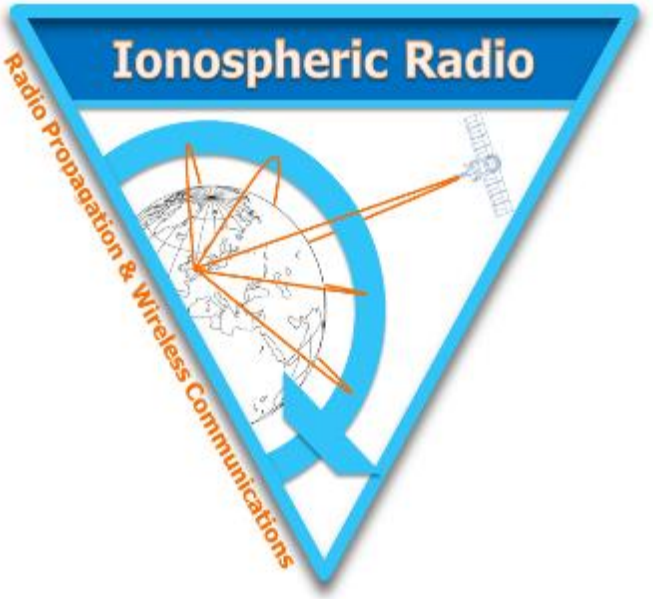
QINETIQ

Preliminary results from the Arecibo Heating EXperiment (HEX): From HF to GPS

CEDAR Workshop 2017

Keystone, Co



Dr Natasha Jackson-Booth

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Collaborators and Acknowledgements

- **QinetiQ**
  - Richard Penney, Poppy Martin, Rachel Buckland, Thomas Morton-Orr
- **U.S. Naval Research Laboratory (NRL)**
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- **Applied Physics Laboratory (APL), Johns Hopkins University**
  - Ethan Miller
- **Air Force Research Laboratory (AFRL)**
- **Acknowledgements**
  - This work was funded by the UK Ministry of Defence
  - The Trinidad deployment was facilitated by the Trinidad and Tobago Defence Force

HEX overview

HEX summary

- **The Heating EXperiment (HEX) was designed to help further our understanding of the phenomena caused by artificially heating the ionosphere, using the Arecibo facility in Puerto Rico**

- **This was achieved by utilizing a HF measurement experiment spread over 3500 km and the deployment of a small scale travelling ionospheric disturbance (TID) network near the heater**

- **Arecibo was in operation 16:00 (LT) on 13th March to 06:00 (LT) on 20th March 2017 and 11:30 (LT) on 21st May to 08:00 (LT) on 26th May**

- **TID network deployed around Arecibo on 15th February 2017**
  - Network left running to collect background statistics

- **Transmissions from ROTHR sites on mainland USA and Puerto Rico**

HEX overview

- ROTHR transmitted from Virginia, Texas and Puerto Rico
- Transmissions passed through heated region of the ionosphere
- Transmissions recorded in Puerto Rico and Trinidad
- Arecibo operated throughout the week and throughout the day
- Used both 8.175 and 5.1 MHz
- Used both CW and pulses

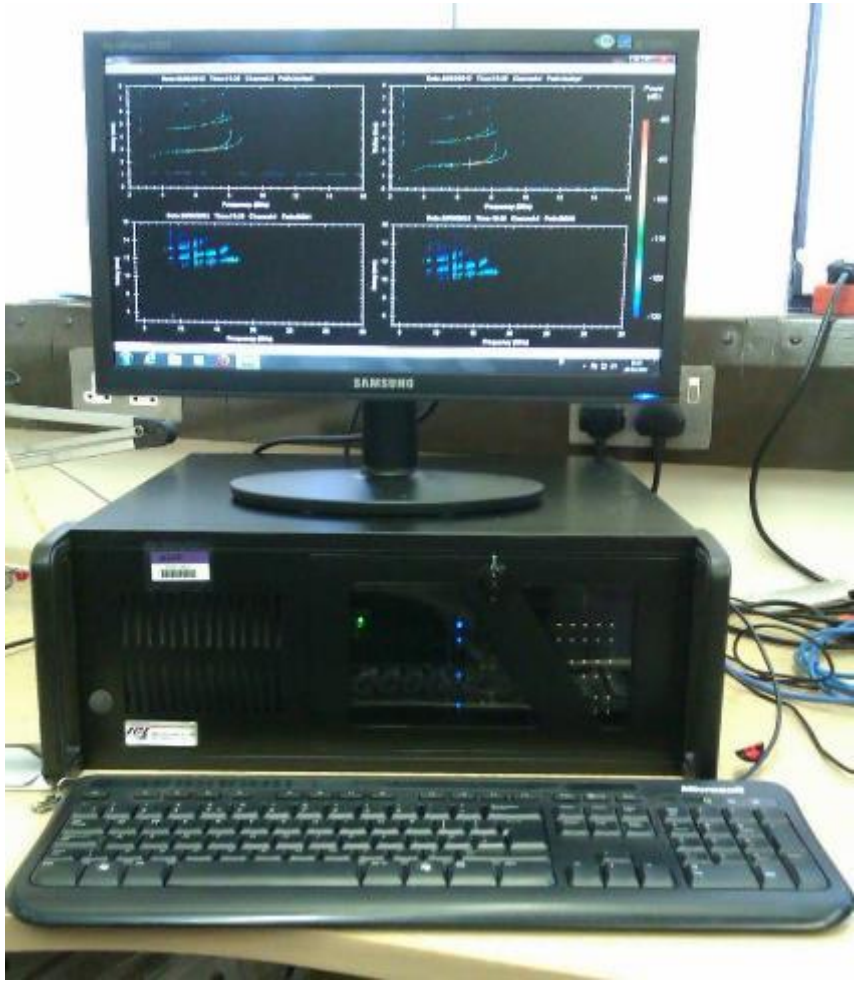
Deployment overview

- **TID monitor near Arecibo**
- **ROTHR in VA, TX and PR**
- **1x RX (Trinidad)**
- **1x APL RX near Arecibo (Culebra)**
- **1x NRL RX Camuy**
- **e-POP satellite**
- **ISR to provide**
  - Ion lines
  - Plasma lines
  - Enhanced ion line plasma

