Detection and Characterization of Travelling Ionospheric Disturbances Using a compact GPS network

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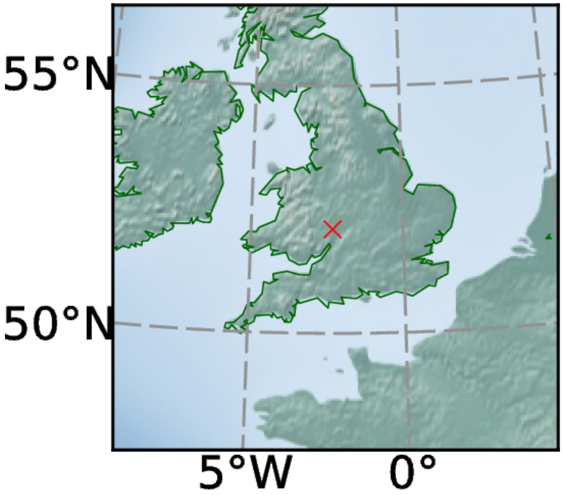
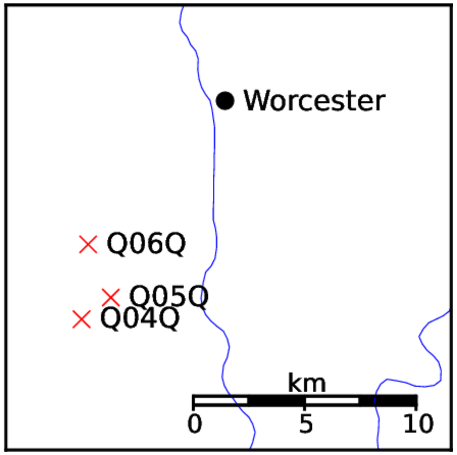
Overview

- Compact GPS network in UK
- Pre-processing of GPS TEC measurements
- TID warning indicators
- TID velocity estimation

"TEMPLAR" GPS network

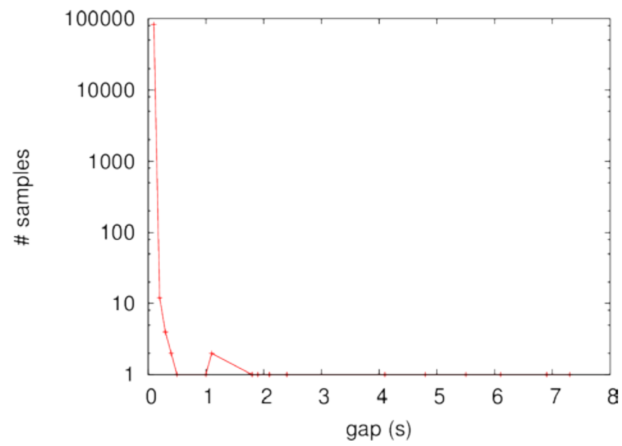
- Project goals include:
  - Live ionospheric monitoring from small dedicated GPS arrays
  - Detection and characterisation of TID activity over UK
  - R&D on TID analysis & forecasting techniques
- Compact network of 3 GPS receivers deployed
  - Semi-autonomous recording, with 3.4 km baseline
- Each receiver station comprises:
  - Navigation-grade COTS dual-band GPS receiver
  - GPS antenna
  - 3G WiFi dongle
  - Rubidium atomic clock
  - Control laptop + external hard drive

