Research Using CASSIOPE GPS Data at UNB and Elsewhere

Richard B. Langley, Ryan White, and Heather Nicholson

Dept. of Geodesy and Geomatics Engineering
University of New Brunswick, Fredericton, N.B.

Jet Propulsion Laboratory, 15 February 2018

Outline

- GPS Attitude, Positioning, and Profiling instrument on CASSIOPE spacecraft
- Collaboration with JPL
- Collaboration with University of Calgary
- UNB student projects
- NB CubeSat

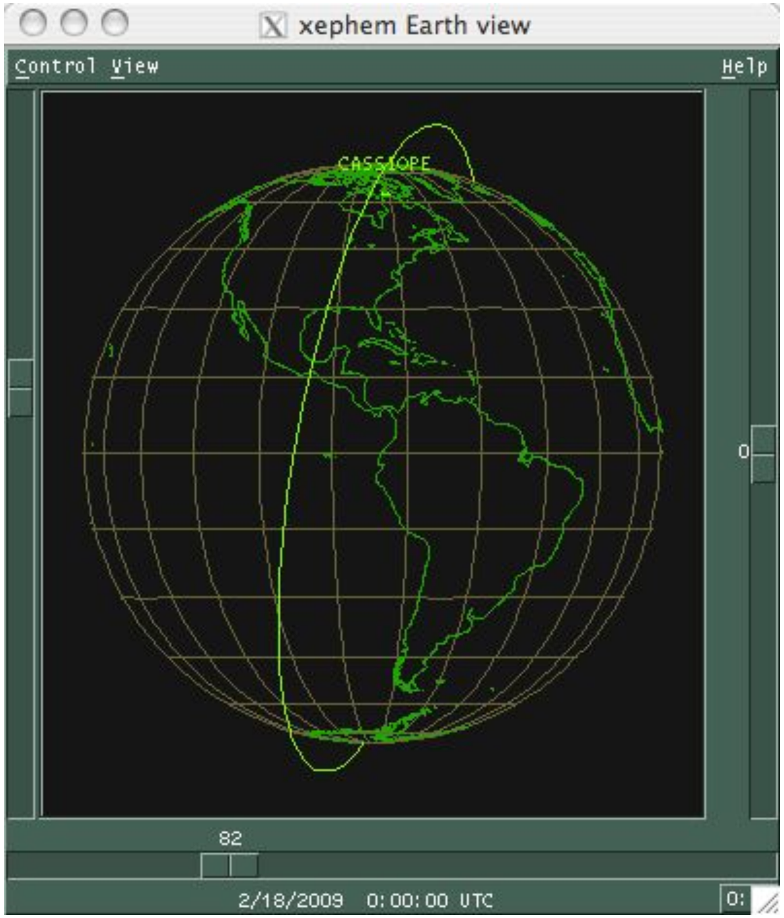
GAP

The *GPS Attitude, Positioning, and Profiling* (GAP[2]) instrument was developed at UNB in collaboration with the University of Calgary, Bristol Aerospace, and MDA as one of eight instruments of the *Enhanced Polar Outflow Probe* platform on the *CAScade, Smallsat and IOnospheric Polar Explorer* (CASSIOPE) spacecraft.

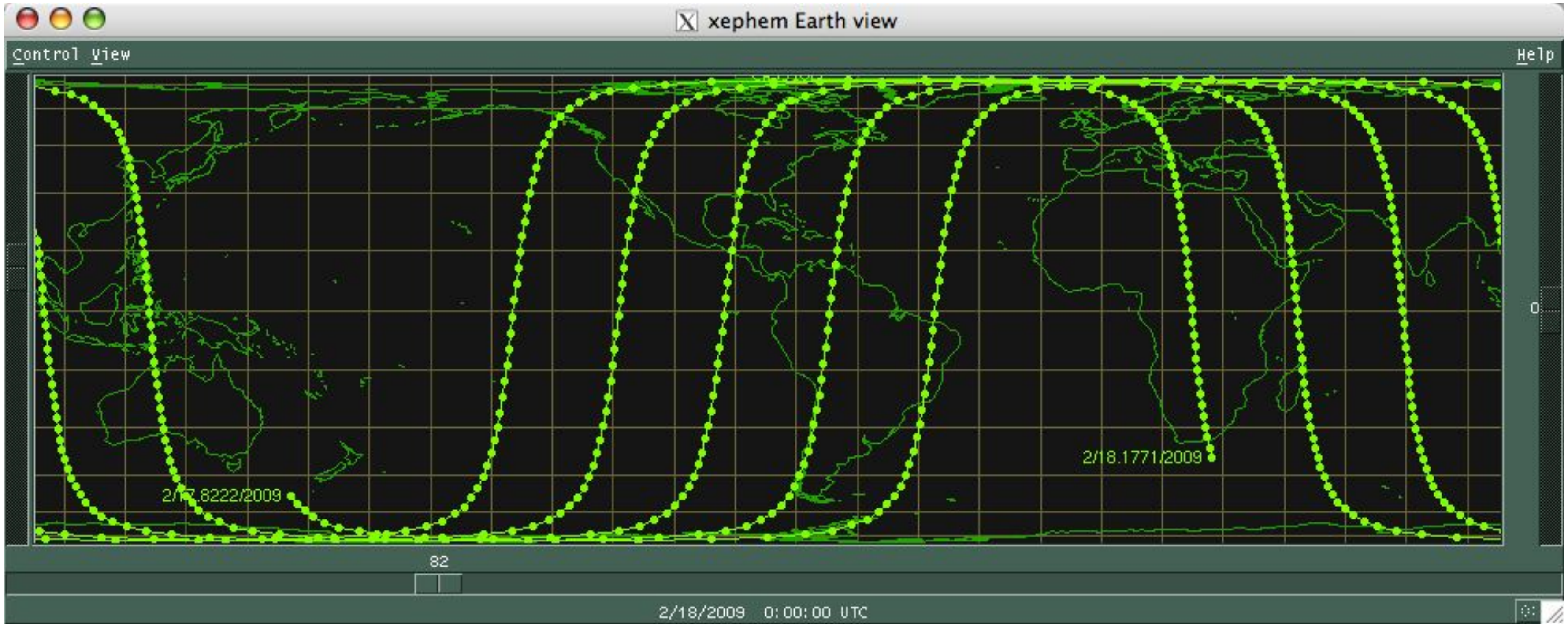
CASSIOPE launched on a Falcon 9 rocket from Vandenburg on 29 September 2013 following a more than 10-years of development, construction, and hibernation .