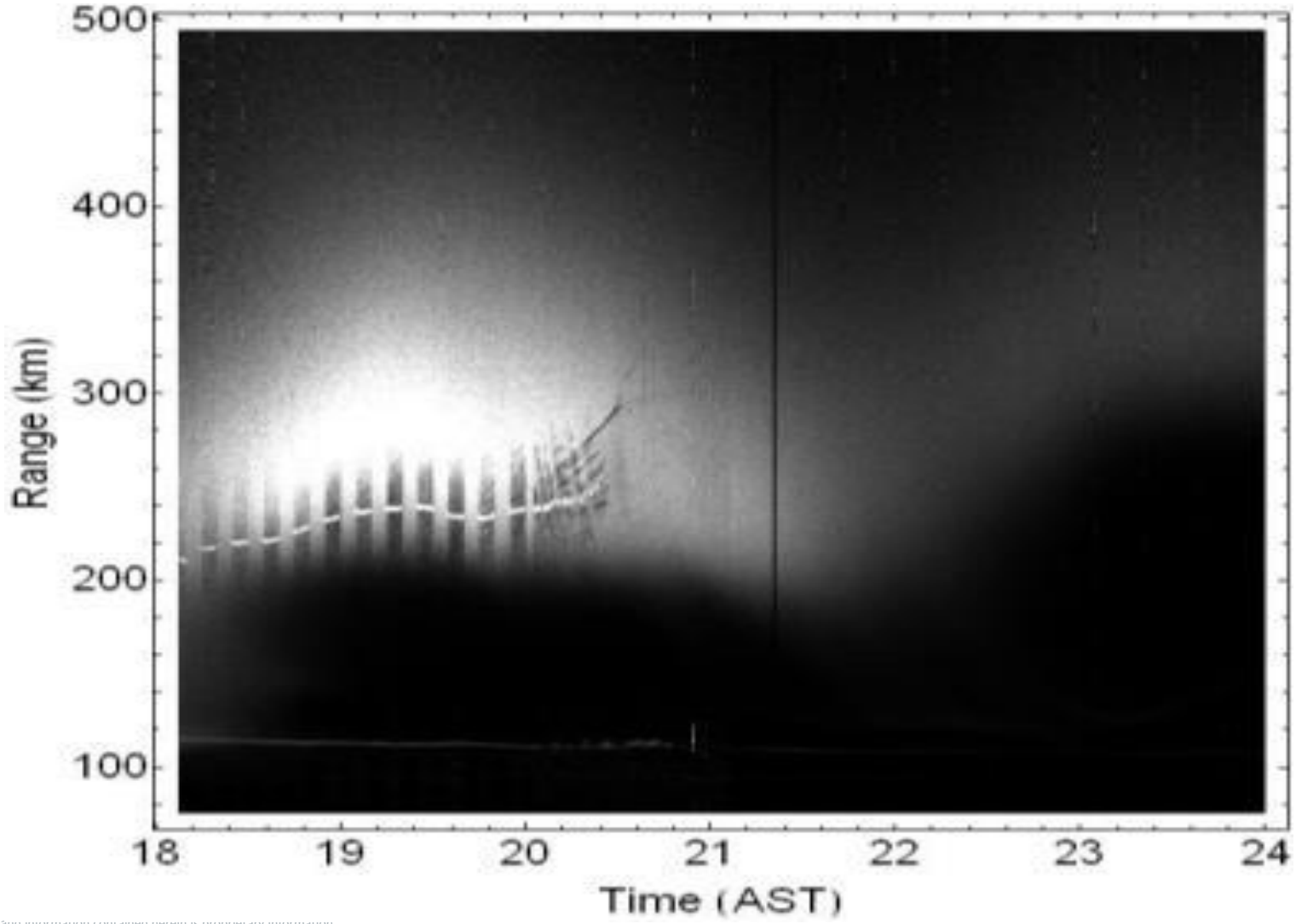
HF results

Receivers : IRIS2

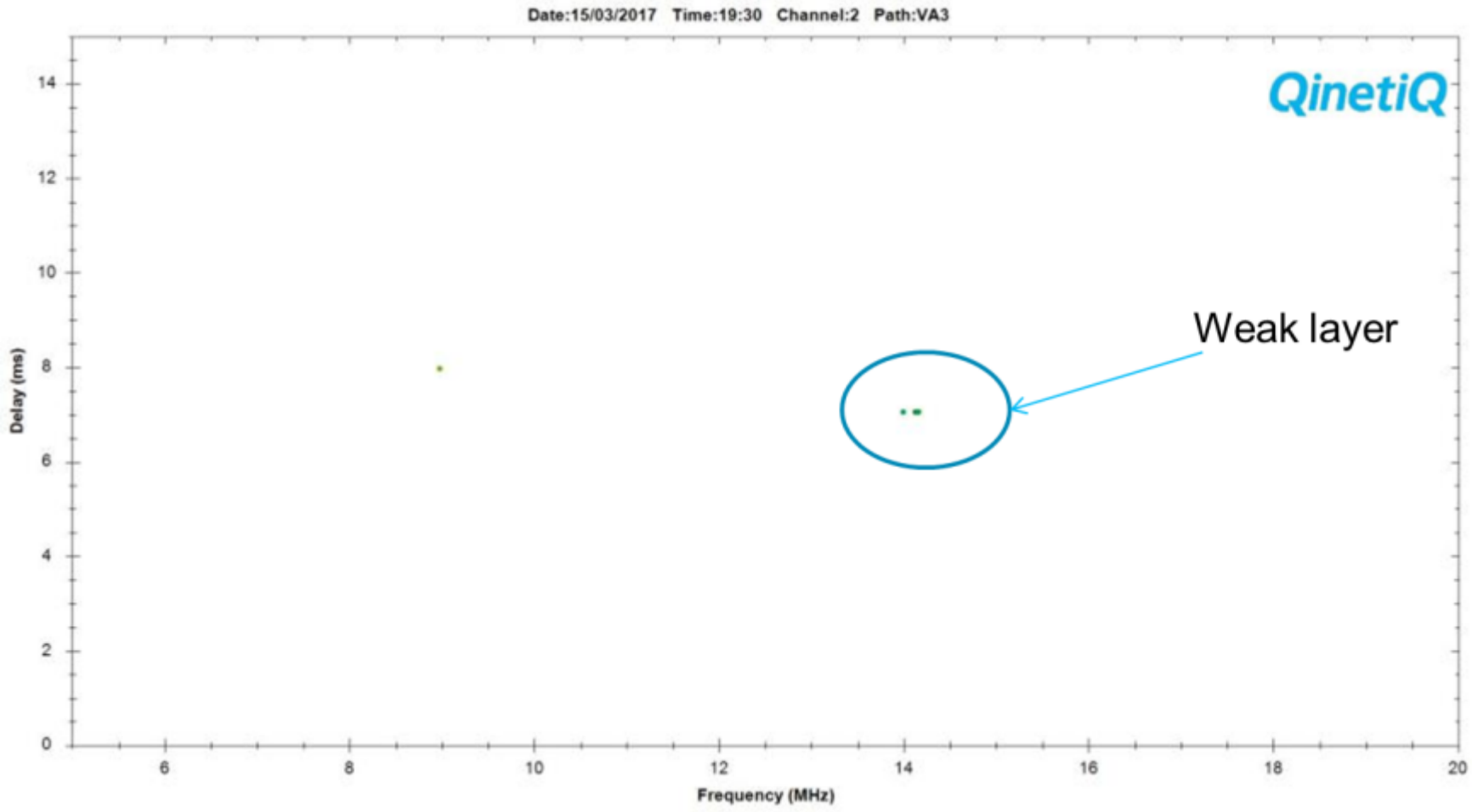
- **Comprises a 4 channel receiver module**
- **Can receive 4 paths simultaneously and do wideband (40 MHz) data capture**
- **Deployed in Trinidad**
  - Chaguaramas TTDF base
- **Received FMCW chirps from VA, TX and PR.**
- **Recorded CW signals from VA, TX, PR and Arecibo.**



