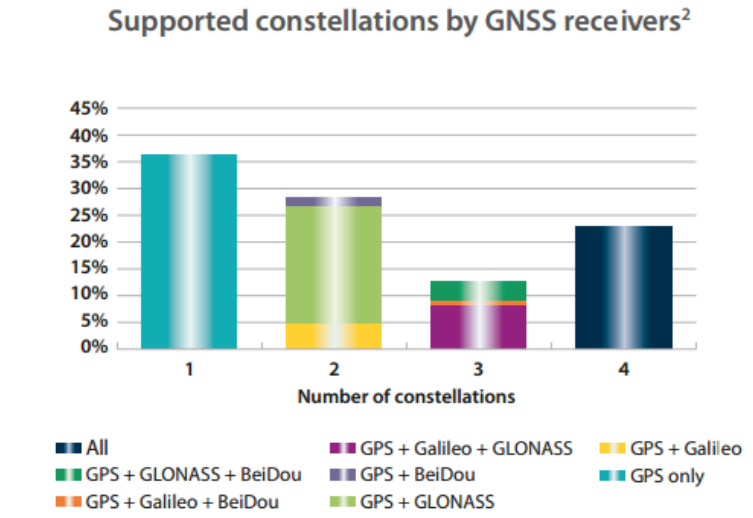
Single frequency civilian (L1):
- Legacy GPS
- Some GPS+GLONASS
- Broadcast ionosphere model
- 10 m positioning accuracy
- With augmentations (DGPS, SBAS) meter-level positioning accuracy

Multi-frequency civilian (L1,L2,L5):
- Rapidly emerging multi-frequency GPS+GLONASS+Galileo
- Exploits carrier phase observations
- Dual-frequency ionosphere corrections
- Susceptible to scintillation
- Meter-level positioning accuracy

Precise Point Positioning (L1,L2,L5):
- GPS+GLONASS+Galileo
- Relies on carrier phase observations
- Dual-frequency ionosphere corrections
- Susceptible to scintillation/diffraction
- Precise clock and orbit products
- Decimeter-level positioning accuracy

>150 GNSS satellites (GPS, GLONASS, Galileo, Beidou/COMPASS)

>500 signals

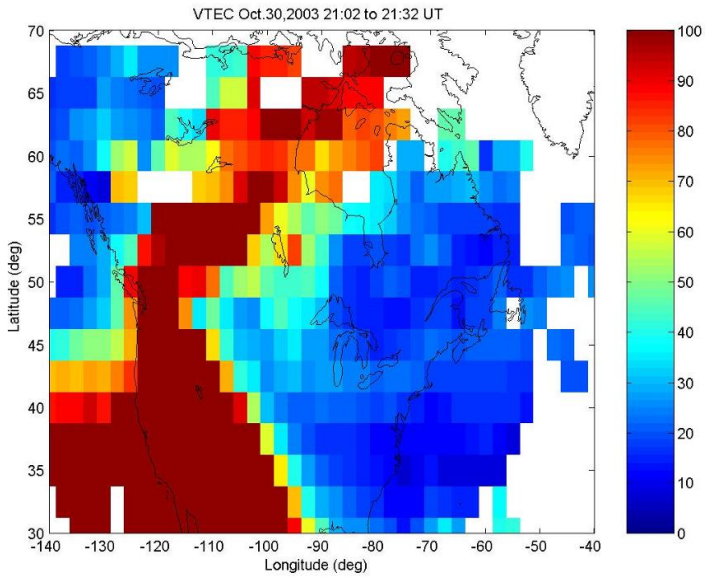


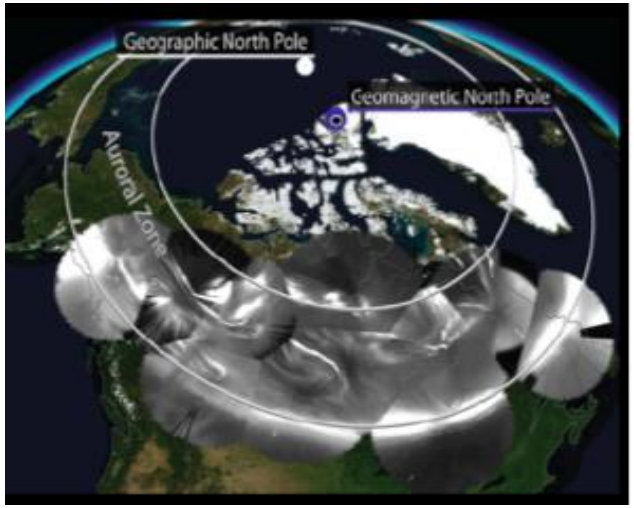
² shows percentage of receivers capable of tracking 1, 2, 3 or all the 4 GNSS constellations