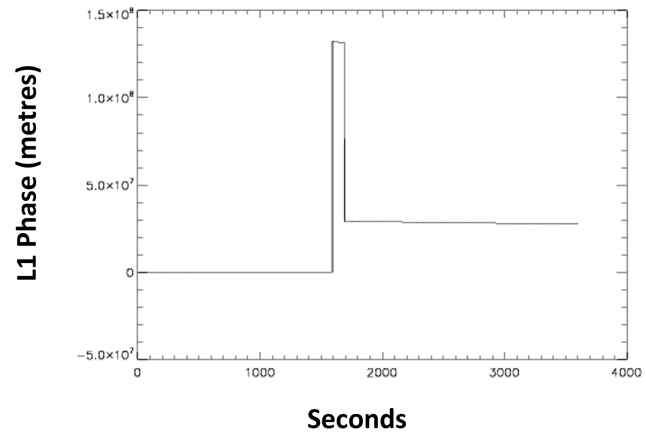




GPS carrier-phase pre-processing

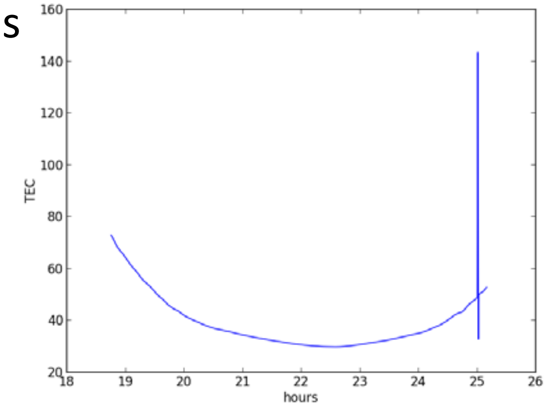
- Estimating TID parameters requires receiver artefacts to be controlled
  - Down-sampling must be robust to drop-outs
  - Discontinuities would invalidate waveform cross-correlation
  - One L1/L2 cycle represents about 1TECu
- Raw data is collected at 10Hz rate
  - Occasional drop-outs of 0.2-5 seconds
  - Discontinuities in carrier-phase due to tracking errors
- A bespoke pre-processing chain has been developed to preserve TID waveform
  - GPSTk used for L1/L2 discontinuity correction
  - Interpolation filters used for down-sampling to 1/30Hz

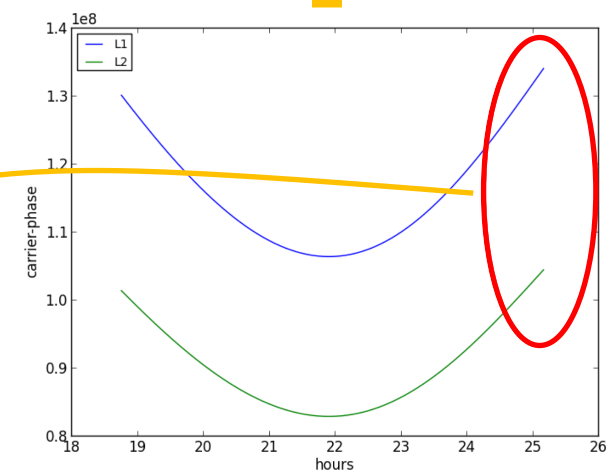


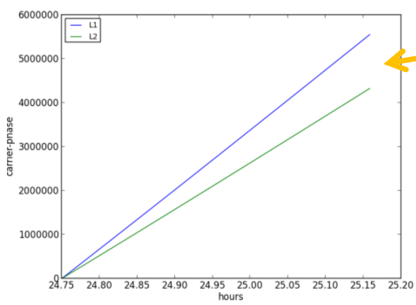


Track trimming

- Carrier phase can change by hundreds of cycles over 0.1s sampling interval
  - Tiny imperfections in cycle-slip correction can produce significant anomalies in TEC
- Anomalies are most likely to occur for satellites at low elevation – typically at ends of track
- Anomalies can be detected using a pair of prediction-error filters
  - Large forwards/backwards prediction-error indicates anomaly somewhere over filter footprint
  - Used to trim ends of tracks – typically removes a few minutes of data per track