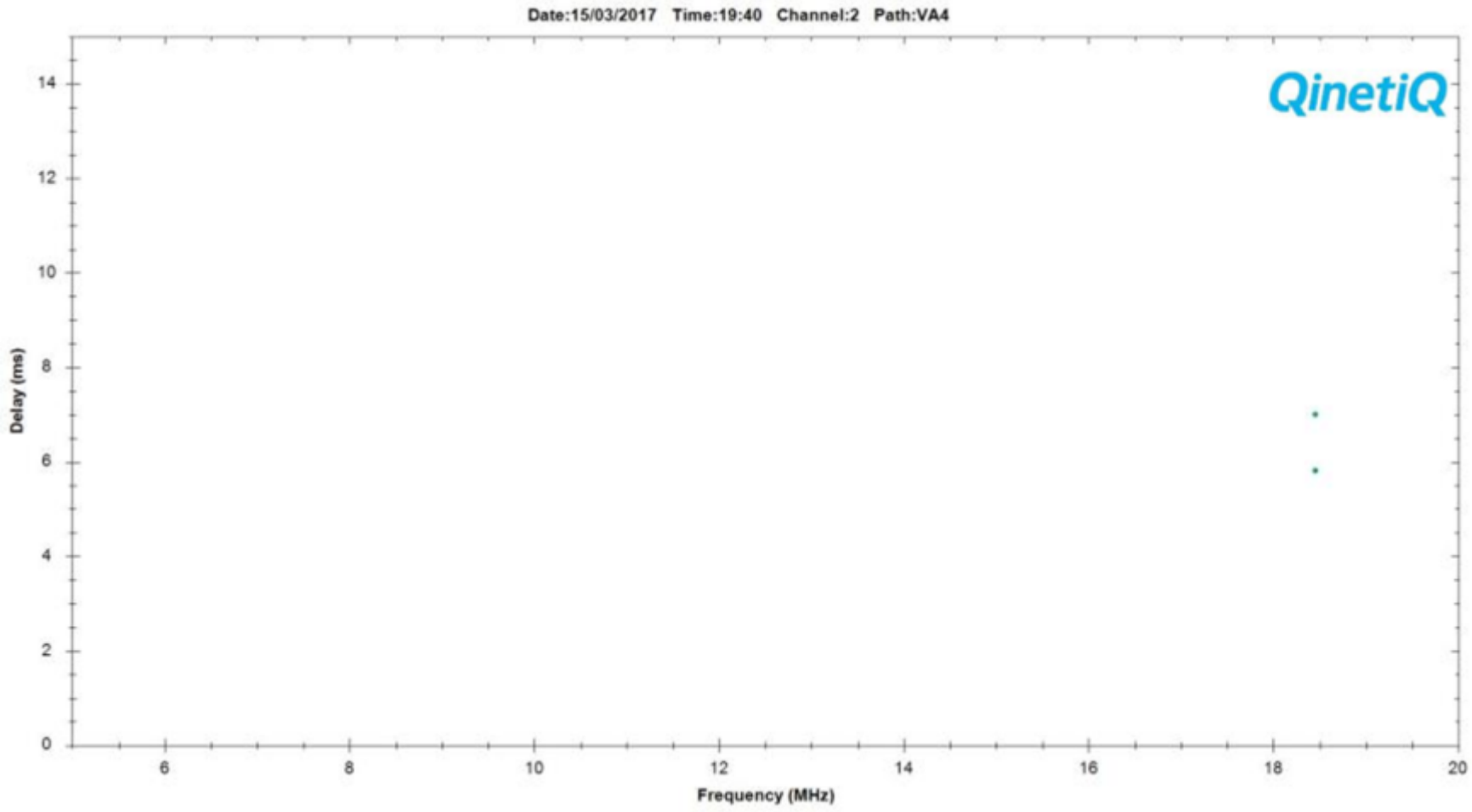
Structure generated



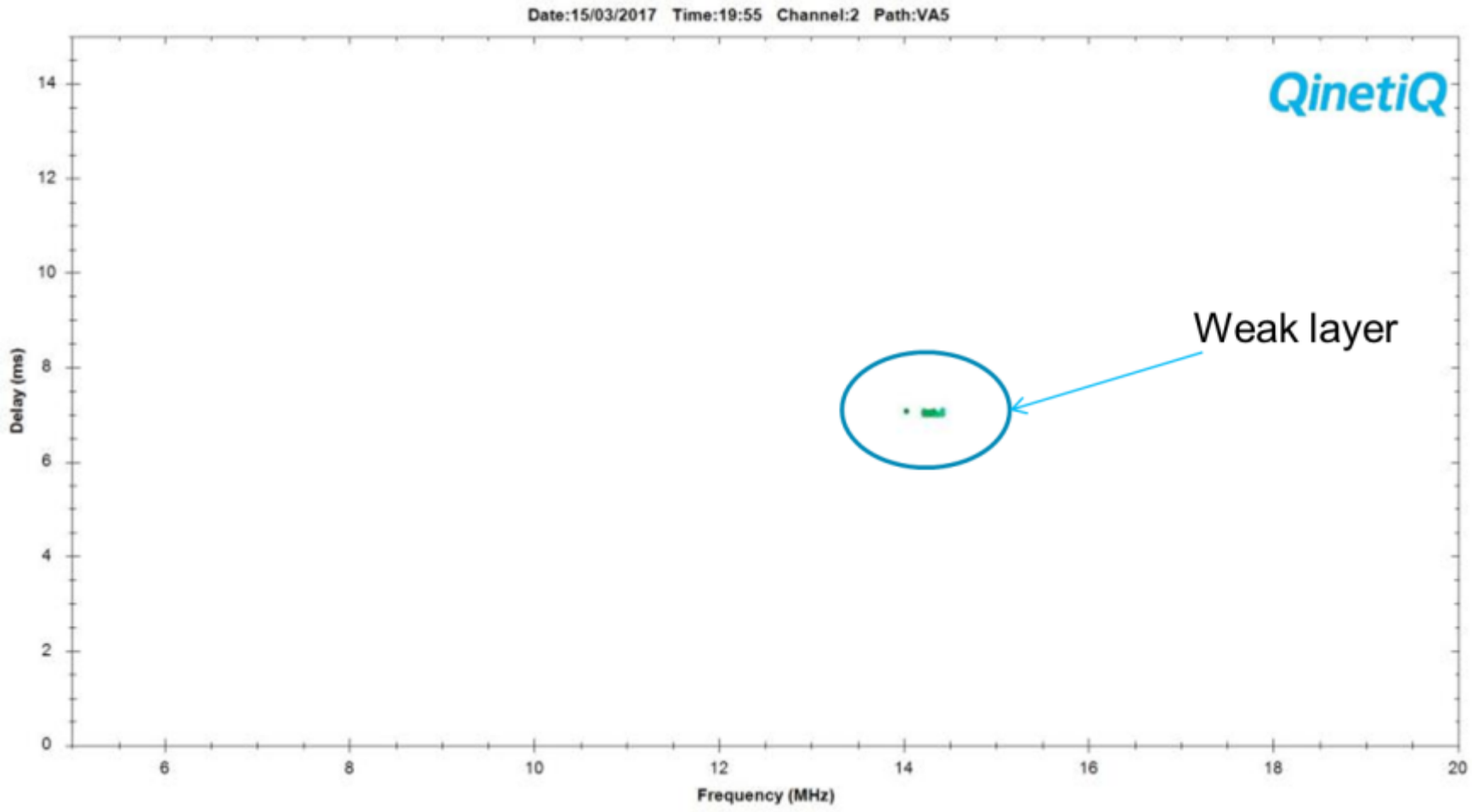
15th March – 19:32 UT CW at 8.175 MHz