Source: GNSS User Technology Report, GSA

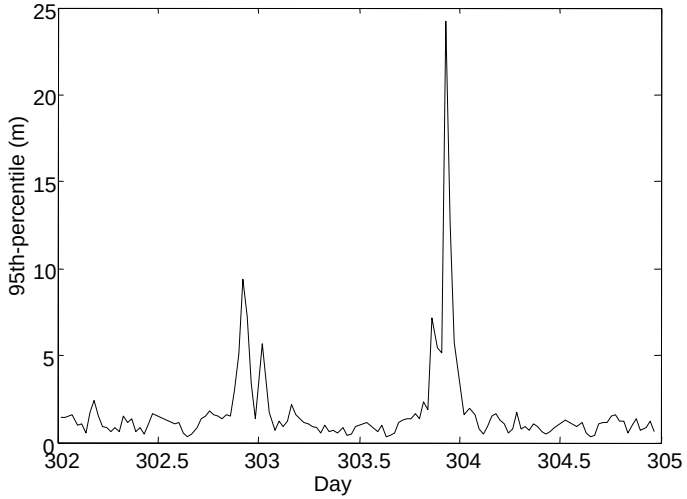
Ionospheric Phenomena Affecting GNSS

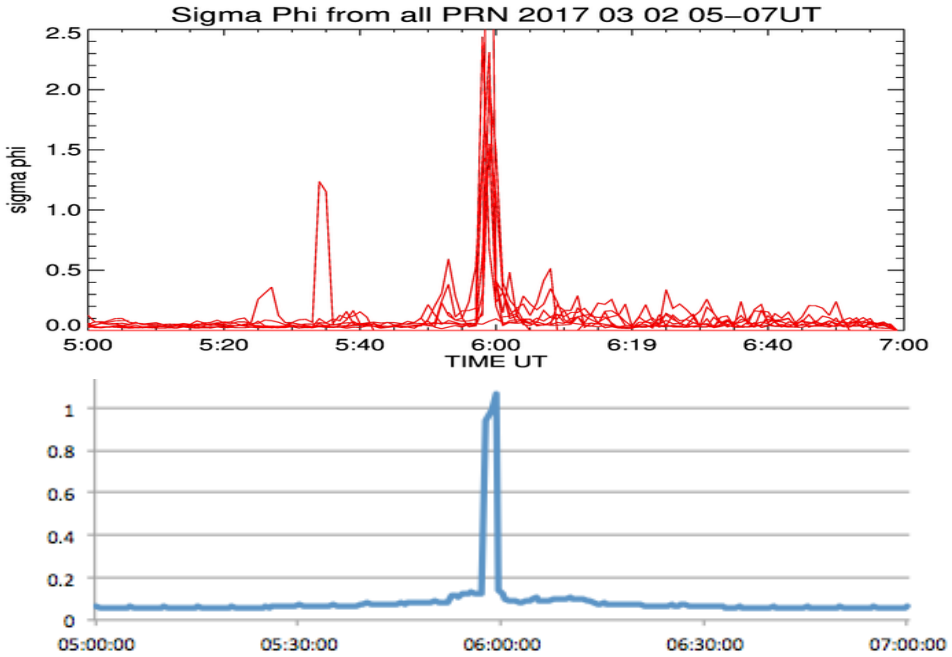
Propagation Conditions





Impact





Safety-critical

High accuracy

Ionospheric Phenomena Affecting GNSS

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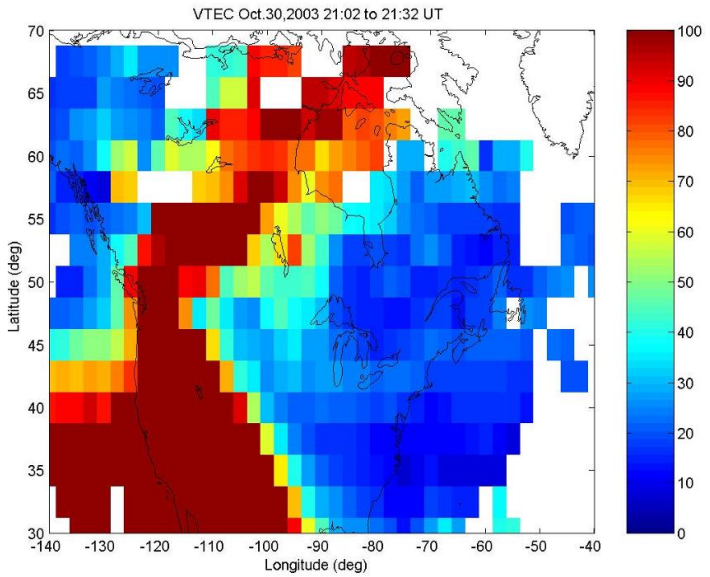

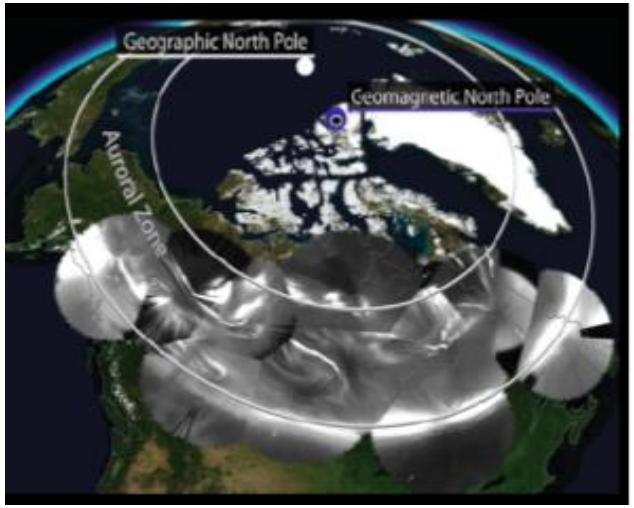

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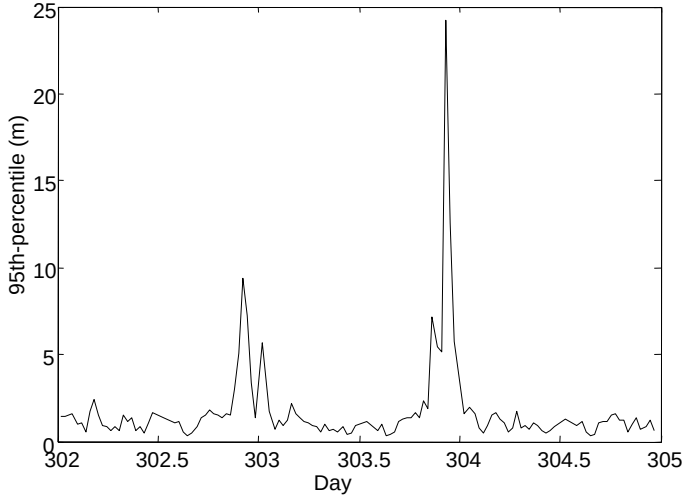