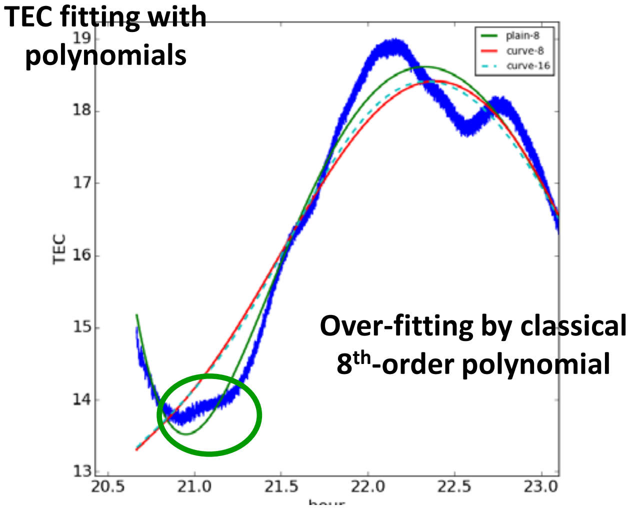


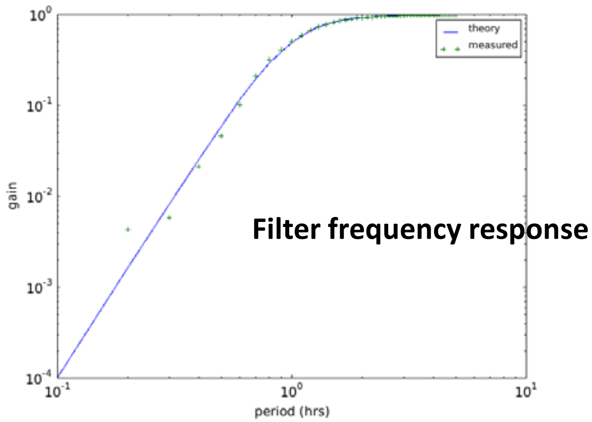




TID waveform extraction

- TID waveform needs to be separated from background diurnal trend
  - Background trend can itself be complex
- Conventional approach is to use low-order polynomials
  - Trade-off between over-fitting & insufficient degrees of freedom
  - Polynomial order is not physically meaningful
- Bespoke Bayesian polynomial fit has been developed
  - Allows high-order polynomials to be used robustly
  - Has well-defined selectivity of TID periods
  - Allows long TEC time-series to be processed without sub-windowing