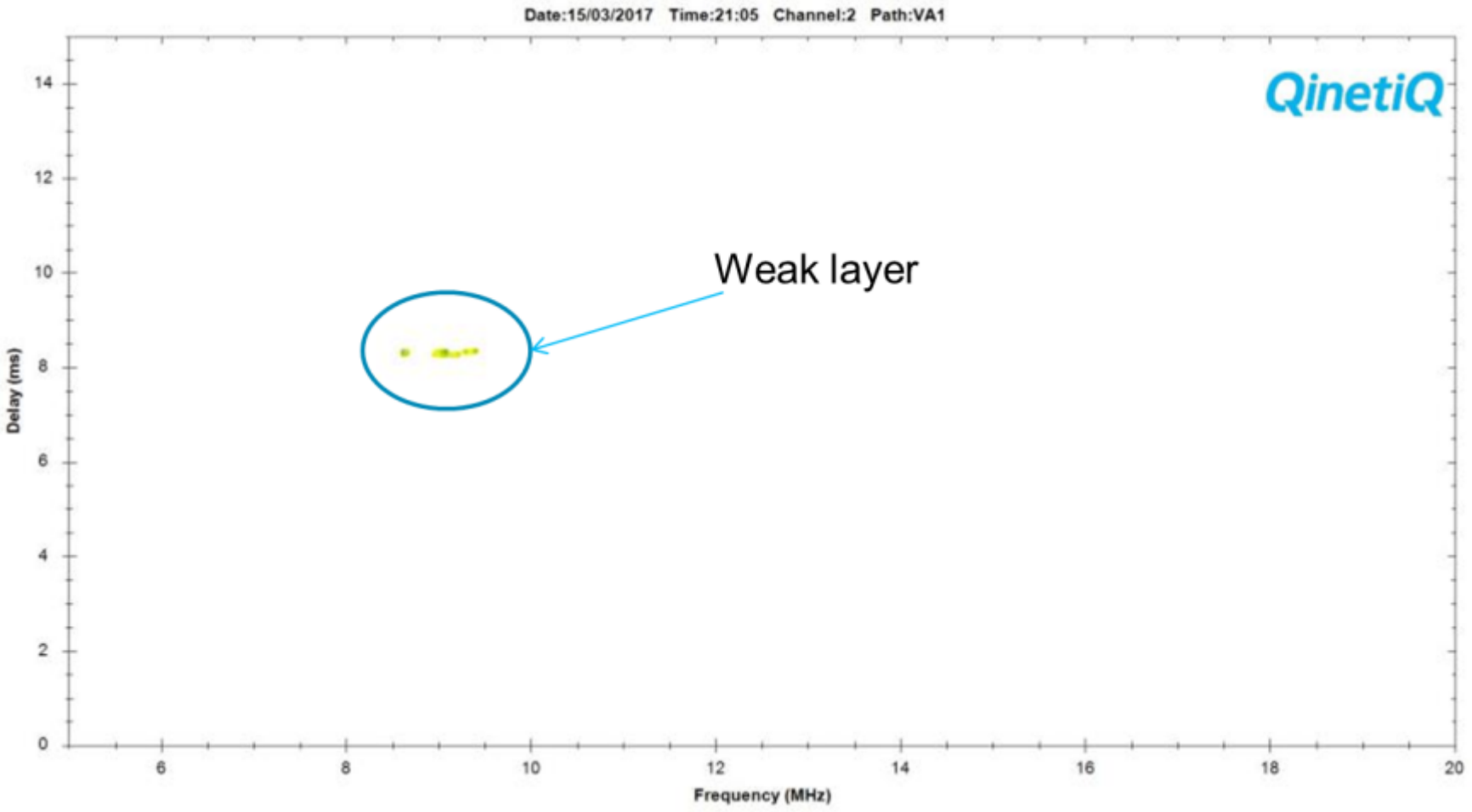
15th March – 19:44 UT heater off



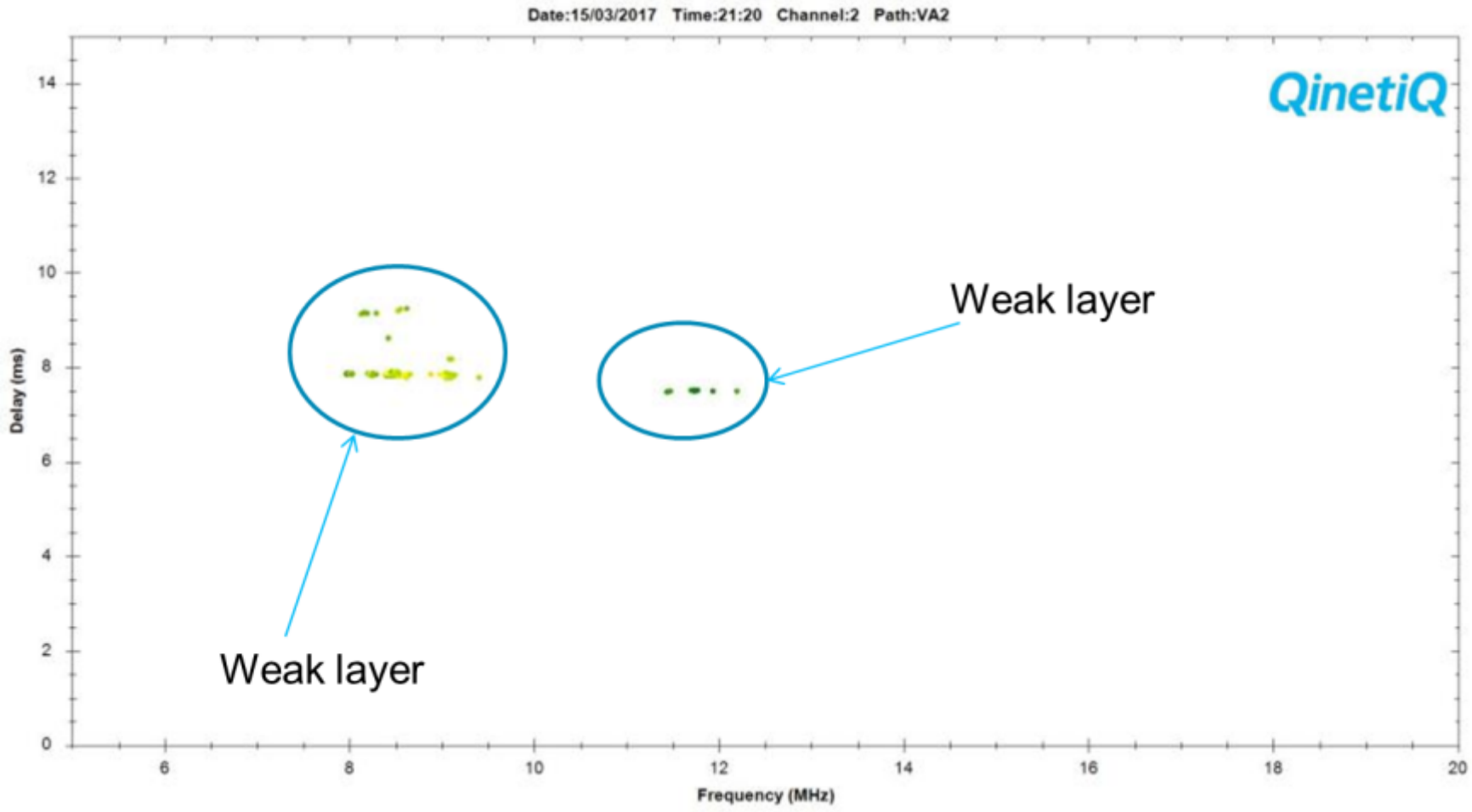
15th March – 19:56 UT 1/3 pulse at 8.175 MHz