CASSIOPE Initial Orbit

Semi-major axis	7280 km
Period	103 minutes
Eccentricity	0.08
Apogee	1485 km
Perigee	325 km
Inclination	81°



CASSIOPE Orbit Ground Track



GAP Objectives-1

GAP is multipurposed. It is both a spacecraft sensor and a science instrument. It can determine:

- spacecraft three-dimensional position, velocity, and attitude
- time referenced to UTC
- ionospheric electron density profiles

Science functions divided into GAP-A and GAP-O

GAP-OD mode (a special version of GAP-A) using one GAP-A receiver frequently activated for routine spacecraft orbit determination

GAP Objectives-2

GAP-A

- Position, velocity, attitude, and time can be determined in *real time* and made available to other spacecraft systems (1 Hz):
  - position to better than 100 metres
  - velocity to better than 10 metres per second
  - attitude to 5 degrees (non-functional)
  - time to better than 1 microsecond

- More accurate results are achievable from down-linked data (up to 20 Hz) including attitude to 0.5 degrees and position to a few dm or better.

- Ionospheric science also possible with GAP-A.

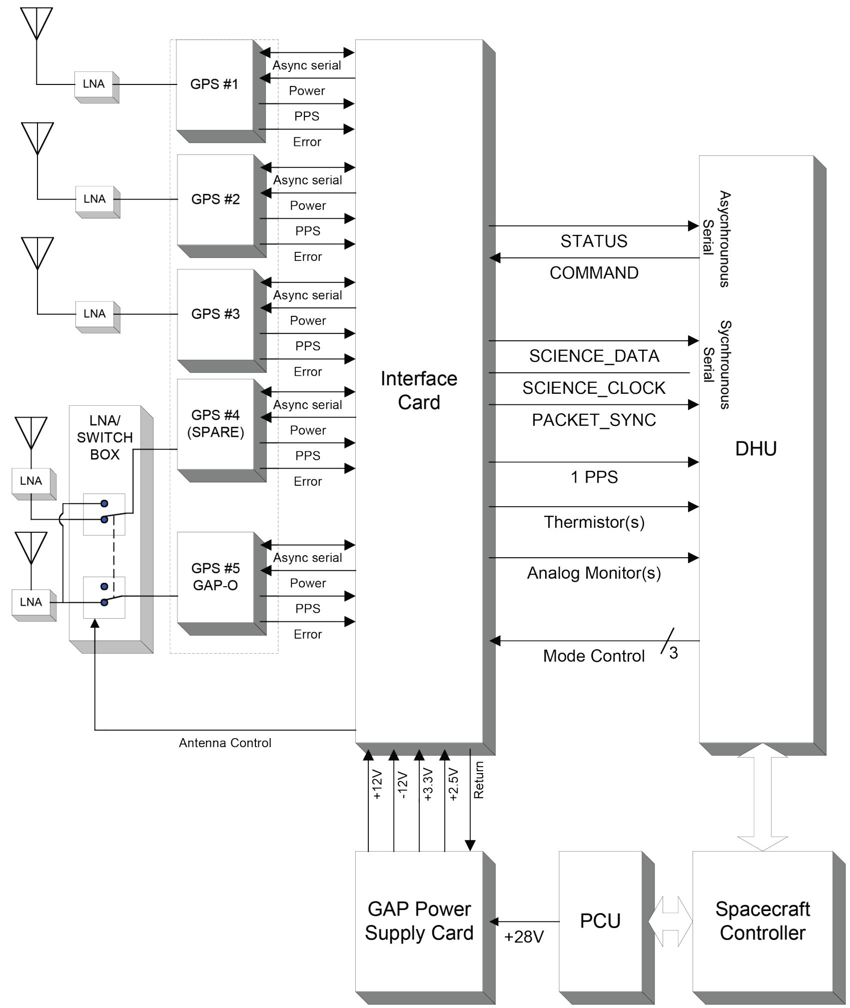
GAP Objectives-3

GAP-O

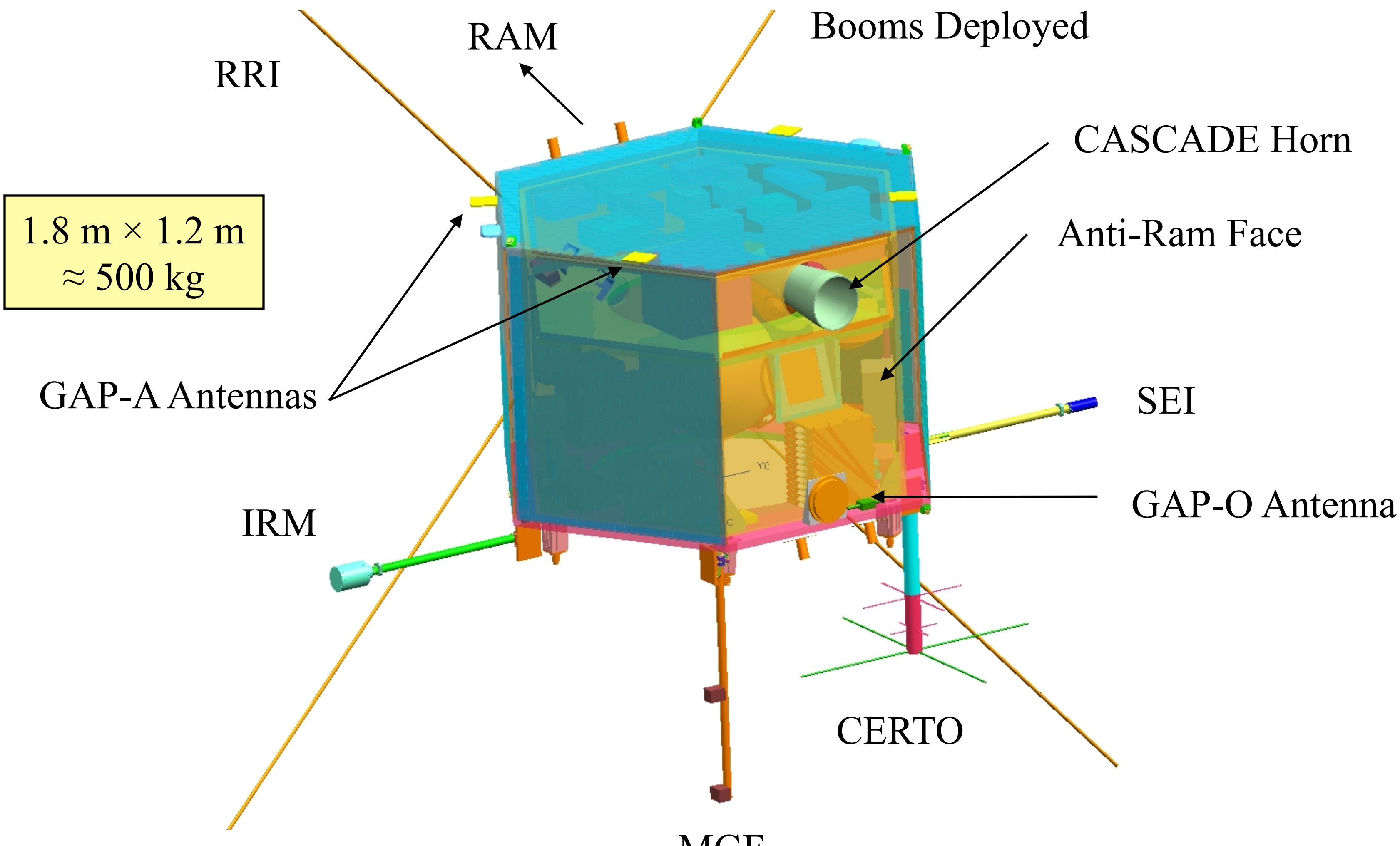
- Electron density profiling using antenna pointed in anti-ram direction.
- High-rate (20, 50, and 100 Hz) measurements on setting (occulted) GPS satellites together with measurements from non-occulted satellites down linked to ground for analysis.
- Analysis provides high resolution (in the vertical) profiles of electron density in the ionosphere and plasmasphere.
- Not mandated to profile neutral atmosphere (likely insufficient antenna gain).

GAP Functional Description

- Instrument consists of:
  - An interface card
  - Power supply card
  - 5 GPS cards (includes one spare)
  - 5 GPS antennas and LNAs
  - Antenna/LNA switch
- GAP-A and GAP-O functions combined into a single instrument



CASSIOPE



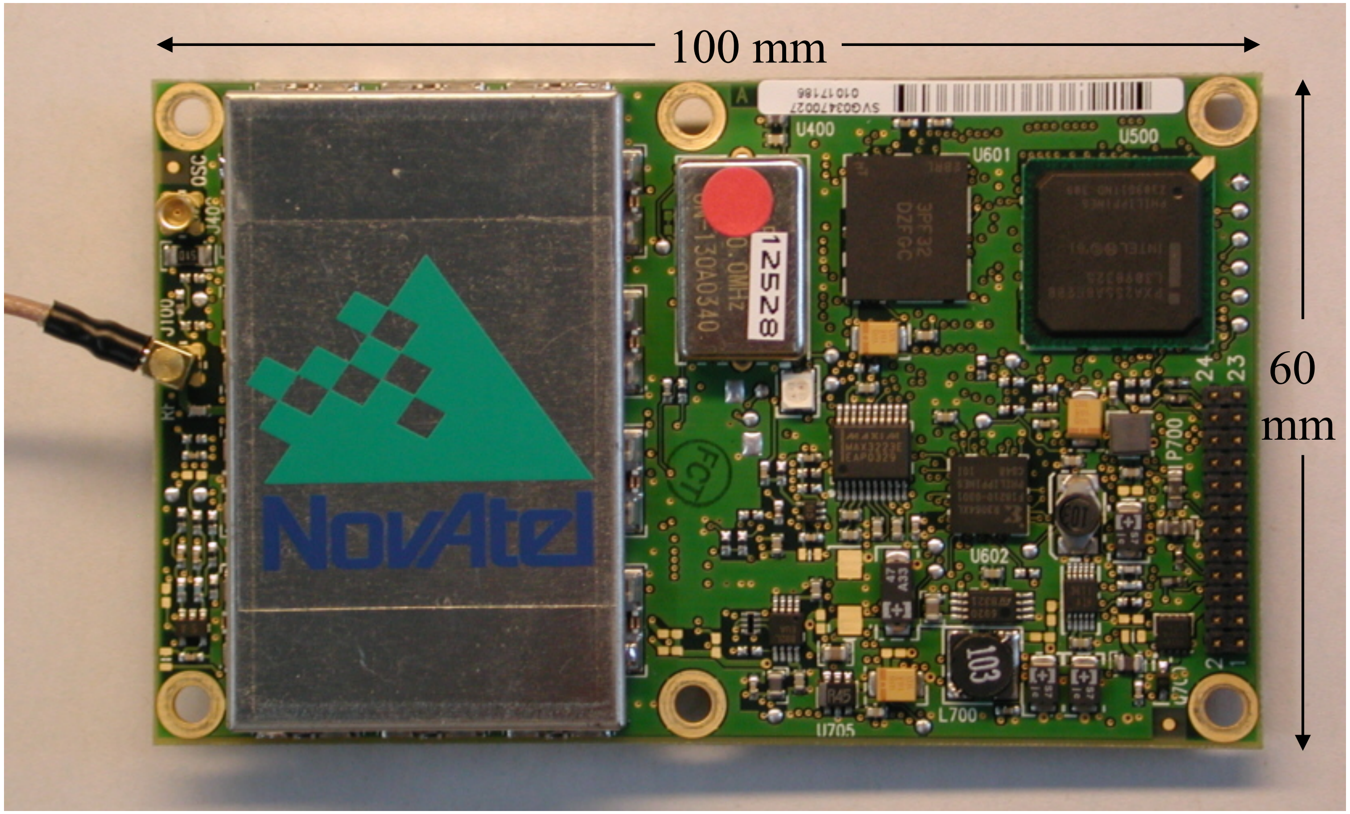
Background image courtesy of Bristol. S/C is for illustrative purposed only.