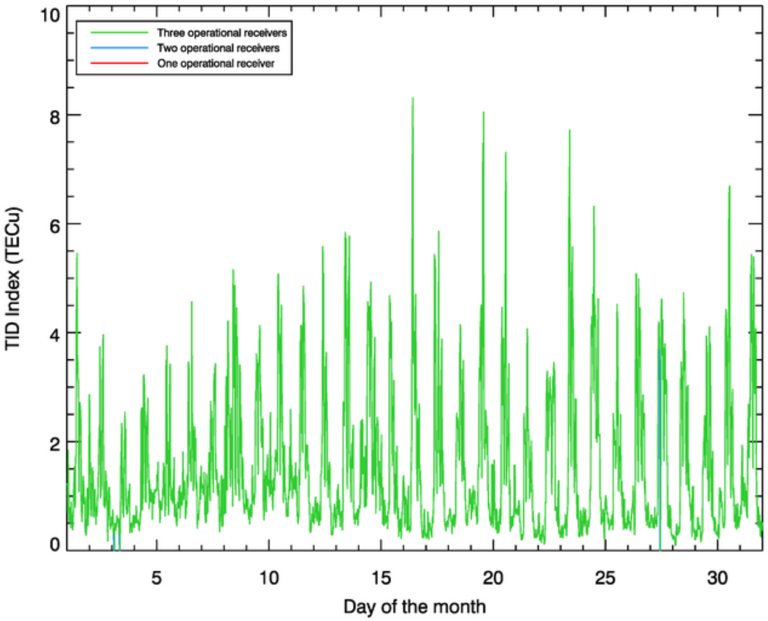




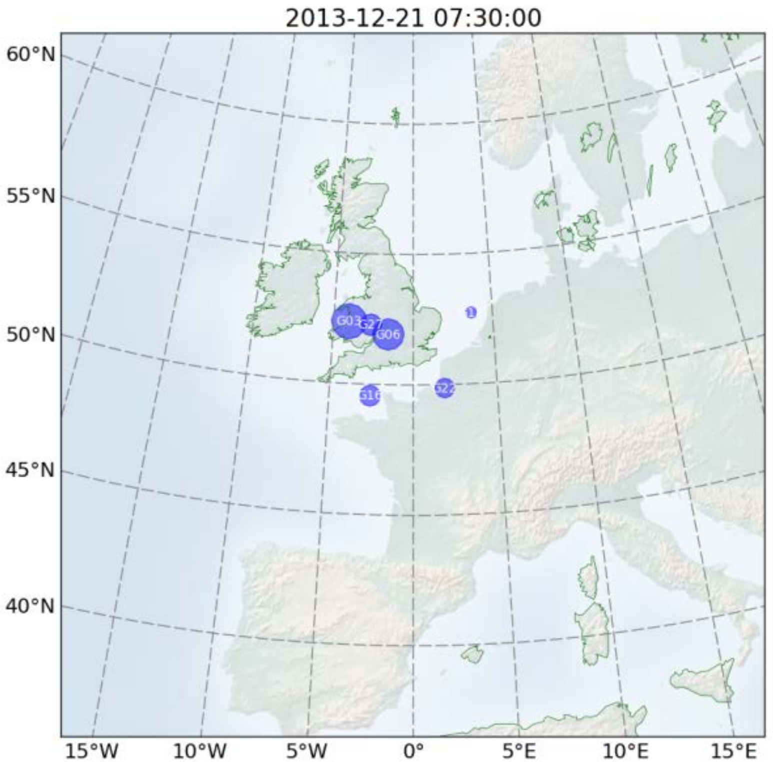
Detection of TID activity

- De-trended TEC time-series can be used to identify TID behaviour
- The first tool developed in this vein was the TID index:
  - A computationally efficient method of identifying presence of TID-like behaviour
  - Provides warning of anomalies on operational HF systems
- TID index is computed by:
  - De-trending raw TEC time-series
  - Estimating TID amplitude over sliding window of 2-6 hours
  - Associating TID amplitude with known satellite ephemeris

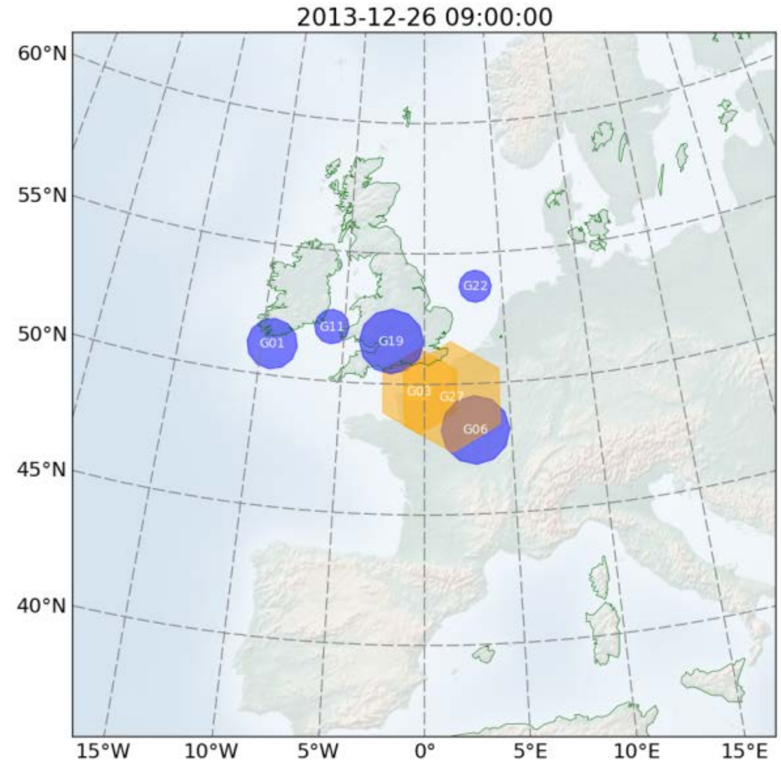
Example of TID Index time-series for December 2013