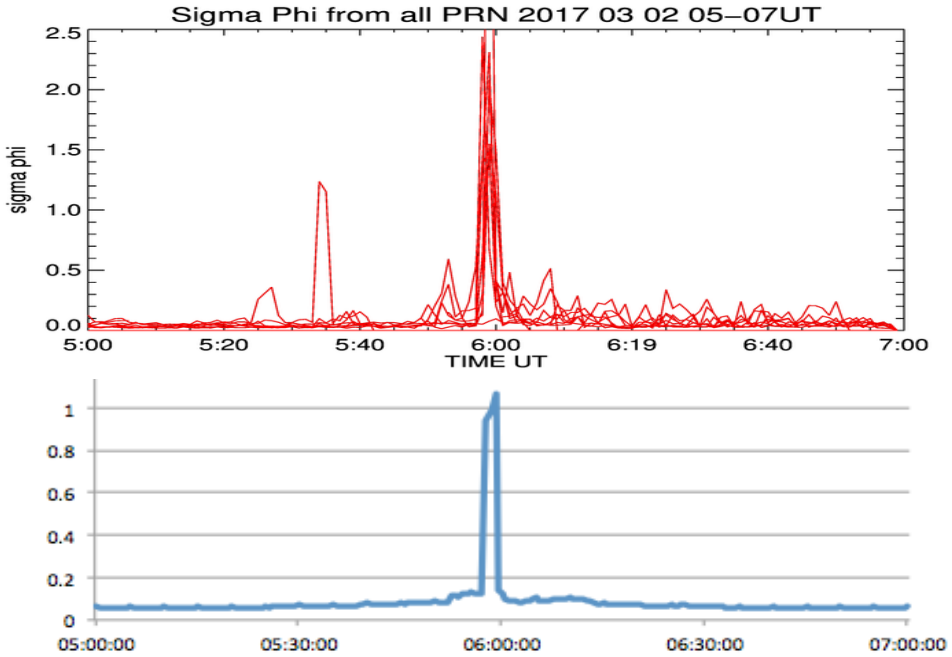

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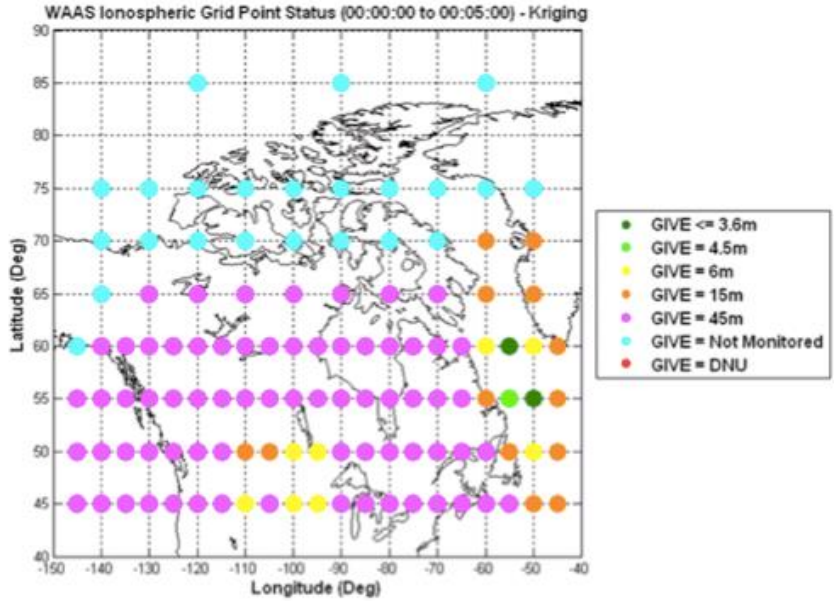
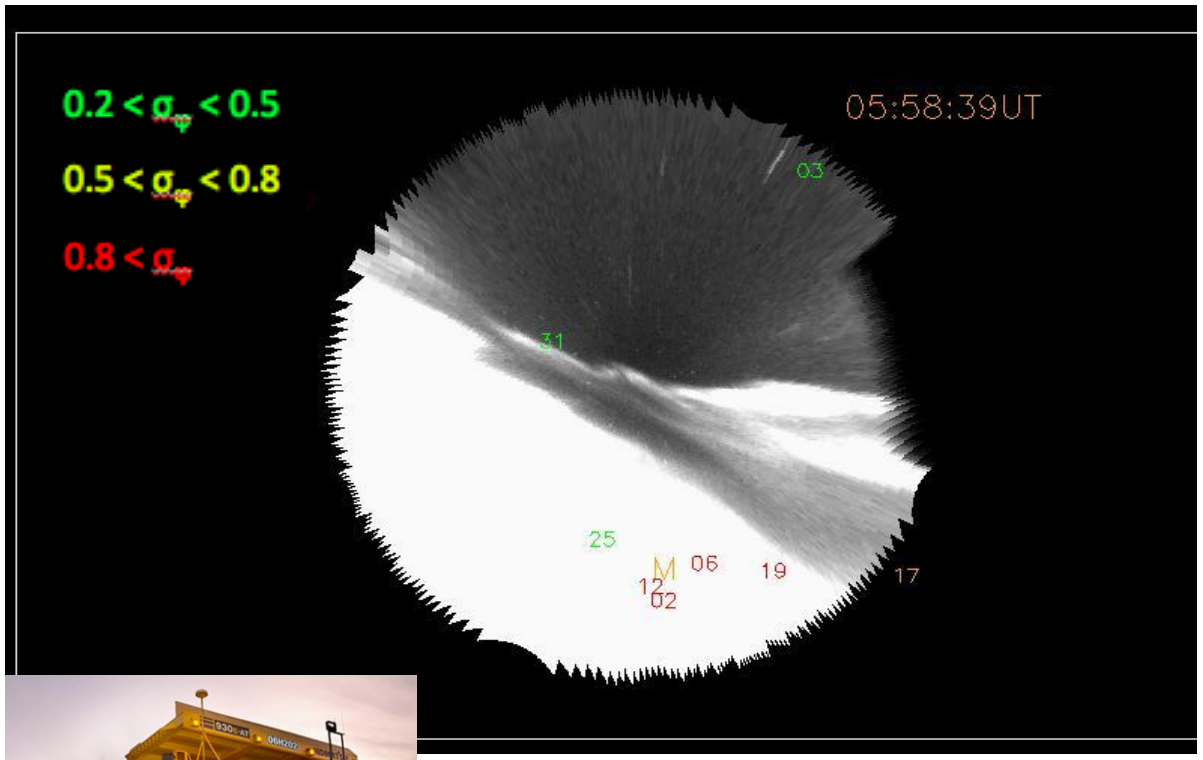
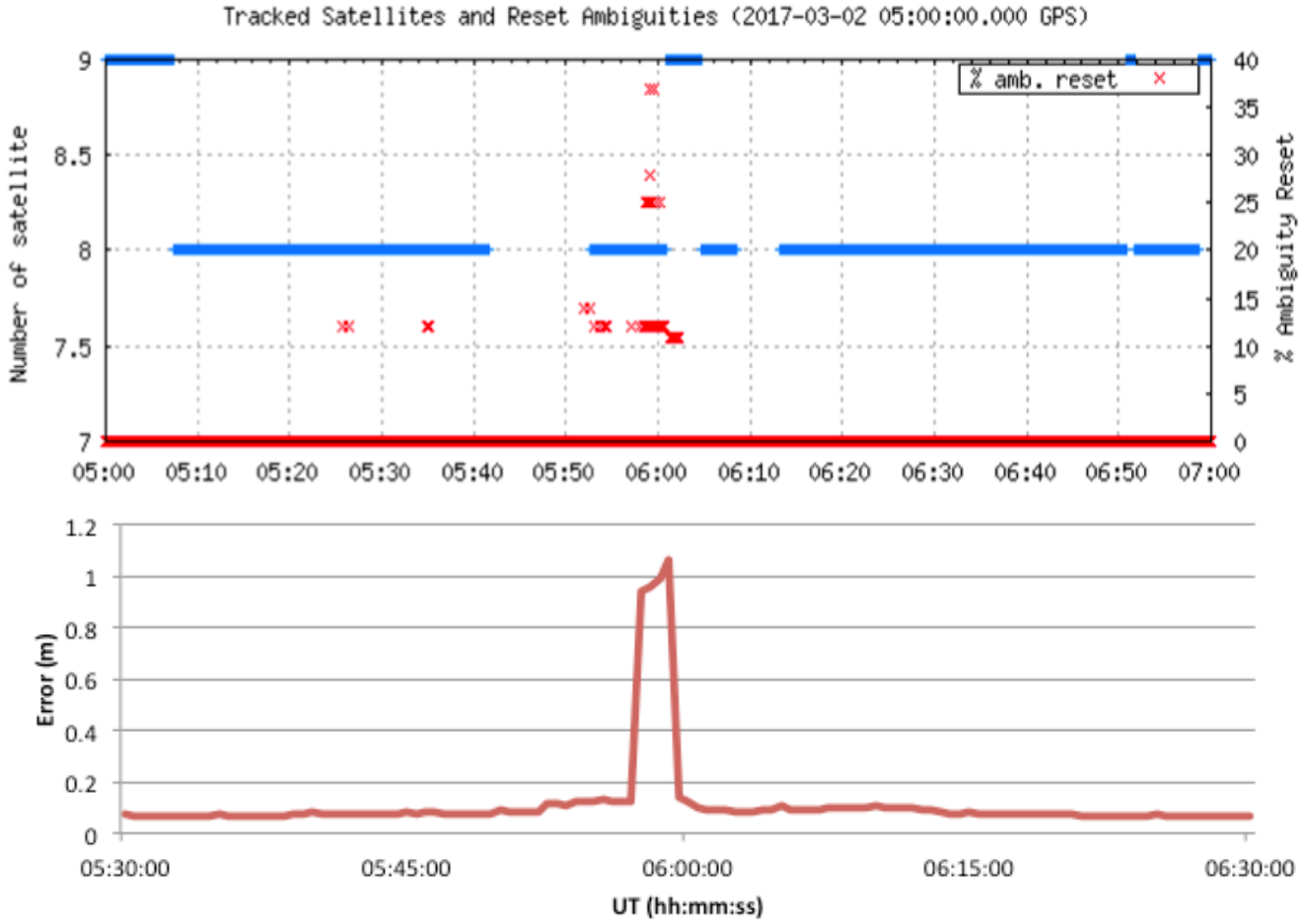