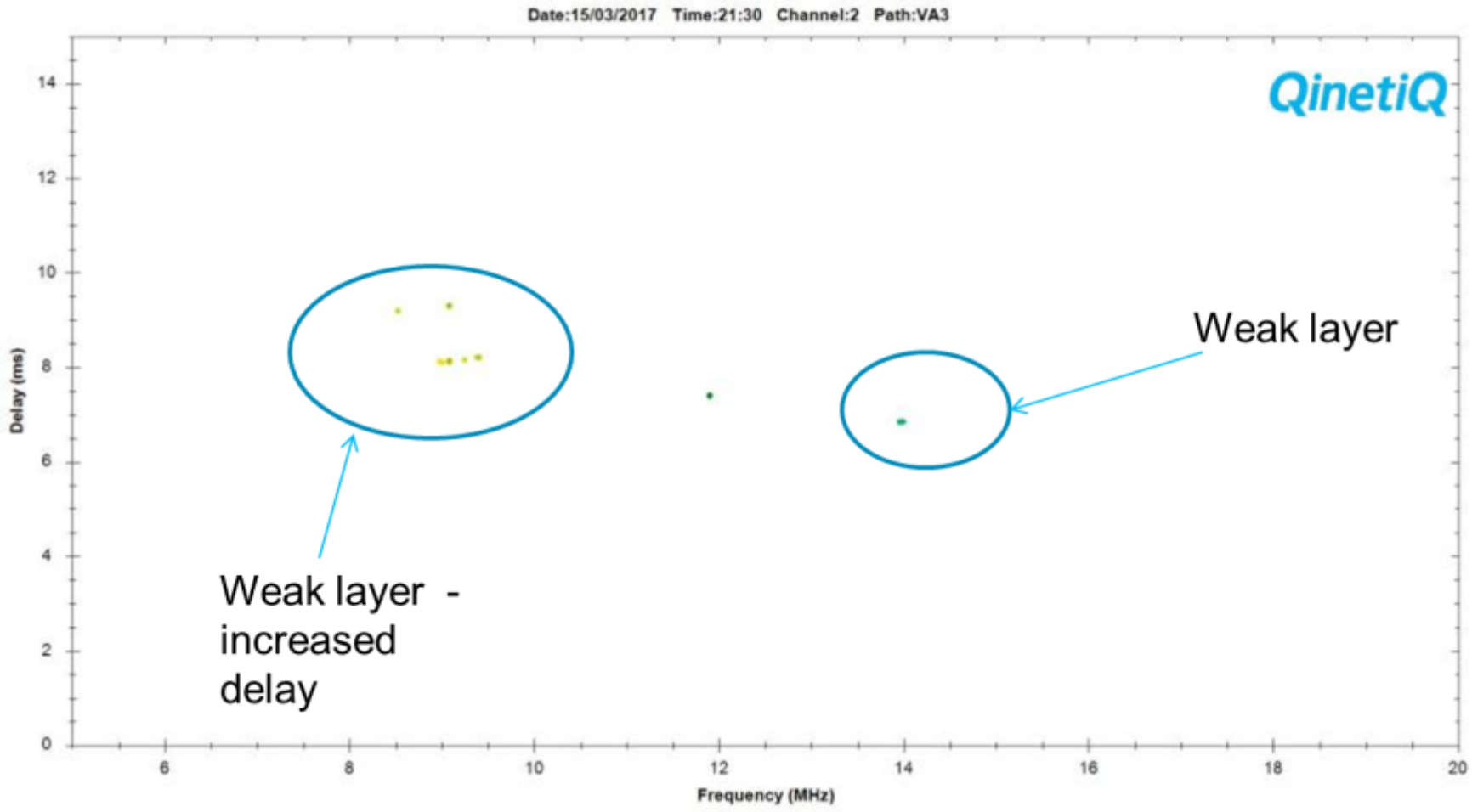
15th March – 21:05 2min/2min pulse



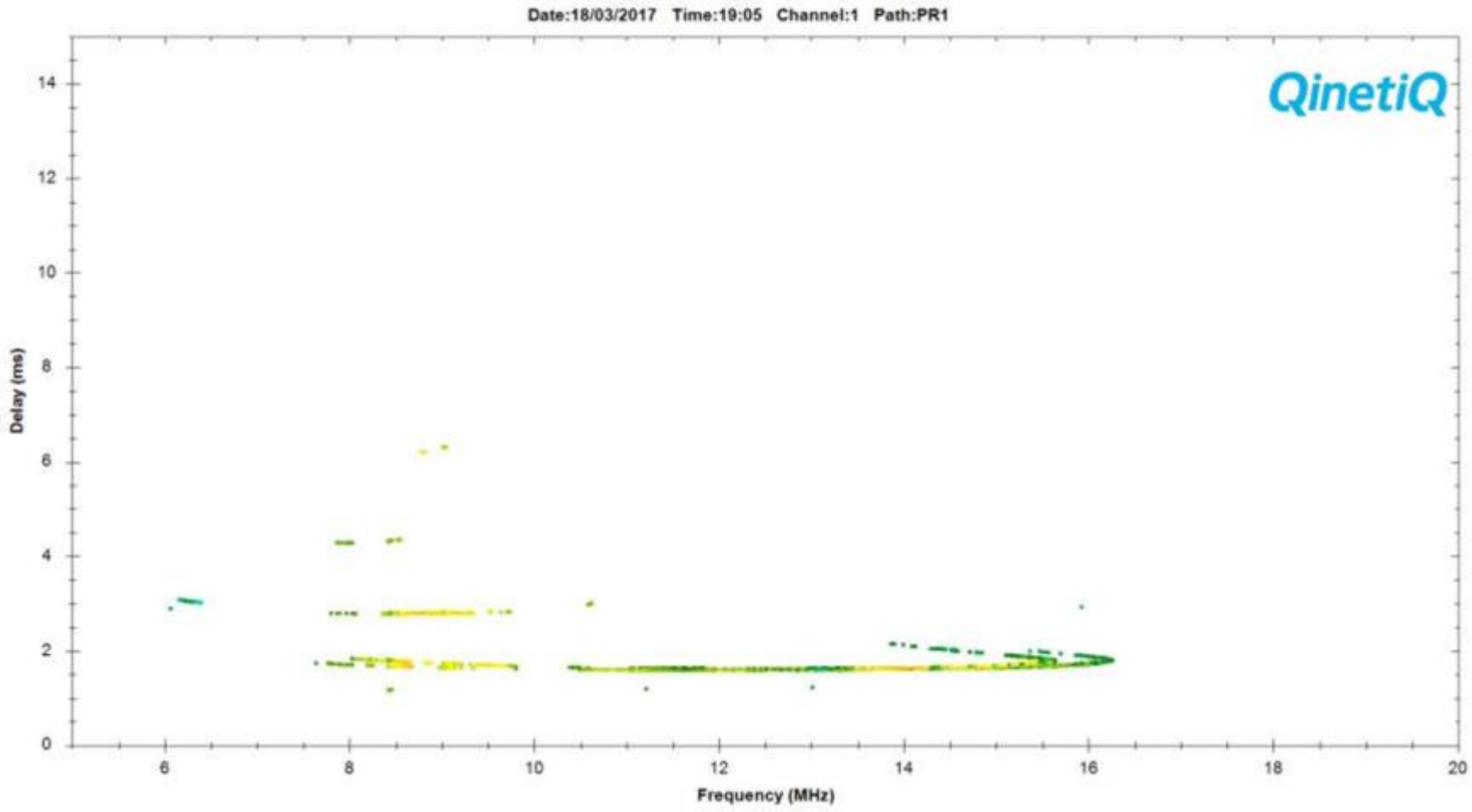
15th March – 21:20 UT HF just turned off