CASSIOPE at David Florida Lab

NovAtel OEM4-G2L

- GAP GPS receivers are basically NovAtel COTS receiver cards.
- Went through extensive testing (with support of DLR, Germany) and slight hardware modification
- Standard firmware (except for height and speed limitation removal).
- This receiver type is now three generations old!

NovAtel OEM4-G2L



JPL Collaboration

- Initial GAP-O science results only possible thanks to JPL collaboration (Shume, Komjathy, Verkhoglyadova, Butula, Mannucci).
- Resulted in first journal publication of GAP science results.
- Intermediate-scale, scintillation-producing irregularities, which correspond to 1 to 40 km scales, were inferred by applying multiscale spectral analysis on the RO phase measurements.
- Found that large length scales and more intense phase scintillations are prevalent in the auroral oval compared to the polar cap.

First Science Results Journal Publication

AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER

10.1002/2014GL062558

Intermediate-scale plasma irregularities in the polar ionosphere inferred from GPS radio occultation

E. B. Shume[1], A. Komjathy[1,2], R. B. Langley[2], O. Verkhoglyadova[1], M. D. Butala[1], and A. J. Mannucci[1]

[1] Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA, [2] Geodetic Research Laboratory, University of New Brunswick, Fredericton, New Brunswick, Canada

Key Points:

- Irregularity scales inferred from high-resolution radio occultation
- Distinct features of phase scintillation in the auroral oval and the polar cap
- Solar wind and magnetospheric control of the irregularities and scintillation

Correspondence to:
E. B. Shume,
Esayas.B.Shume@jpl.nasa.gov

Citation:
Shume, E. B., A. Komjathy, R. B. Langley, O. Verkhoglyadova, M. D. Butala, and A. J. Mannucci (2015), Intermediate-scale plasma irregularities in the polar ionosphere inferred from GPS radio occultation, *Geophys. Res. Lett.*, *42*, 688–696, doi:10.1002/2014GL062558.

Abstract We report intermediate-scale plasma irregularities in the polar ionosphere inferred from high-resolution radio occultation (RO) measurements using GPS (Global Positioning System) to CASSIOPE (CAScade Smallsat and IOnospheric Polar Explorer) satellite radio links. The high inclination of CASSIOPE and the high rate of signal reception by the GPS Attitude, Positioning, and Profiling RO receiver on CASSIOPE enable a high-resolution investigation of the dynamics of the polar ionosphere with unprecedented detail. Intermediate-scale, scintillation-producing irregularities, which correspond to 1 to 40 km scales, were inferred by applying multiscale spectral analysis on the RO phase measurements. Using our multiscale spectral analysis approach and satellite data (Polar Operational Environmental Satellites and Defense Meteorological Satellite Program), we discovered that the irregularity scales and phase scintillations have distinct features in the auroral oval and polar cap. We found that large length scales and more intense phase scintillations are prevalent in the auroral oval compared to the polar cap implying that the irregularity scales and phase scintillation characteristics are a function of the solar wind and magnetospheric forcings.

Further JPL Collaboration

- Continued JPL collaboration (Shume, Vergados, Komjathy, and Durgonics) resulted in a second journal publication.
- First GAP electron number density profiles obtained using a novel inverse Abel transform algorithm on high rate (100-Hz) RO total electron content measurements.
- Identified, for the first time, differences in the characteristics of the electron number density profiles retrieved over landmasses and oceans.

Second Product of JPL Collaboration

AGU PUBLICATIONS

Radio Science

RESEARCH ARTICLE

10.1002/2017RS006321

Electron number density profiles derived from radio occultation on the CASSIOPE spacecraft

Esayas B. Shume[1,2], Panagiotis Vergados[1], Attila Komjathy[1,3], Richard B. Langley[3], and Tibor Durgonics[4]

[1] Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA, [2] Department of Astronomy, California Institute of Technology, Pasadena, California, USA, [3] Geodetic Research Laboratory, University of New Brunswick, Fredericton, New Brunswick, Canada, [4] National Space Institute, Technical University of Denmark, Kongens Lyngby, Denmark

Key Points:

- The study provides realistic and high spatial resolution electron density profiles inferred using a novel Abel inversion algorithm
- The study provides for the first time distinct properties of electron density profiles over ocean and landmass
- The study provides valuable electron density data for ionospheric modeling, geospace research, space weather applications, etc.

Correspondence to:
E. B. Shume,
Esayas.B.Shume@jpl.nasa.gov

Citation:
Shume, E. B., P. Vergados, A. Komjathy, R. B. Langley, and T. Durgonics (2017), Electron number density profiles derived from radio occultation on the CASSIOPE spacecraft, *Radio Sci.*, *52*, doi:10.1002/2017RS006321.

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Abstract This paper presents electron number density profiles derived from high-resolution Global Positioning System (GPS) radio occultation (RO) observations performed using the Enhanced Polar Outflow Probe payload on the high inclination CAScade, Smallsat and IOnospheric Polar Explorer (CASSIOPE) spacecraft. We have developed and applied a novel inverse Abel transform algorithm on high rate RO total electron content measurements performed along GPS to CASSIOPE radio links to recover electron density profiles. The high-resolution density profiles inferred from the CASSIOPE RO are (1) in very good agreement with density profiles estimated from ionosonde data, measured over stations nearby to the latitude and longitude of the RO tangent points; (2) in good agreement with density profiles inferred from GPS RO measured by the Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC); and (3) in general agreement with density profiles estimated using the International Reference Ionosphere climatological model. Using both CASSIOPE and COSMIC RO observations, we identify, for the first time, that there exist differences in the characteristics of the electron number density profiles retrieved over landmasses and oceans. The density profiles over oceans exhibit widespread values and scale heights compared to density profiles over landmasses. We provide an explanation for the ocean-landmass discrepancy in terms of the unique wave coupling mechanisms operating over oceans and landmasses.