High accuracy

Natural Resource Extraction: Impact on Autonomous Operations

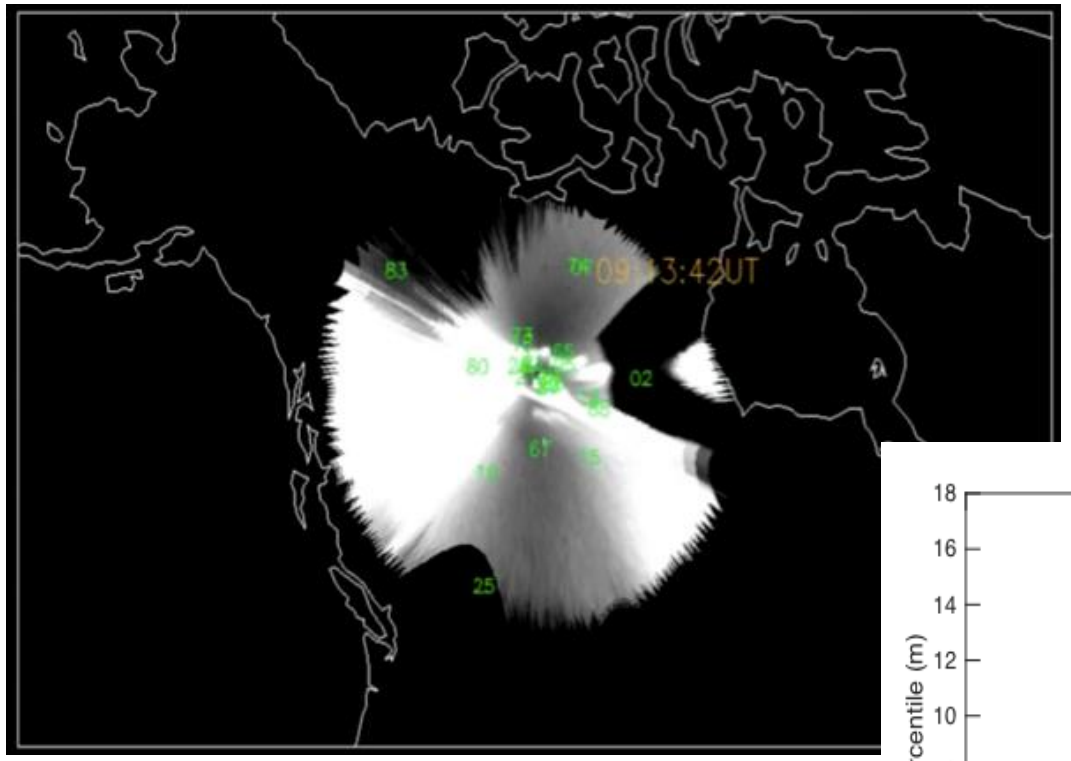
- Surface mining activities in northern Alberta affected by space weather
- Autonomous haulage disrupted by errors in GPS PPP services

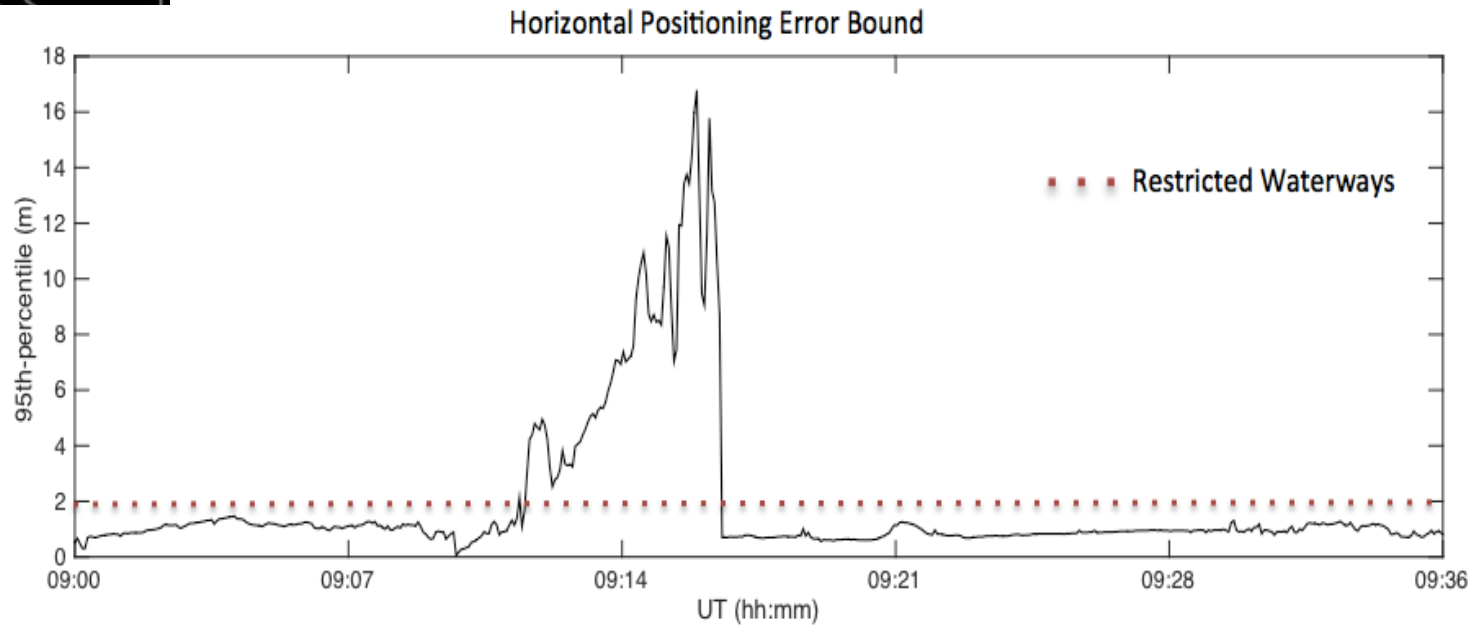




GNSS Marine Receiver Performance

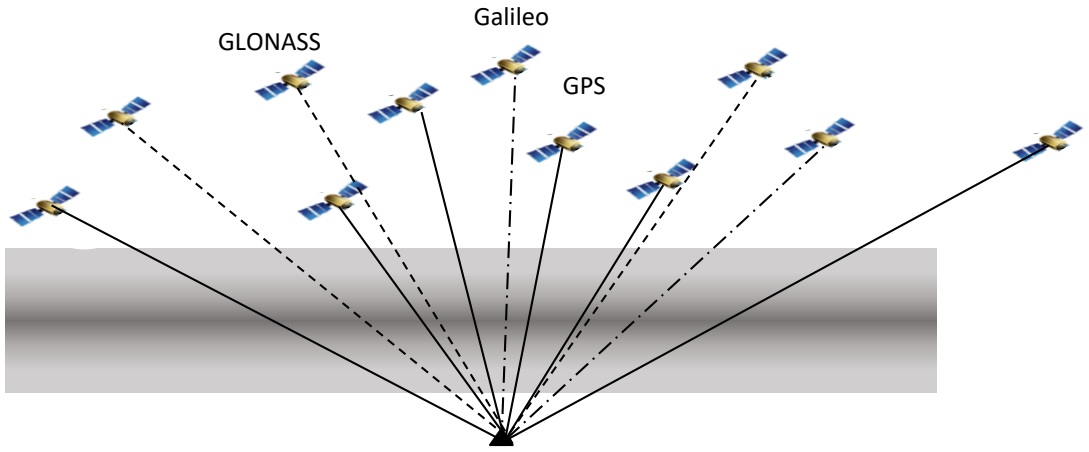
Horizontal positioning accuracy of 2-5 m (95%) required for navigating restricted waterways