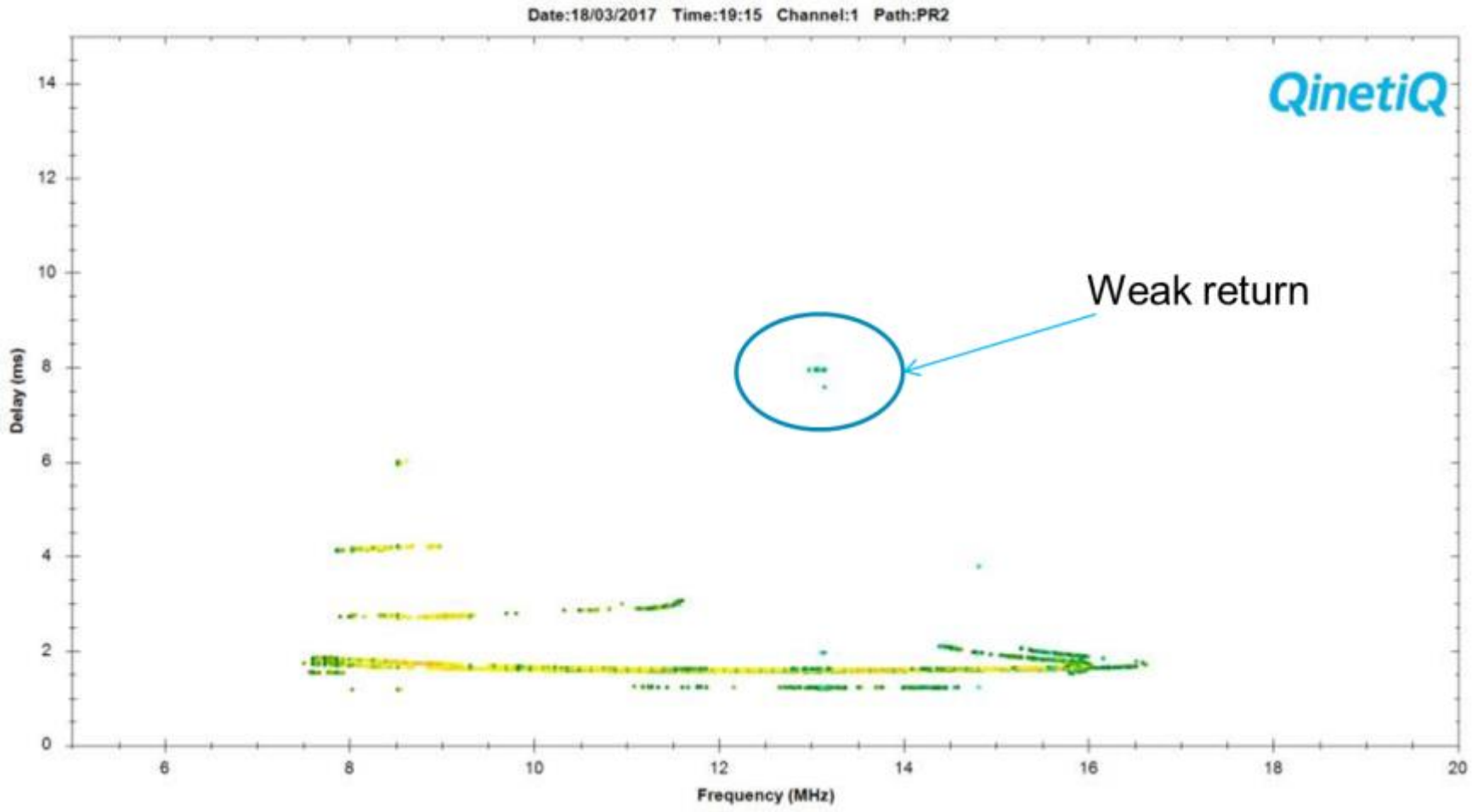
15th March – 21:32 UT HF turned off 2 mins prior to start of recording



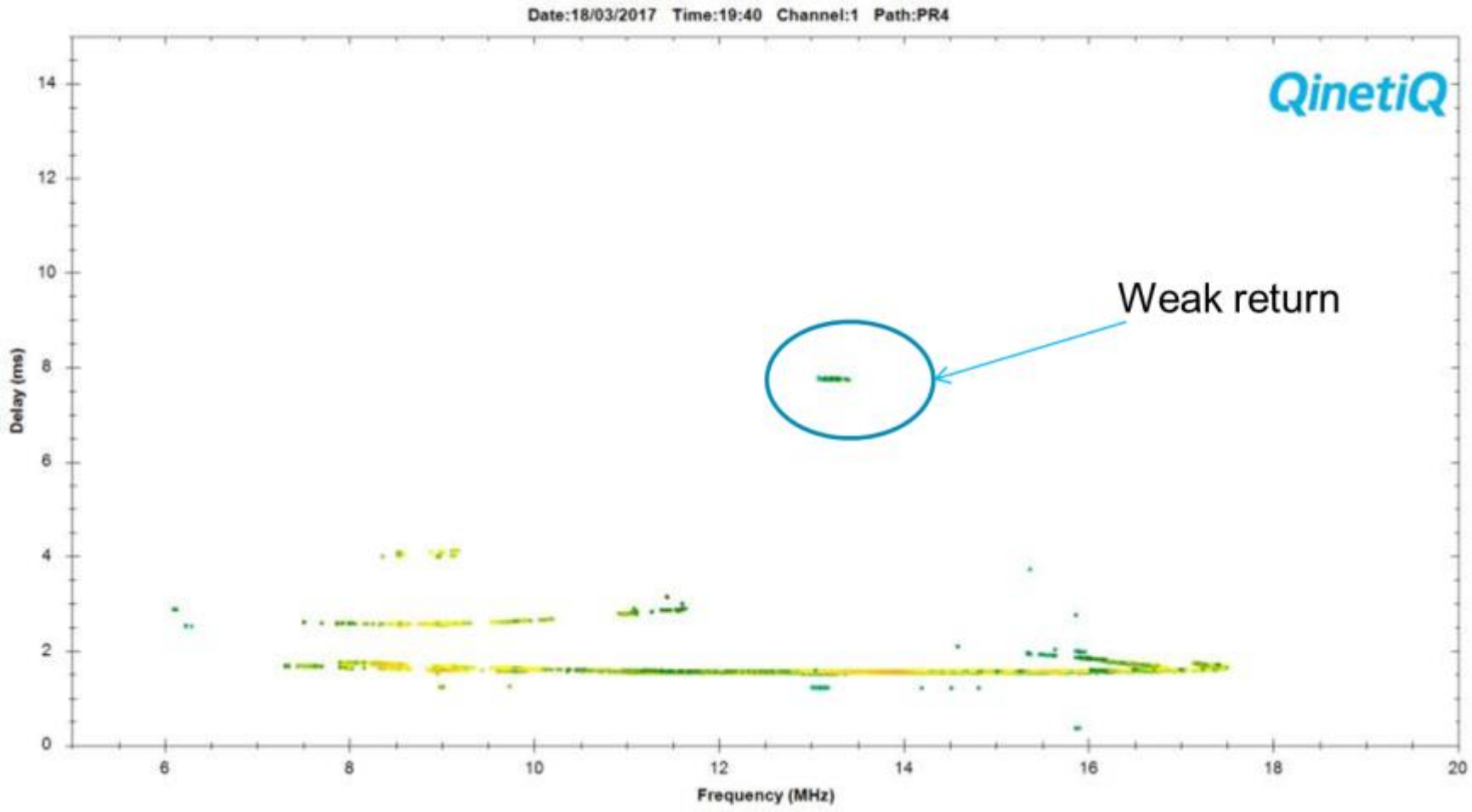
18th March – 19:05 UT Heater on 3/1 pulse