Collaboration: On the Buses in Halifax

And on Billboards

Also Good Collaboration with U. of C.

- Collaborators include Watson, Yau, and Howarth (also Themens and Jayachandran from UNB)
- Three year's worth of GAP-O data processed.
- Minimization of standard deviations technique showed the most promise for receiver DCB estimation, with estimates ranging from about 40 to 28 total electron content units, including a long-term decrease in magnitude and variability over the first three years of instrument operation.
- Electron density profiles showed good agreement with F-region densities of ground-based incoherent scatter radar measurements.

Product of U. of C. Collaboration

AGU PUBLICATIONS

Radio Science

RESEARCH ARTICLE
10.1002/2017RS006453

Special Section:
URSI General Assembly and Scientific Symposium (2017)

Enhanced Polar Outflow Probe Ionospheric Radio Occultation Measurements at High Latitudes: Receiver Bias Estimation and Comparison With Ground-Based Observations

C. Watson[1,2], R. B. Langley[3], D. R. Themens[4], A. W. Yau[2], A. D. Howarth[2], and P. T. Jayachandran[4]

[1]COSMIC Program Office, University Corporation for Atmospheric Research, Boulder, CO, USA, [2]Department of Physics and Astronomy, University of Calgary, Calgary, Alberta, Canada, [3]Department of Geodesy and Geomatics Engineering, University of New Brunswick, Fredericton, New Brunswick, Canada, [4]Physics Department, University of New Brunswick, Fredericton, New Brunswick, Canada

Key Points:
- GAP-O provides high-resolution radio occultation and topside TEC measurements of the ionosphere, primarily at northern high latitudes
- GAP-O receiver bias estimates are in the range of -40 to -28 TECU, with a long-term decrease in bias magnitude and day-to-day variability
- *F* region ionospheric density profiles retrieved from inversion of occultation TEC correlate well with ISR and ionosonde measurements

Abstract This paper presents validation of ionospheric Global Positioning System (GPS) radio occultation measurements of the GPS Attitude, Positioning, and Profiling Experiment occultation receiver (GAP-O). GAP is one of eight instruments comprising the Enhanced Polar Outflow Probe (e-POP) instrument suite on board the Cascade Smallsat and Ionospheric Polar Explorer (CASSIOPE) satellite. One of the main error sources for certain GAP-O data products is the receiver differential code bias (rDCB). A minimization of standard deviations (MSD) technique has shown the most promise for rDCB estimation, with estimates ranging primarily from −40 to −28 total electron content units (TECU = 10^{16} el m^{-2}; 21.6 to 15.1 ns), including a long-term decrease in rDCB magnitude and variability over the first 3 years of instrument operation. In application of the MSD method, the sensitivity of bias estimates to ionospheric shell height are as large as 4.5 TECU per 100 km. MSD calculations also agree well with the "assumption of zero topside TEC" method for rDCB estimate at satellite apogee. Bias-corrected topside TEC of GAP-O was validated by statistical comparison with topside TEC obtained from ground-based GPS TEC and ionosonde measurements. Although GAP-O and ground-based topside TEC had similar variability, GAP-O consistently underestimated the ground-derived topside TEC by up to 7 TECU. Ionospheric electron density profiles obtained from Abel inversion of GAP-O occultation TEC showed good agreement with *F* region densities of ground-based incoherent scatter radar measurements. Comparison of GAP-O and ionosonde measurements revealed correlation coefficients of 0.78 and 0.79, for peak *F* region density and altitude, respectively.

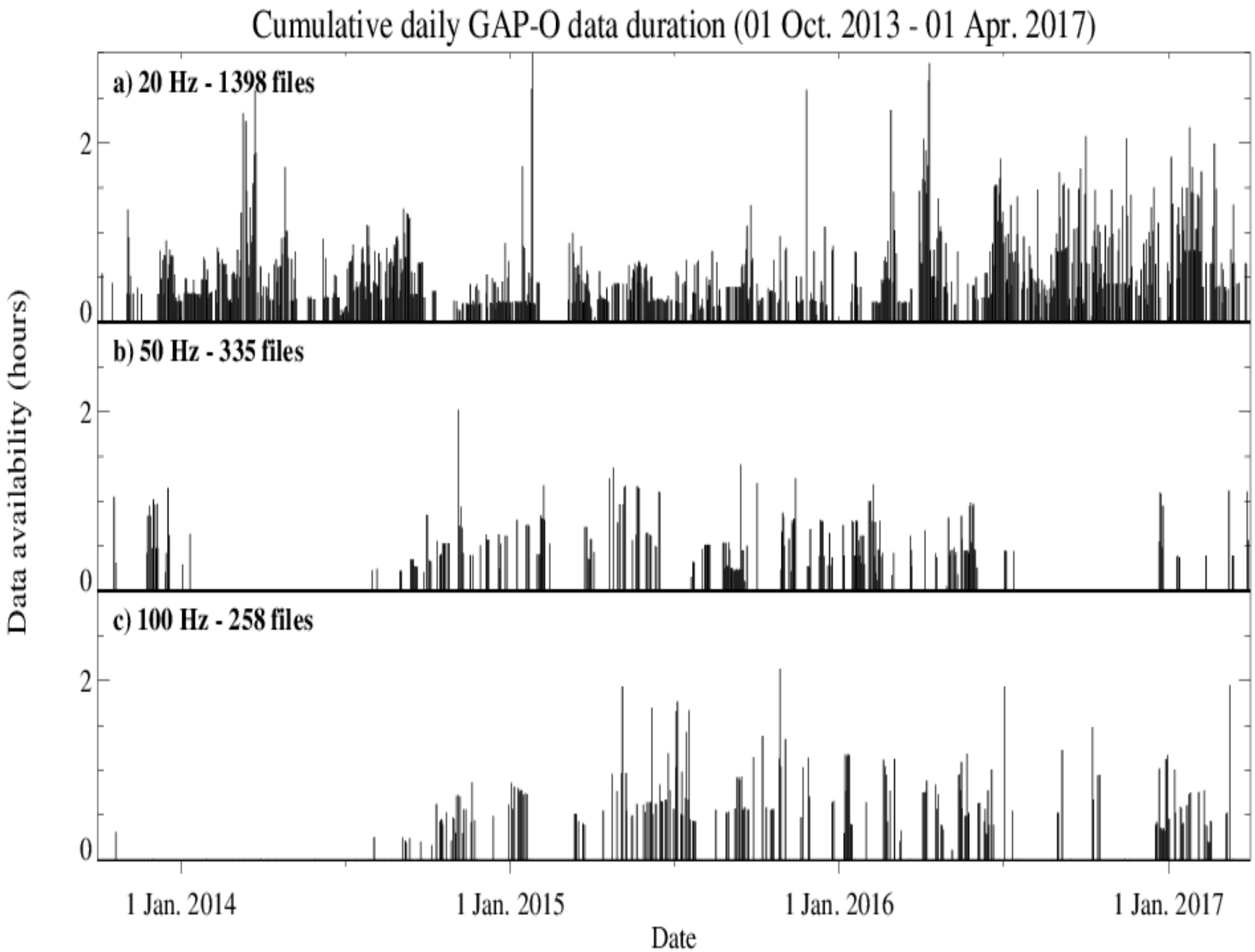
Correspondence to:
C. Watson,
christowatso@gmail.com