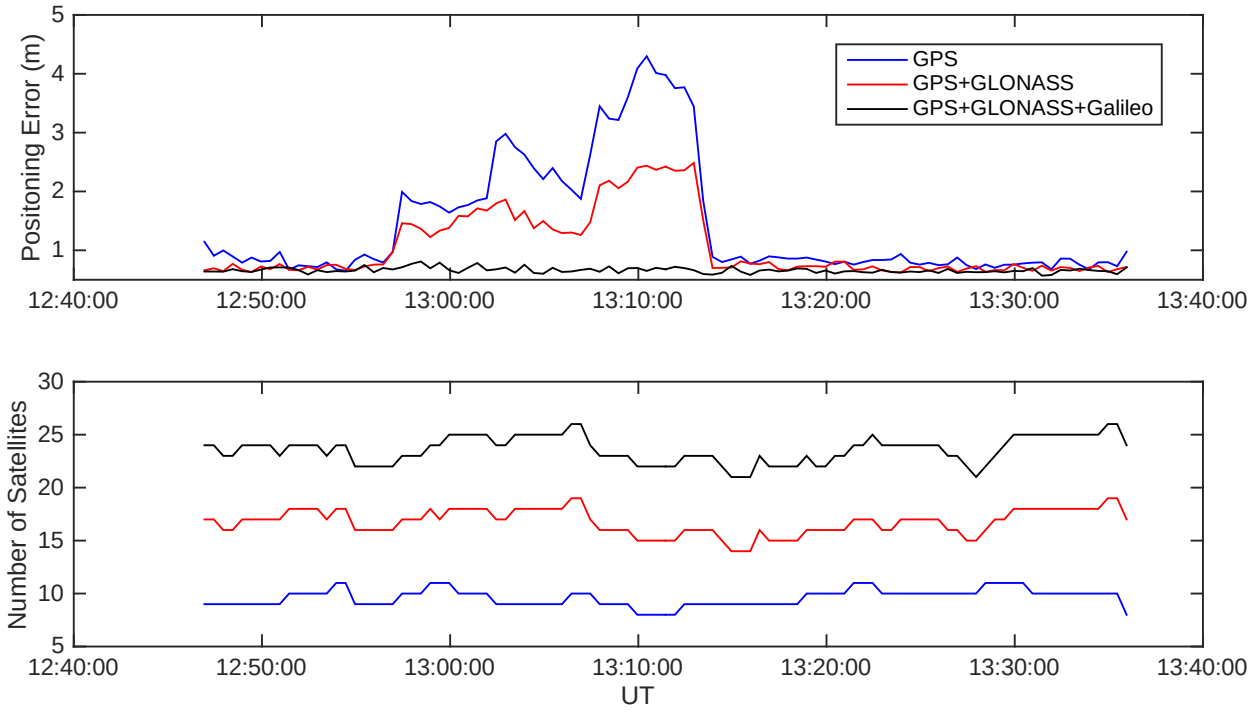




GNSS Receiver Technologies and Methods

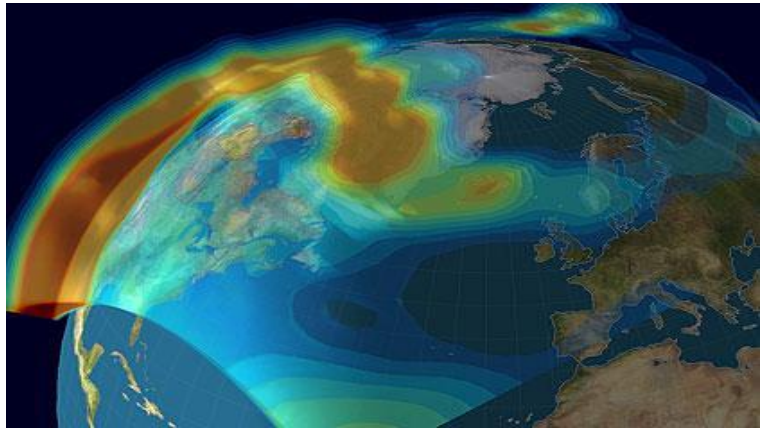
- Impact on users/systems can vary widely
- Space weather effects are best captured in a technologically independent manner
- Key parameters of physical properties should translate readily into various PNT applications

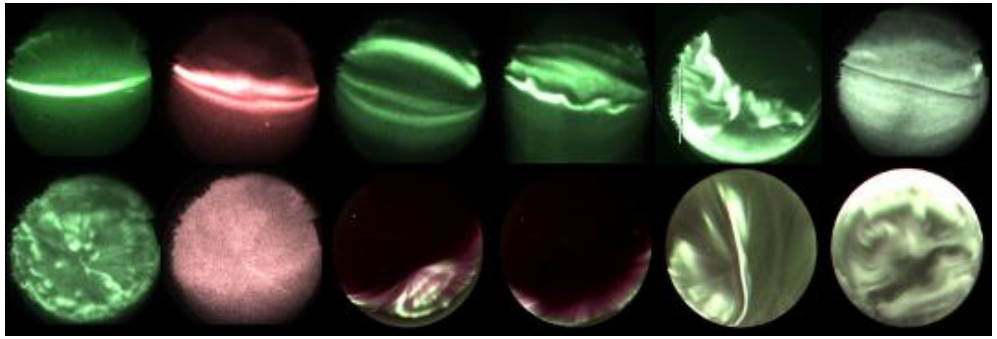


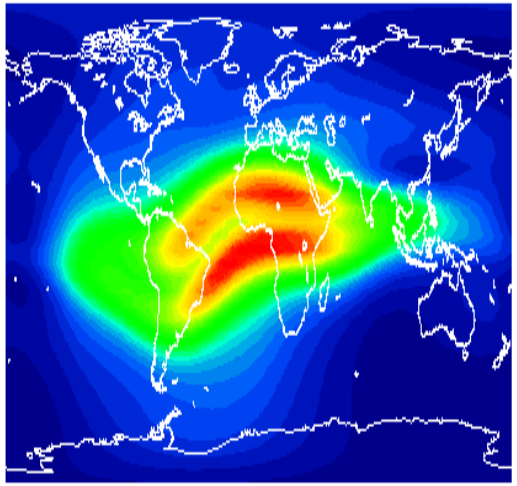


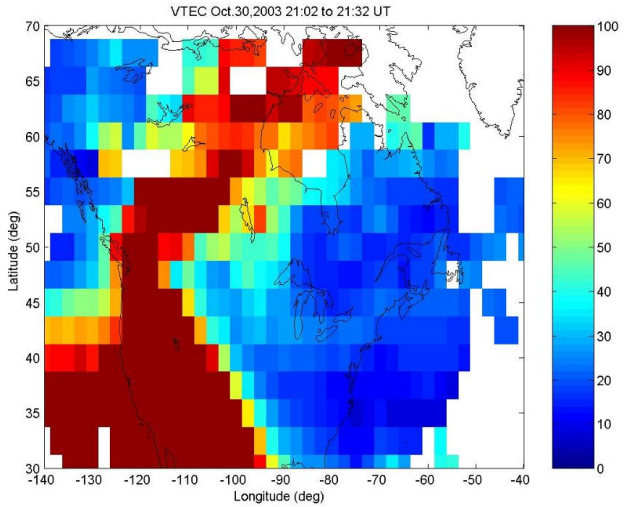
Phenomena?

