Estimation of DCB bias error term for ground and space-based observations using the Spire TEC Environment Assimilation Model (STEAM)

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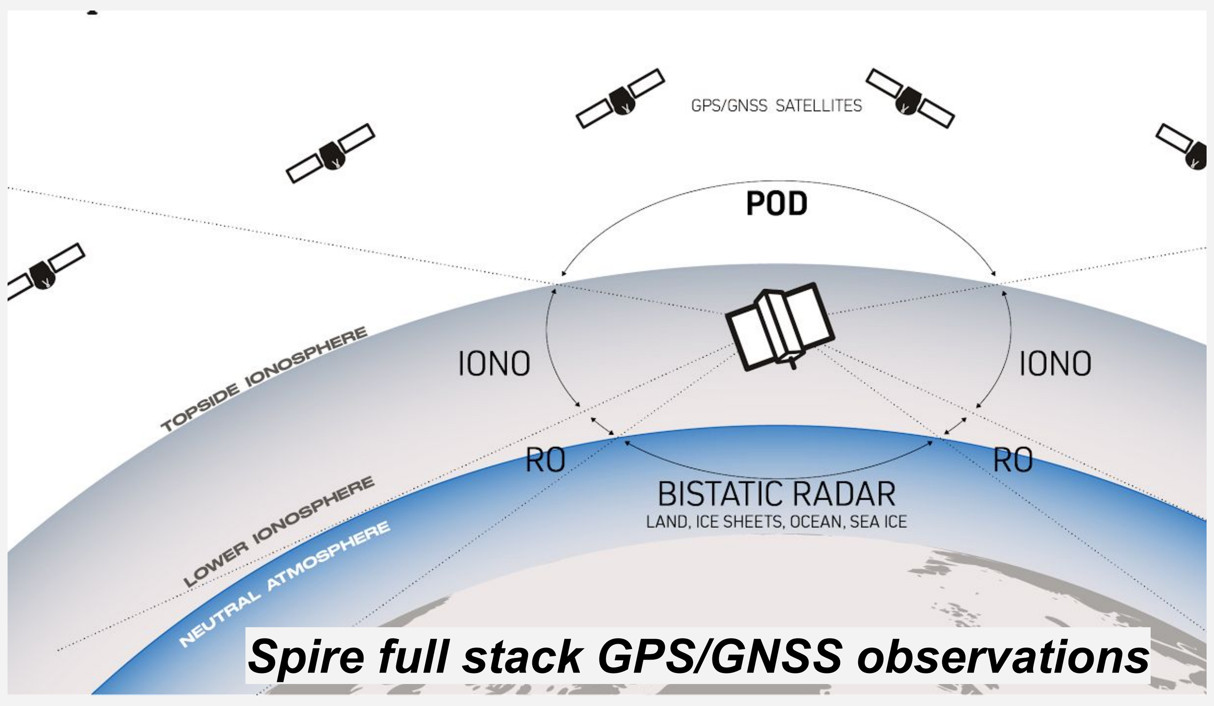
Spire Global

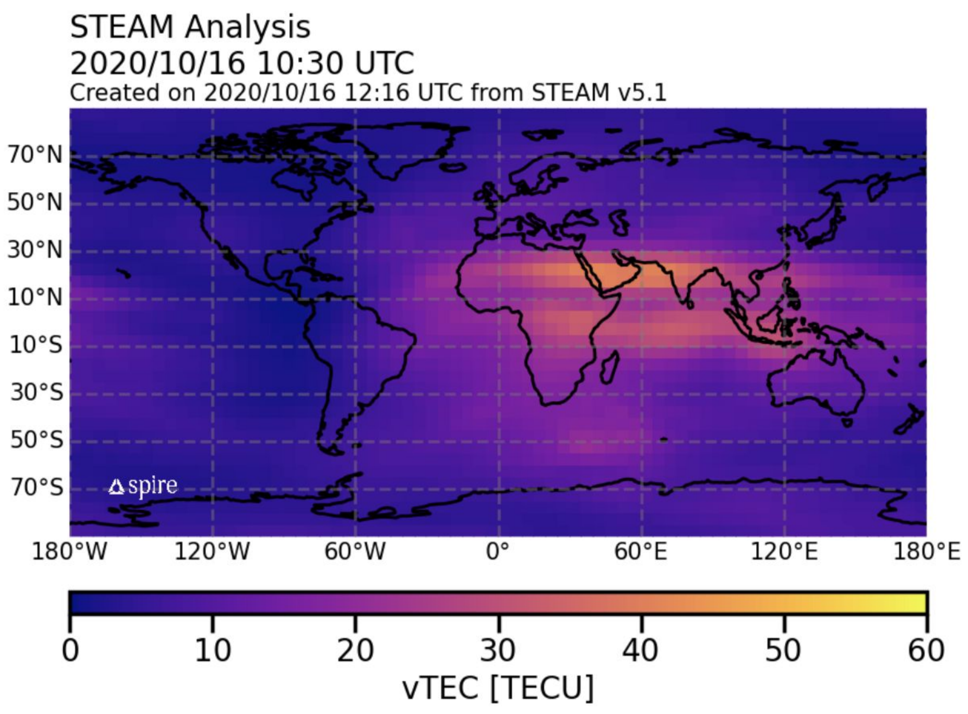
- Advanced, rapidly refreshed 3U CubeSat constellation with 90+ satellites in 400-650 km orbits
- Ground station network (30+ stations)
- Fast hardware upgrades (6 months from design to launch, short design timeframe)
- On-orbit performance upgrades. Demonstrated increase in data performance and tasking on operating satellites