Citation:
Watson, C., Langley, R. B., Themens, D. R., Yau, A. W., Howarth, A. D., & Jayachandran, P. T. (2018). Enhanced Polar Outflow Probe ionospheric radio occultation measurements at high latitudes: Receiver bias estimation and comparison with ground-based observations. *Radio Science*, *53*. https://doi.org/10.1002/2017RS006453

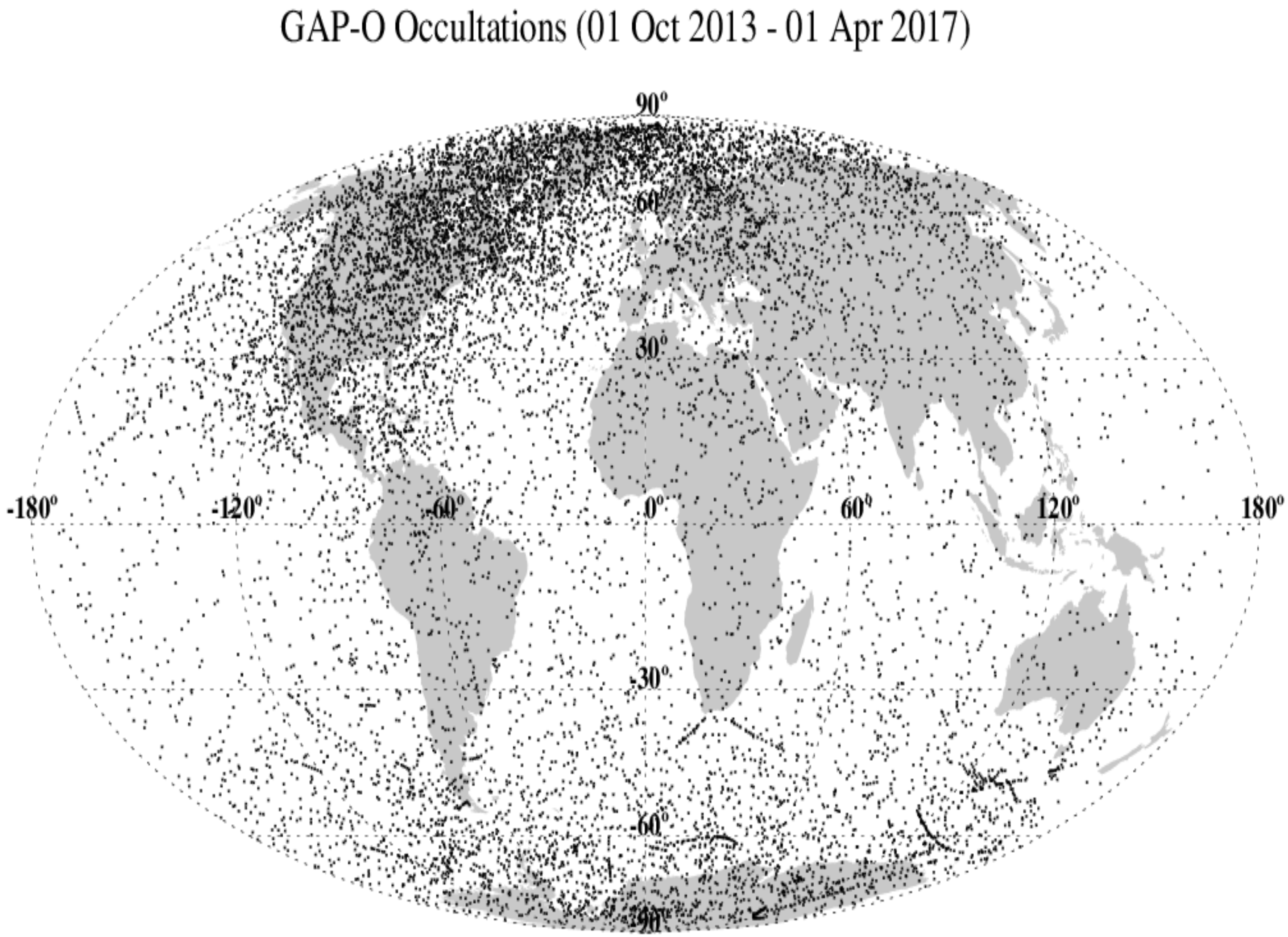
Received 7 SEP 2017

GAP-O Data Availability

GAP RINEX files are currently available at http://epop-data.phys.ucalgary.ca.