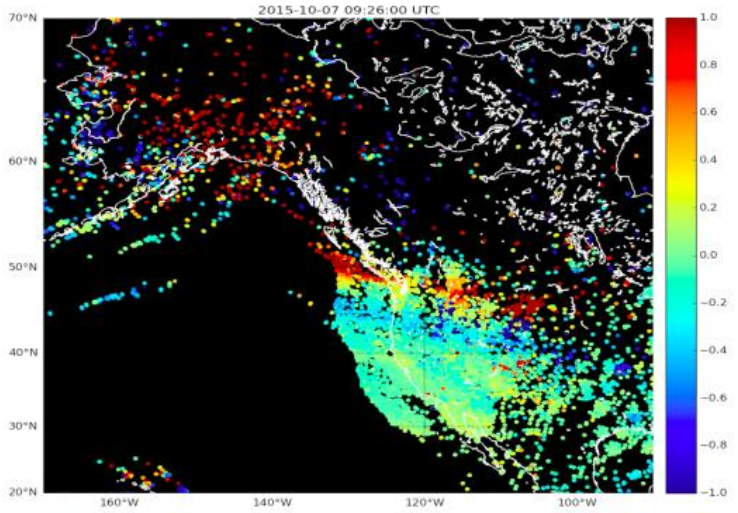
- Polar and auroral structures/irregularities affect GPS/GNSS signals
- Equatorial irregularities block GPS/GNSS signals
- Mid-latitude variability can impact GPS/GNSS performance











Federal Radionavigation Plan 2019 (DoD, DHS, DoT)

System parameters: accuracy, availability, coverage, integrity, reliability, fix rate, fix dimensions

User segments: space, aviation, maritime and land

Sample User Positioning and Navigation Requirements [FRNP,2019]

Requirements	Horizontal Accuracy (95%)	Availability	Time to Alert	Integrity (Alert Limit)
Maritime safety of navigation restricted waterways	2-5 m	99.9%	N/A	N/A
Highway navigation and route guidance	1-20 m	>95%	5 s	2-20 m

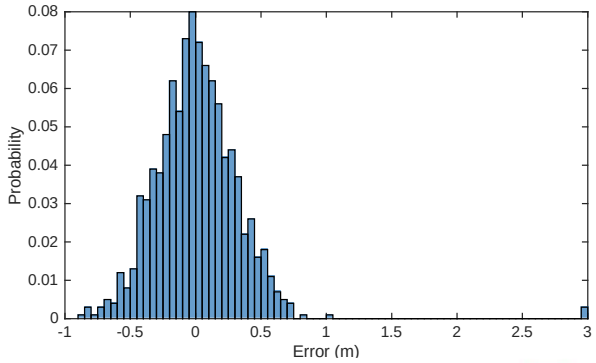
Sample Timing Requirements [FRNP, 2019]

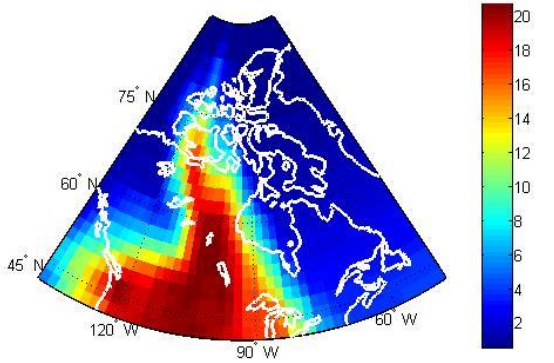
Requirements	Accuracy (95%)
Telecommunications timing	340 ns