Geospatial TID activity



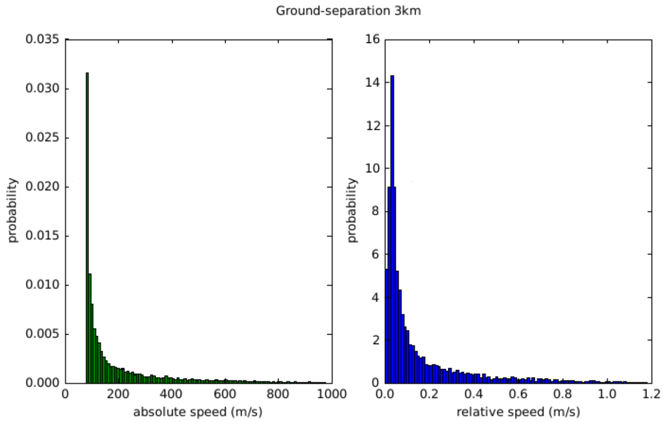
TID amplitude and extent on "quiet" day

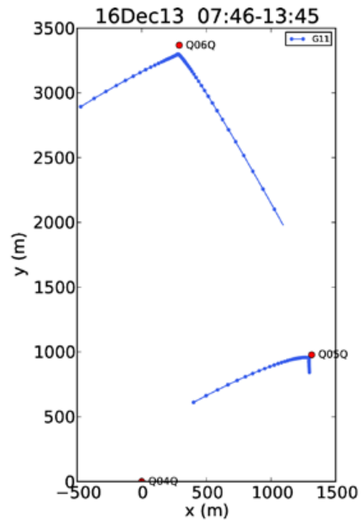


TID footprint on "active" day

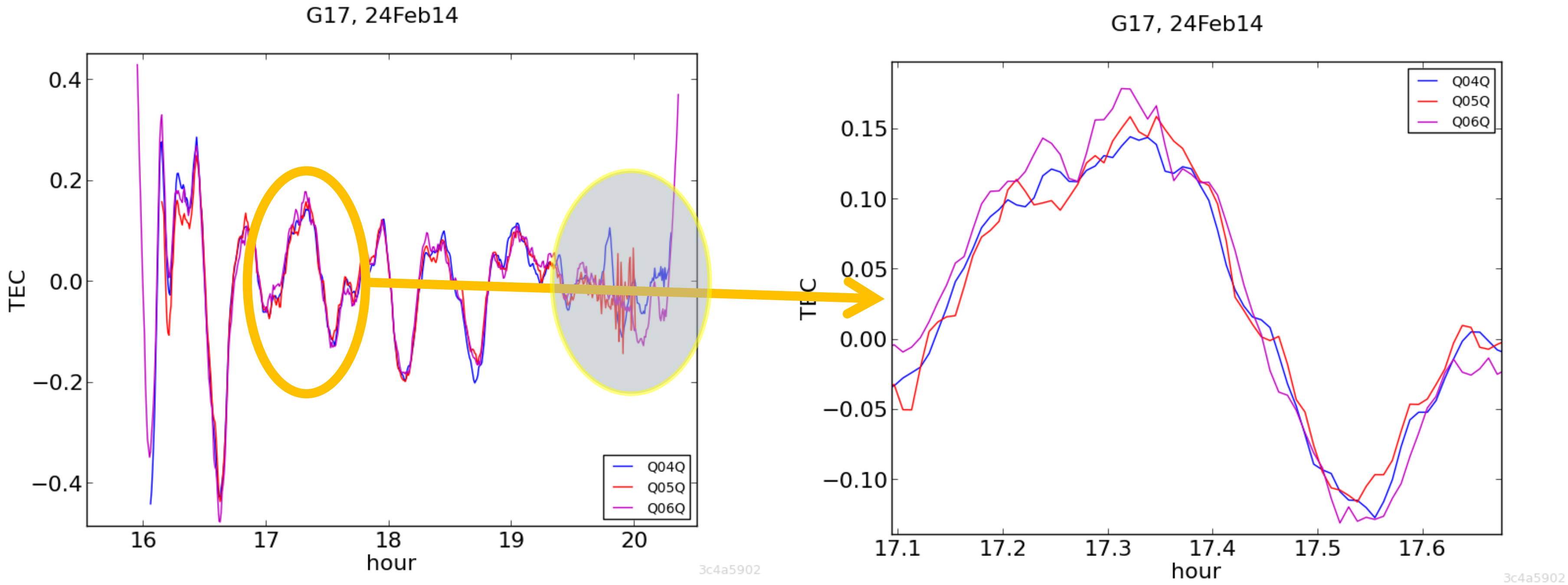
TID motion estimation

- Differences in TID waveform across the array are indicative of TID motion
- Time-delay estimation by cross-correlation is complicated by satellite motion
  - Spacing of pierce-points varies on same timescale as TID waveform
  - Effective baseline of Templar array varies by about 1km over each satellite track
- Bespoke ephemeris-aware cross-correlation technique has been developed
  - Estimates best-fit TID “slowness” to account for observed TID waveforms and Doppler shifts
  - Can be used to estimate observed SNR and TID period





Cross-correlation & GPS receiver noise



- TEC time-series from the three sensor sites generally show qualitative similarity between TID waveforms
- Noise levels are rarely so low as to make time-delay estimates easy
  - Even after careful cycle-slip correction, dropout-aware downsampling, etc.

TID velocity estimates