GAP-O Occultation Tangent Points



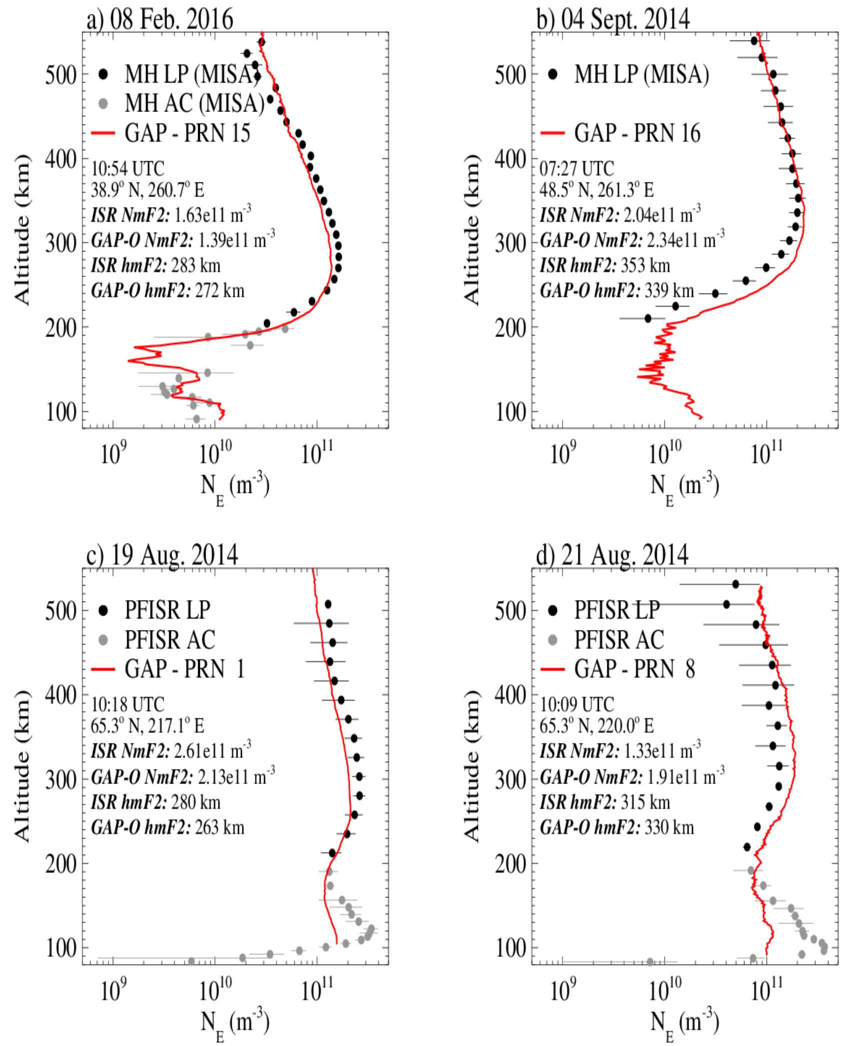
Density Profiles – Abel Inversion

GAP-O (red)

Incoherent scatter radar
(black and grey)

- Millstone Hill (MH)
- Poker Flat (PFISR)

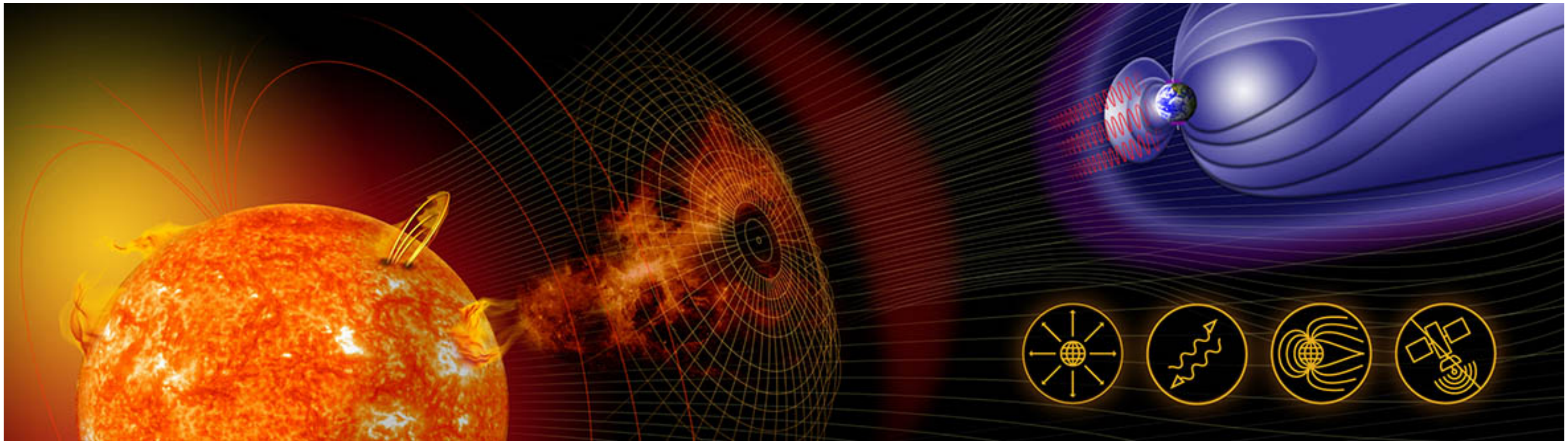
(from Madrigal Database)



UNB GGE Team

- Ryan White, Ph.D. student
  - Determination of thermospheric/ionospheric density variations via estimation of spacecraft position and acceleration using GAP-A data
- Heather Nicholson, M.Sc.E. student
  - Topside ionospheric total electron content estimation using GAP-A data
- Research projects part of a new Canadian Space Agency – European Space Agency collaboration in support of the continued operation of CASSIOPE; also closer collaboration between the e-POP and Swarm missions.

CSA: Studying Space Weather (1)



The Canadian Space Agency (CSA) is supporting nine Canadian research teams that are studying space weather so that we better understand it and are better equipped to predict and respond to its effects.

In analyzing data from instruments aboard Canadian and international satellites (sometimes combined with ground-based observations), the researchers will advance scientific knowledge and understanding of the physical processes occurring in geospace (the region of space closest to Earth) and improve our understanding of what causes space weather.

The research grants for these projects represent a total investment of $2.16 million over three years, starting in March 2017, to maximize the use and scientific benefits of satellites like Canada's CASSIOPE (ePOP) and the European Space Agency's Swarm constellation.