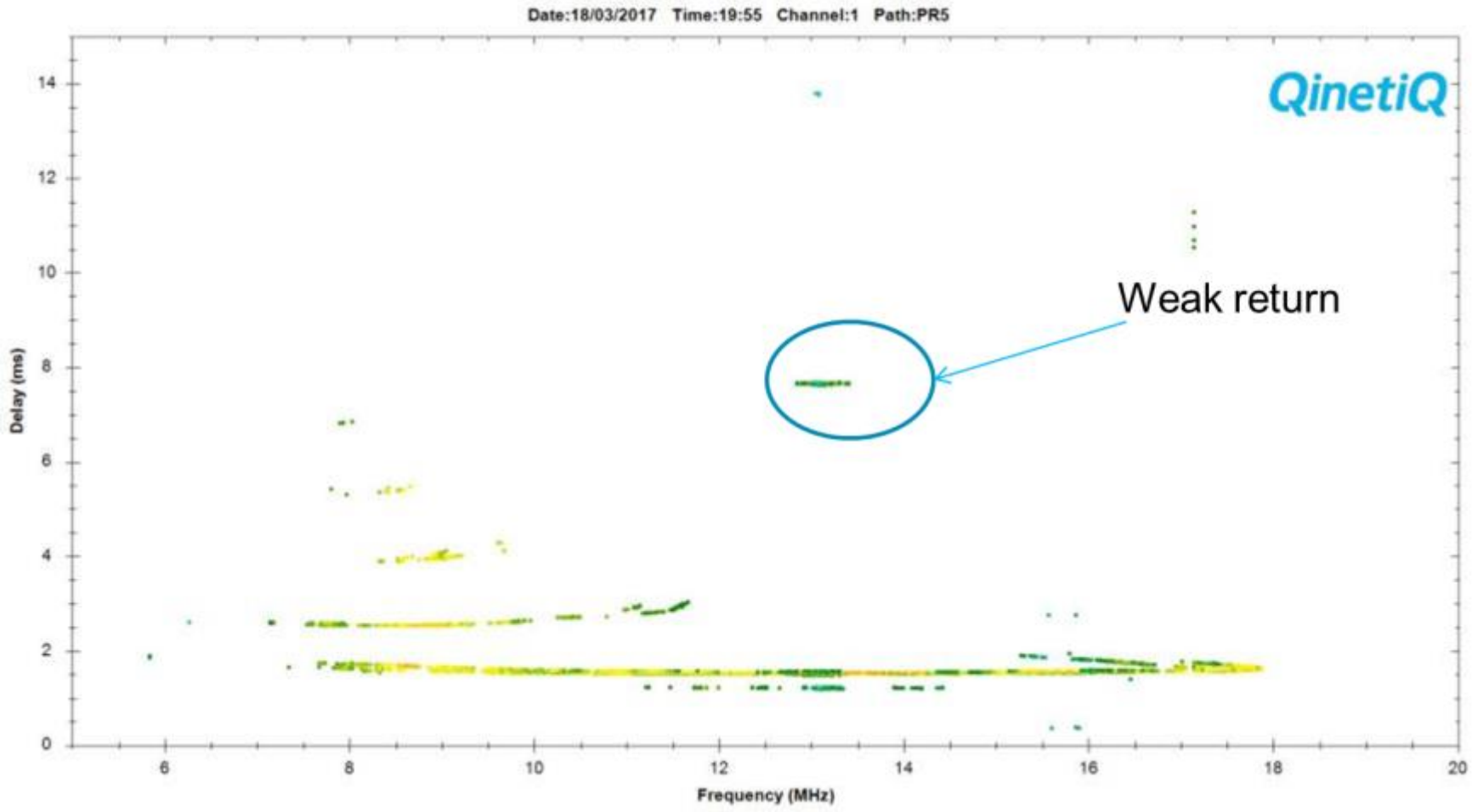
18th March – 19:19 UT Heater on 3/1 pulse (after 10 min off)



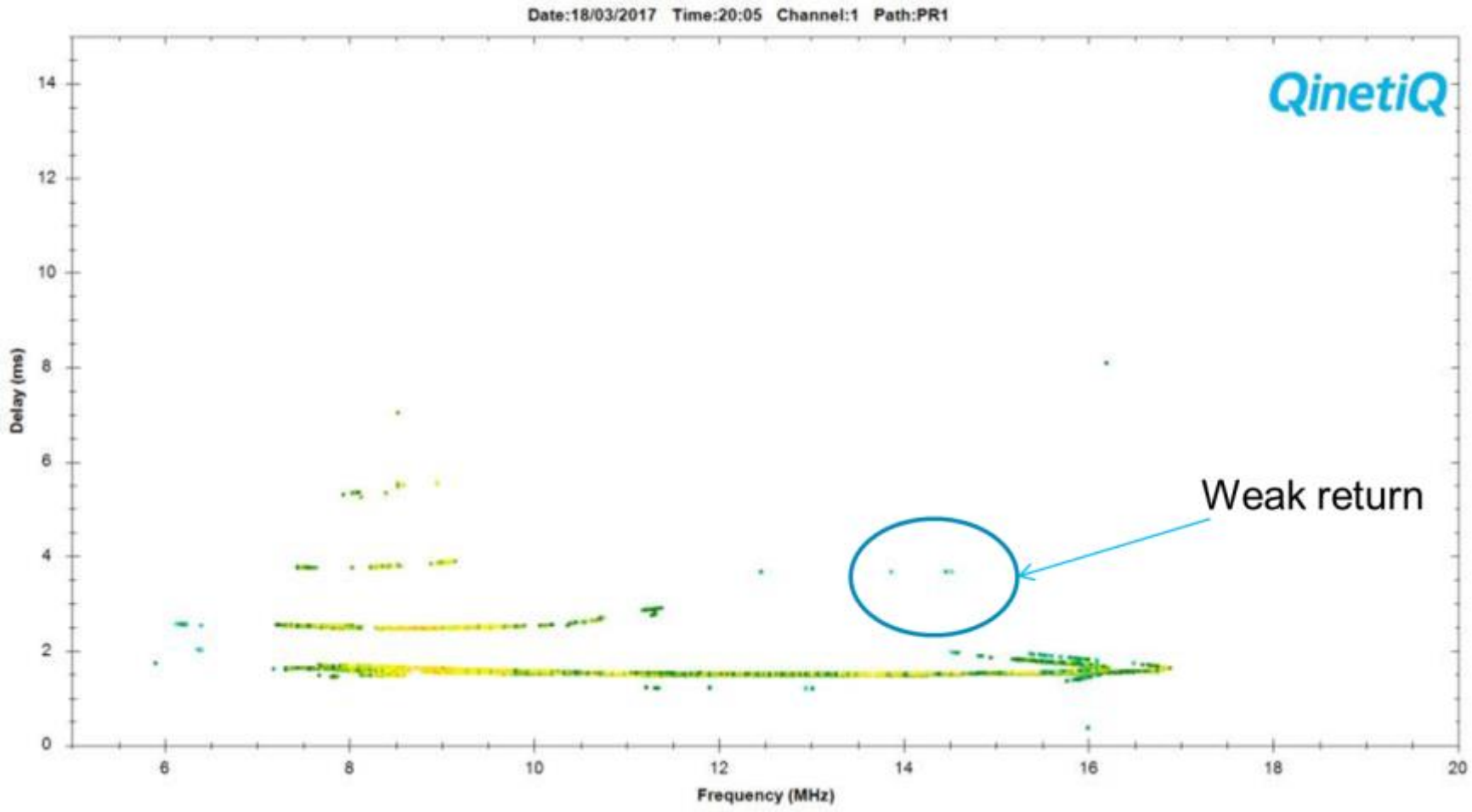
18th March – 19:43 UT Heater on 2/2 pulse