Combining GPS data from multiple receivers allows TID speed & heading to be estimated

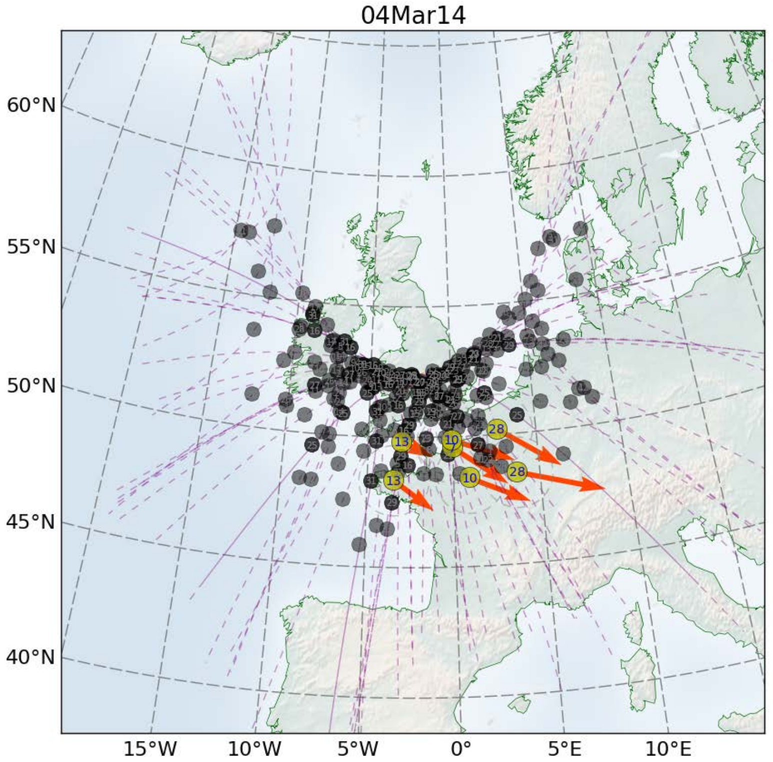
- Many open challenges in "repurposing" navigation device as an ionospheric measuring system

South-easterly TID motion at ~150m/s is common over the UK

- Simulation results confirm that other TID headings are correctly estimated

Combination of TID footprint and velocity provides basic forecasting of TID effects

- Timescale of hours, lengthscale of ~500km



Conclusions

- Small GPS receiver networks can give informative observations of the ionosphere
- Careful pre-processing is essential to obtain reliable TID parameters
  - Discontinuities must be handled robustly
  - Suitably down-sampled datasets can be processed efficiently to identify annual trends
- TID velocities can be extracted from suitably sophisticated cross-correlation techniques
  - Must allow for modulation of TID waveform by satellite motion and change in effective array baseline during TID motion
- Open questions being tackled by on-going work include:
  - Estimation of TID vertical structure (tomography?)
  - Fusion of TID waveforms from multiple satellites