CSA: Studying Space Weather (2)

What will researchers study or develop?

Atmosphere Escape

1. Space weather causing ions to escape the ionosphere
2. Irregularities in the ionosphere and their impact on geospace

Energy Transfer

3. Magnetic waves that transfer energy from the ionosphere to the magnetosphere
4. Fast electrons that make the aurora light up
5. Enhanced models to understand how the aurora are generated

Geospace Regions

6. The uneven distribution of energy (ions and electrons) across the ionosphere
7. The Van Allen radiation belts – highly dynamic regions surrounding the Earth

Technology Disruptions

8. Radio waves that travel in the ionosphere
9. Simulating severe space weather to improve satellite navigation systems

New GAP Processing Software

Pre-processing

- Data gap detection
- Outlier and cycle-slip detection
- Cycle-slip correction
- In-flight multipath analysis

Processing I

- PPP sequential least-squares filter
  - Precise orbit determination
  - Spacecraft acceleration
  - Partial ambiguity resolution
  - Slant TEC

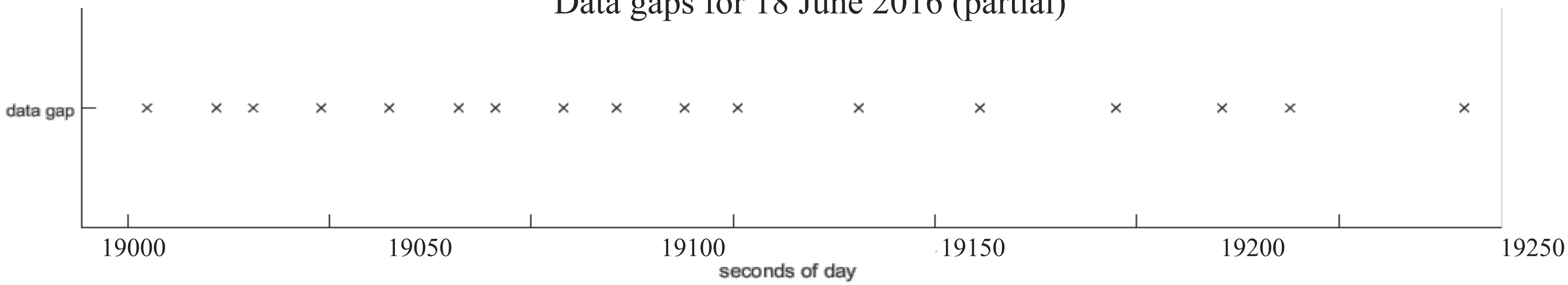
Processing II

- A-PPP sequential least-squares filter
  - Satellite and receiver DCBs
  - Receiver coordinates
  - Slant TEC

GAP-A Data Gaps and Cycle Slips (1)

- Data gaps and cycle slips are a big problem for GAP-A.

Data gaps for 18 June 2016 (partial)



- Detection procedure:
  - Multiple, small phase-connected arcs (not ideal)
  - Cause appears to be bottle-necking issues with data transmission
- Mitigation procedure:
  - Once a data gap is flagged, propagate stochastic errors over missing epochs
  - Hardware related – no evidence of effect on observables (e.g., cycle slips)

GAP-A Data Gaps and Cycle Slips (2)

- Data gaps can be minimized via:
  - Decreasing observation rate to 1 Hz or lower
  - Minimizing GAP-A receiver data packets (other than raw observation data)
  - Minimizing simultaneous use of other e-POP instruments

GAP-A Data Gaps and Cycle Slips (3)

- Cycle-slip Correction
  - Old procedure: Instantaneous cycle-slip correction for real-time PPP applications (Banville & Langley, 2010); significant number of unsuccessful corrections (greater than 50%) so that float ambiguity estimate and fixed value not within 0.25 cycle
  - More robust procedure needed to handle ionospheric activity and data gaps
- Current improvements:
  - Complete redesign of the processing algorithm using uncombined PPP with ambiguity resolution (Banville, 2017)

CSA CubeSat Project

- Through the Canadian CubeSat Project, teams of professors and students can take part in a real space mission. The CSA will award up to 13 grants to fund selected proposals to build a miniature satellite called a cubesat. Professors and students from every province and territory are encouraged to participate in this innovative project. Nominally, one cubesat per province/territory. $2.85M CDN total funding.
- The cubesats will be deployed from the International Space Station. The teams will operate their satellites and conduct science according to the objectives of their missions, which could last up to 12 months.

New Brunswick CubeSat Proposal (1)

- The New Brunswick cubesat will be jointly built by the University of New Brunswick (UNB), the Université de Moncton (UdeM), and the New Brunswick Community College (NBCC) campus in Saint John. The systems design will be from UNB, the software from UdeM, and manufacturing at NBCC.
- The cubesat will determine its precise orbital location using GNSS. Also, multiple sensors will be used to take photos as well as science measurements of the oxygen in the atmosphere.

New Brunswick CubeSat Proposal (2)

- Each time the cubesat orbit passes near Fredericton, the stored data will be transmitted to the UNB ground station (VHF up / UHF down).
- Cubesat objectives:
  - Characterize spatially and time varying parameters of the neutral atmosphere and ionosphere by using receivers for signals from the global navigation satellite systems to determine pseudoranges and carrier-phase observations, estimate precise spacecraft position and velocity.
  - Cameras for oxygen red and green spectral information from the Earth's atmosphere, as well as a regular visual camera for Earth images.

New Brunswick CubeSat Proposal (3)

- GNSS Receiver preliminary design:
  - Single commercial-off-the-shelf NovAtel OEM7 high-rate, multi-frequency, multi-constellation GNSS receiver card
  - Tallysman TW3972 patch antenna (with or without preamp)
  - Various trade-off studies for power consumption, acceptable C/N_0 values, and acquisition and tracking performance to be performed before final selection and construction

New Brunswick CubeSat Proposal (4)

- 2U cubesat design
- Preliminary name: *NB CubeSat*
- Final name to be decided by a contest
- Up to $200,000 CDN funding from CSA per satellite; additional support to come from elsewhere
- Decisions expected in first quarter of 2018

Thank You