PNT: GNSS Simulation and Risk Assessment

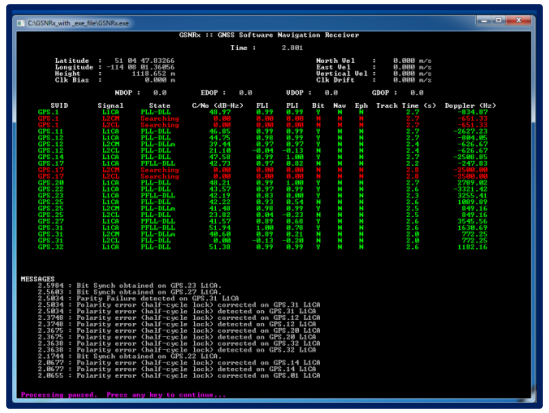
1. GNSS hardware signal generator

Mode (land, marine, aviation) and trajectory



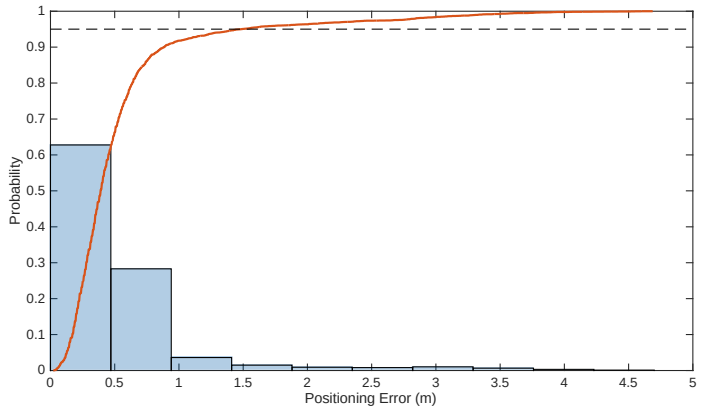


2. Space weather threat



3. GNSS Receiver: PNT accuracy and integrity

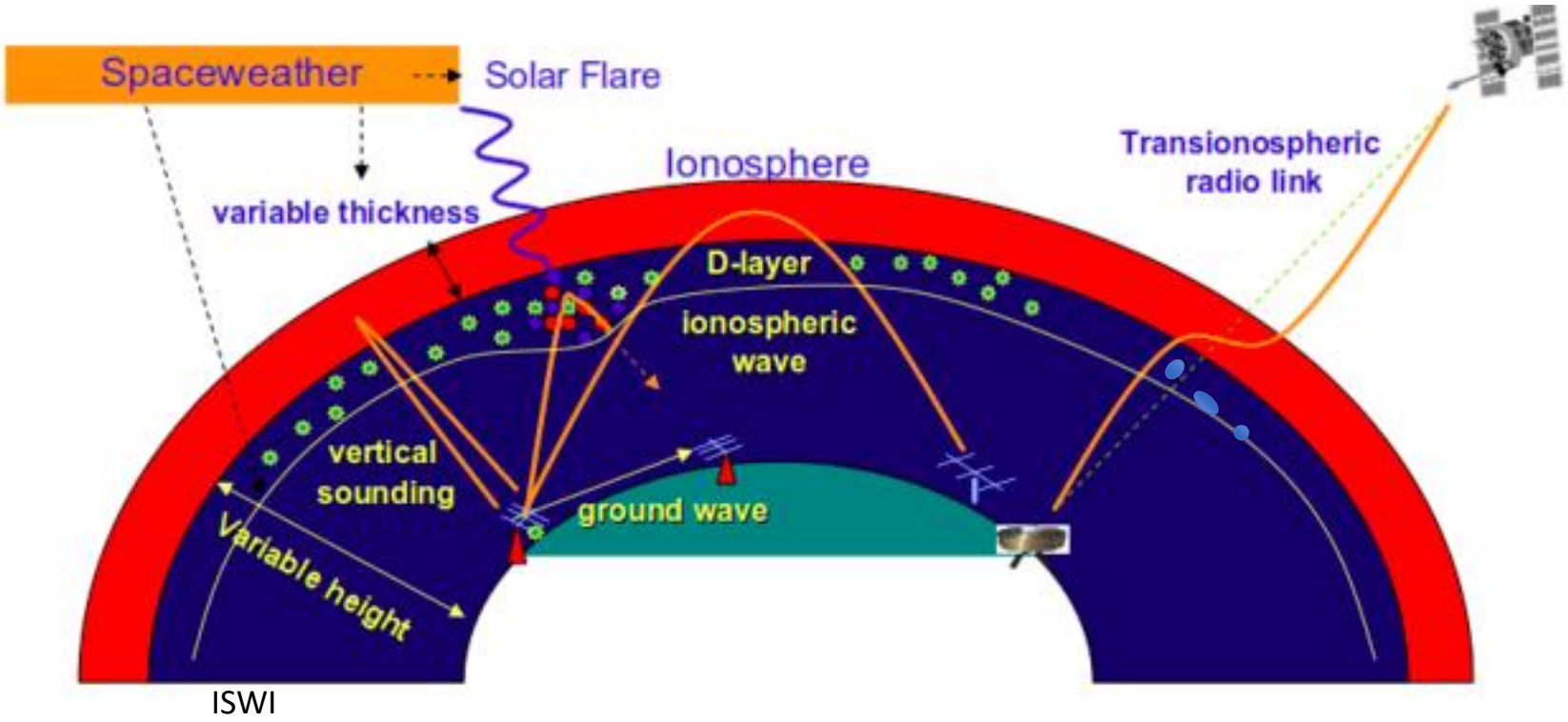
Risk indicators



Next Step Space Weather Benchmarks: Ionospheric Disturbances

Phase 1 Benchmarks	Recommended Key Parameters
F region: Total Electron Content (TEC), peak density (NmF2), peak height (hmF2) Turbulence: phase and amplitude scintillation	F region: Vertical TEC and variability, NmF2, hmF2 Turbulence: CkL

(IDA Group Report NS GR-10982, November 2019)



Do we have the right phenomena parameterized in the right way?

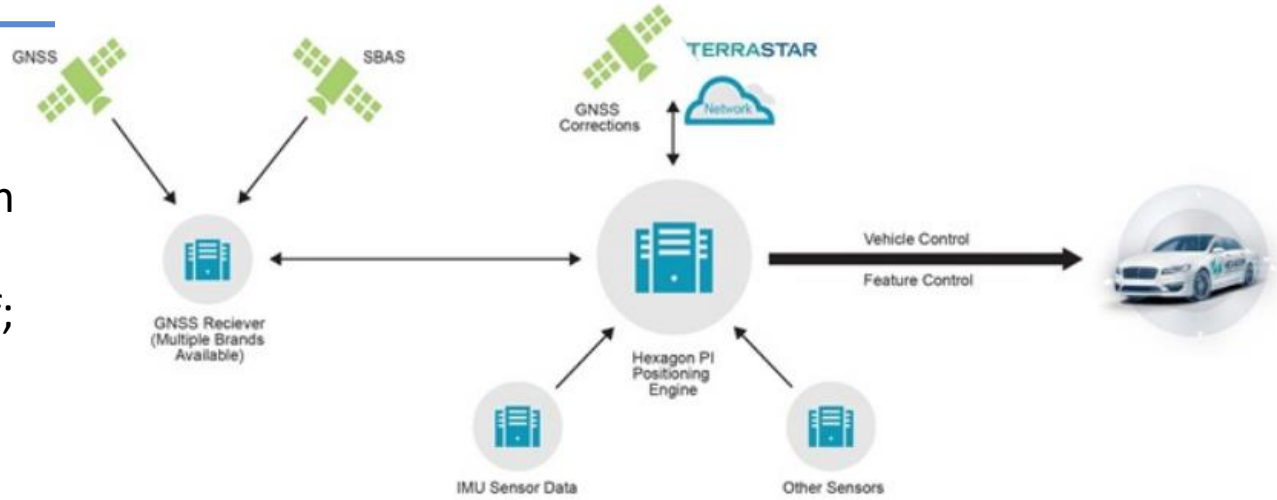
Do we capture physical properties?

Can we translate to user/operator impact metrics?

New Technology: Autonomy and Integrity

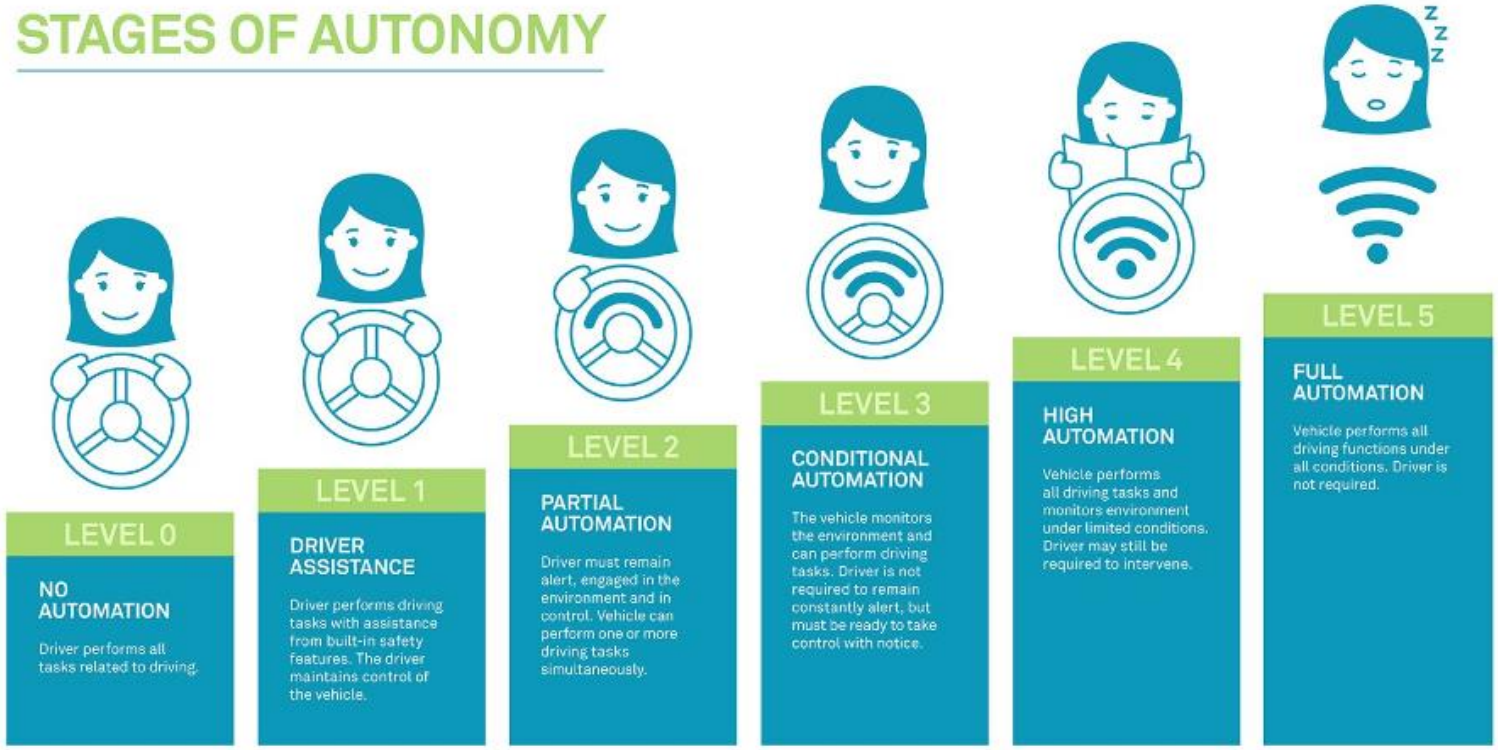
Autonomous Systems

- Drones, self-driving vehicles, robotics require localization
- Redundancy ensures never fully reliant on GNSS PNT
- Competitive industry with cost versus accuracy trade-off; no two systems are alike



Integrity?