GNSS Earth observation

The satellite constellation is equipped with low power GNSS receivers measuring:

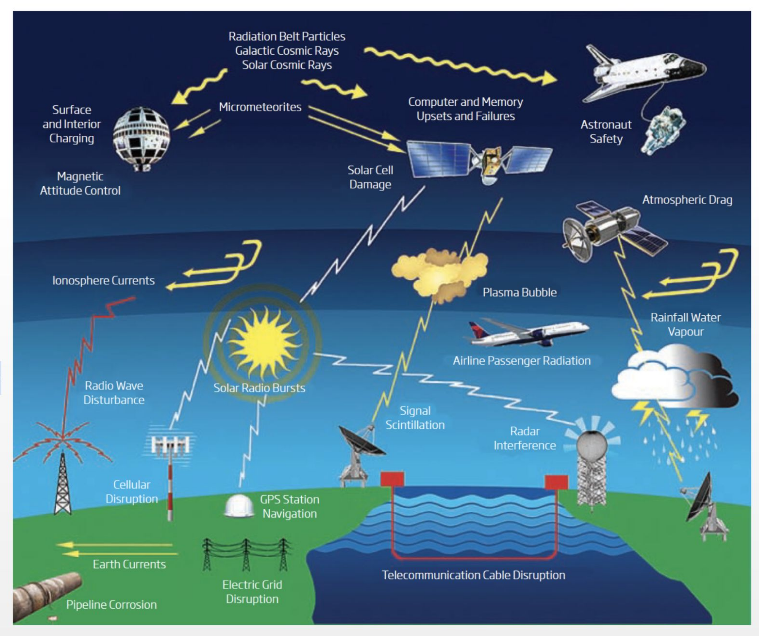
- Radio occultation (RO):
  - Atmospheric sounding for NWP, climate
  - Ionospheric sounding for space weather monitoring
- Thermospheric density through precise orbit determination
- GNSS-R scatterometry (soil moisture, ocean winds, sea ice)
- Grazing angle bistatic radar altimetry



Space weather and ionosphere

Space weather refers to conditions on the sun, in the solar wind, and within Earth's magnetosphere, ***ionosphere*** and thermosphere that can influence the performance and reliability of space-borne and ground-based technological systems and can endanger human life or health.

The **Ionosphere**, located at an altitude between 80 and about 600 km, is **important** because it reflects and modifies radio waves used for communication and navigation [1].



Spire TEC Environment Assimilation Model (STEAM)

- STEAM estimates near real-time 3D electron density (Ne) field and produces various products including Vertical Total Electron Content (VTEC) maps.
- Assimilates Slant Total Electron Content (STEC) into a 4D Local Ensemble Transform Kalman Filter (LETKF) permitting the use of data with varying latency
- Background model is an empirical ionosphere model called NeQuick

Observation production

- STEC observations are produced using geometry free method:

$$y_o = -\frac{f_1^2 f_2^2}{40.3(f_1^2 - f_2^2)}(L_1 - L_2) + b - DCB_{Rx} - DCB_{Tx} \quad (1)$$

- STEAM observation operator integrates along the line-of-sight between transmitter (Tx) and receiver (Rx) which is corrected with the differential code bias (DCB) value for relative TEC observations:

$$y_m = \int_{Rx}^{Tx} Ne\, dv + DCB_{Rx} + DCB_{Tx} \quad (2)$$

Motivation for estimating DCBs

- STEAM currently uses only those International GNSS Service (IGS) ground STEC observations for which the DCB corrections are provided by the Chinese Academy of Science (< 50% of IGS ground stations used)
- Being able to estimate the DCBs would:
  - Improve global observation coverage
  - Correct DCB biases in observations and improve STEAM analysis

Augmented state setup

- The unknown DCB values can be estimated along with the electron densities themselves via augmented state DA
- Extend state vector with DCB parameters from those receivers and signal combinations for which we have relative TEC observations.

$$x_i^b = [Ne_i, DCB_i]^T \in \Re^{N_x \times 1} \quad (3)$$

$$X^b = [x_1^b, x_2^b, \ldots, x_{N_s}^b] \in \mathcal{R}^{N_x \times N_s} \quad (4)$$

where

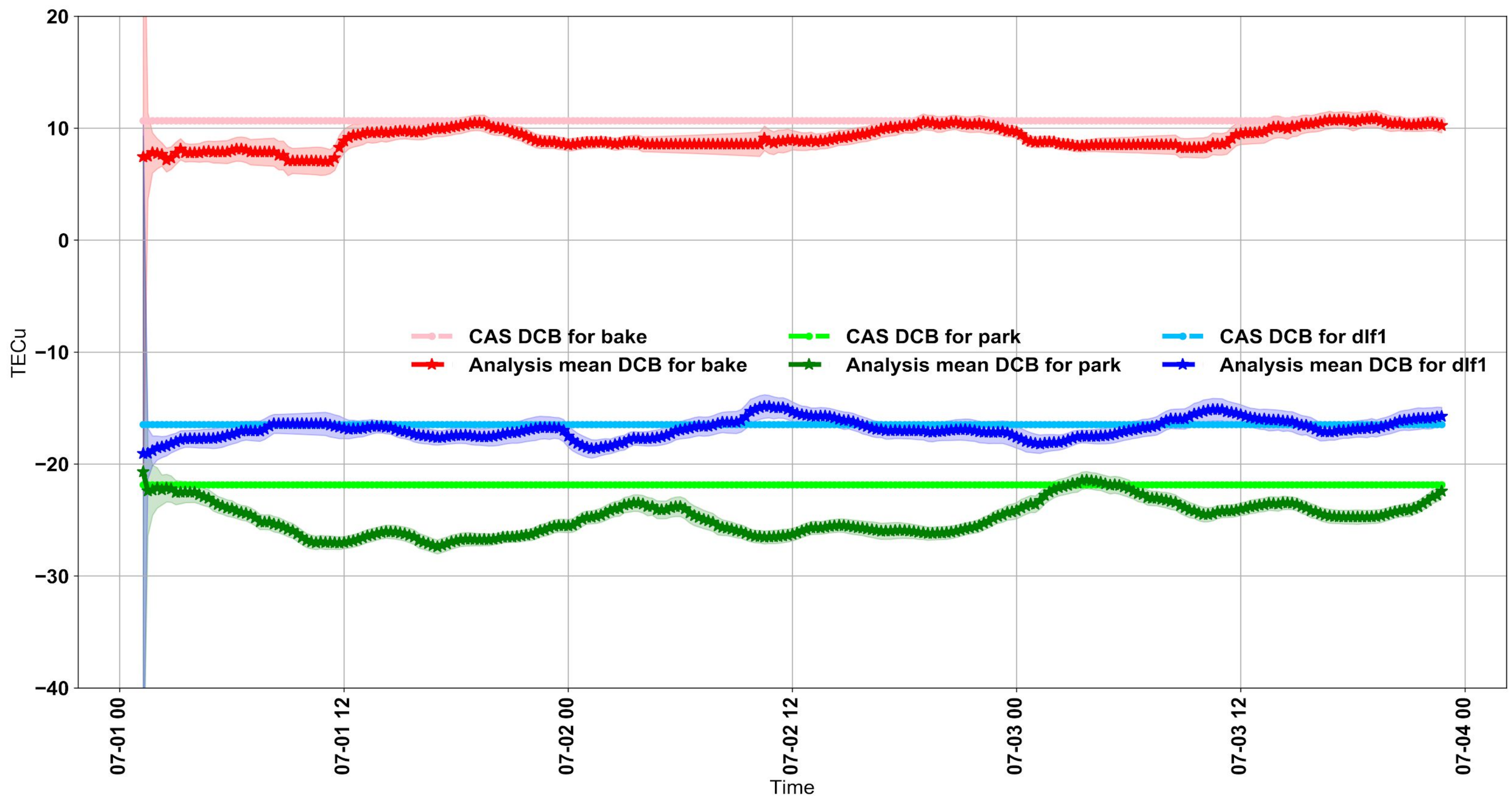
$$N_x = NrLat * NrLon * NrAlt * NrTimes + NrDCB(\widehat{Rx})$$

- Use only local observations for each DCB parameter estimation, ones that come from the same receiver.
- DCB values are forecasted in time using persistence i.e. they remain the same in between data assimilation steps.
- DCB standard deviation is inflated by 2% in between assimilation timesteps.
- DCB initialisation:
  - Use known DCB values if available
  - Otherwise DCB values and errors are initiated to climatology using DCB mean = 0 TECu and DCB std = 50 TECu

Current augmented state results

Initial test performed estimating DCB using relative STEC observations from 3 ground stations: BAKE in Canada, DEF1 in Holland and PARK in Western Australia show that it is possible to estimate DCBs along with electron densities using relative STEC observations.

- Global VTEC RMSE performance is comparable to assimilating only calibrated STEC where DCBs are known
- Similarly local VTEC timeseries around the chosen stations have comparable results to the run with only calibrated observations



References

[1] https://www.swpc.noaa.gov/phenomena/ionosphere

Conclusions

- Spire has a rapidly growing RO-capable constellation
- STEAM augmented state DA shows promising results for estimating unknown ground receiver DCBs Continuing analysis to understand how much of observation bias can be removed by estimating DCBs especially for space based receivers.

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