- To ensure safety: test, test and test
- Industry adopting some WAAS/aviation approaches
- Threat detection highly relevant
- Autonomous levels 1-5
- New safety standards: ISO 26262, SOTIF, ISO 61508, RTCM SC-134, 3GPP and EN16803



Ubiquitous PNT

World's first dual-frequency GNSS smartphone hits the market

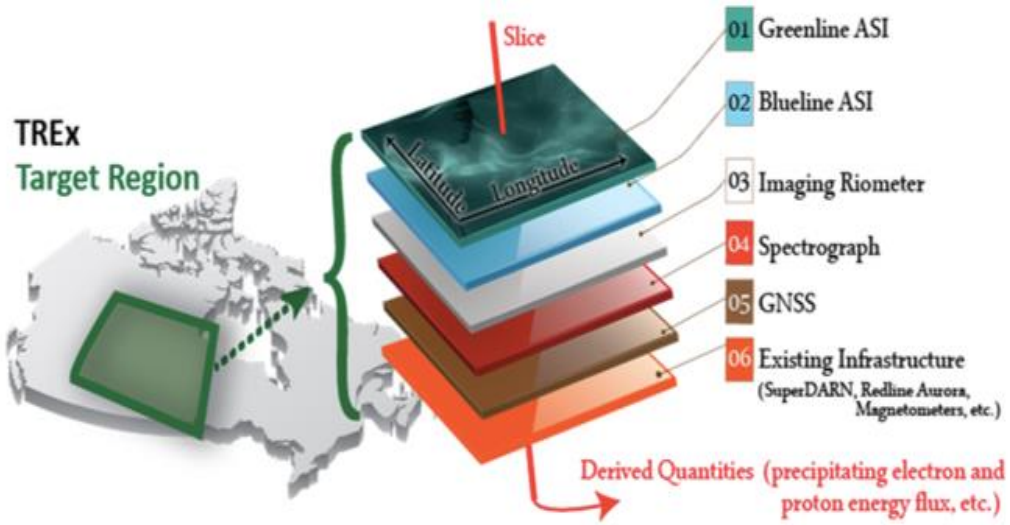
Published: 04 June 2018

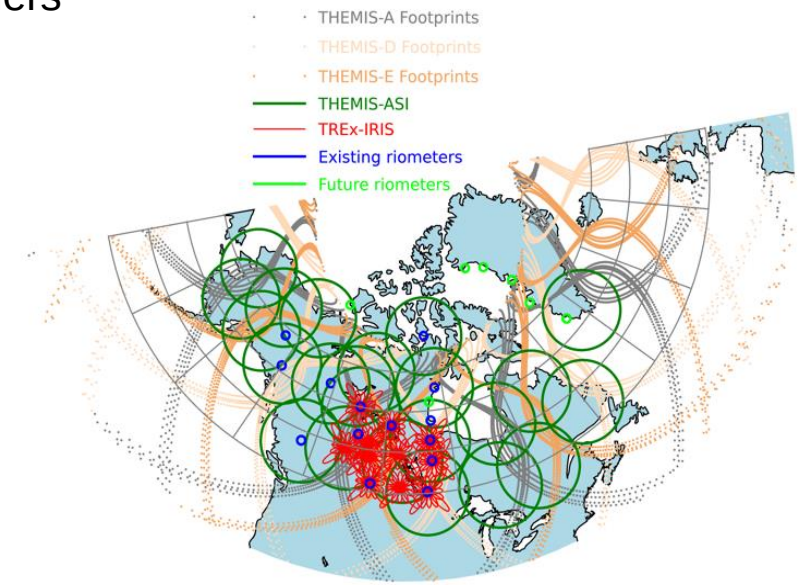
Providing enhanced performance, the Mi 8 offers users better positioning in urban environments

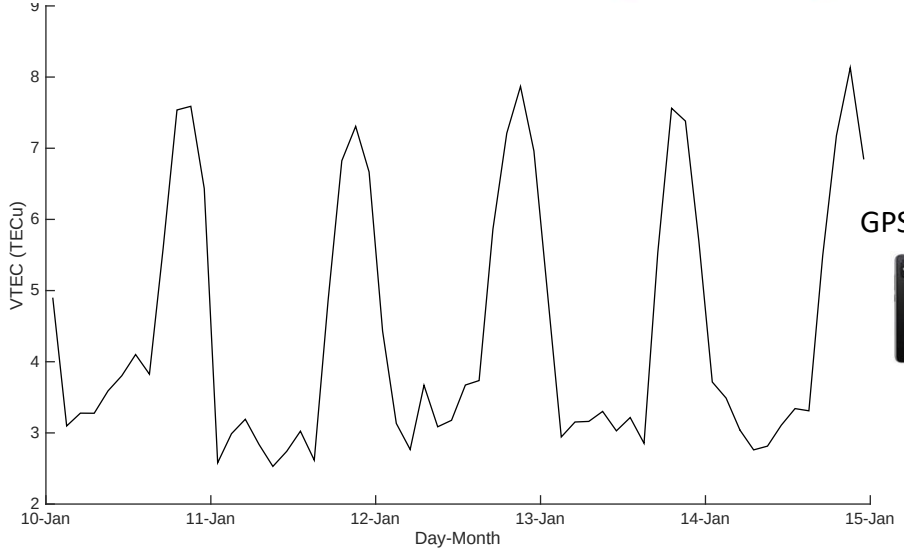
- Smart phone GNSS: Xiaomi Mi 8 with Broadcom Chip BCM47755; L1/E1+L5/E5 signals from GPS and Galileo
- Precise positioning accuracy of 30 cm expected

Transition Region Explorer (TREx) Testbed

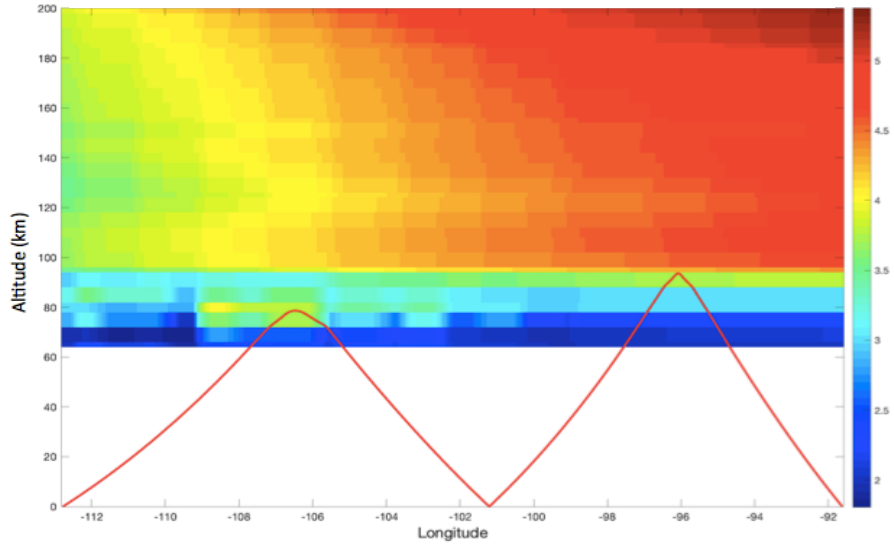
- 50+ optical, magnetic and radio instruments across Canada: 18 auroral cameras, 11 imaging riometers, 2 spectrographs, 9 GNSS TEC/scintillation rx, 4 RF front-end samplers
- Commercial GNSS receivers and smart phone devices







GPS+Galileo



Precise Positioning: The Future