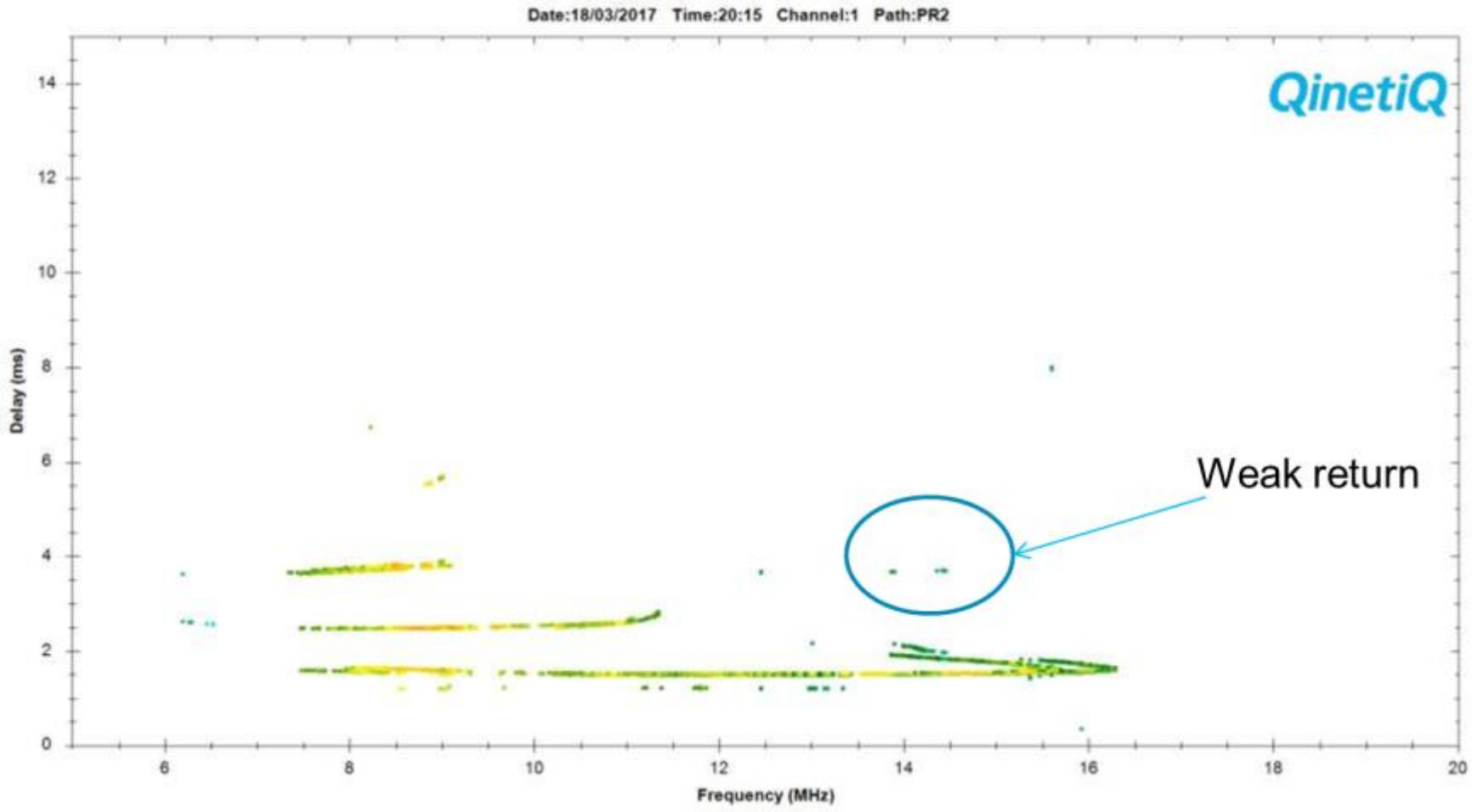
18th March – 19:55 UT Heater off



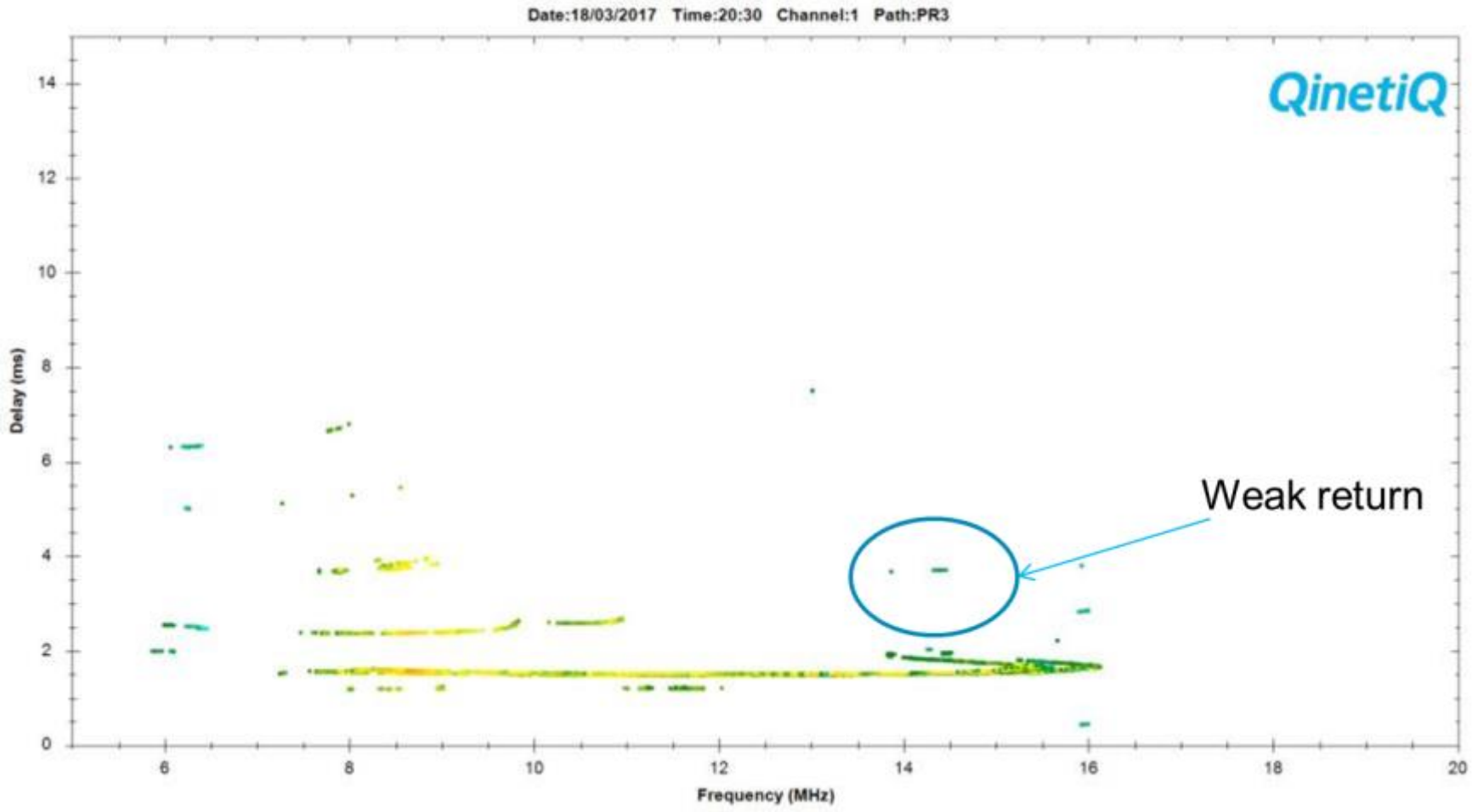
18th March – 20:07 UT Heater off



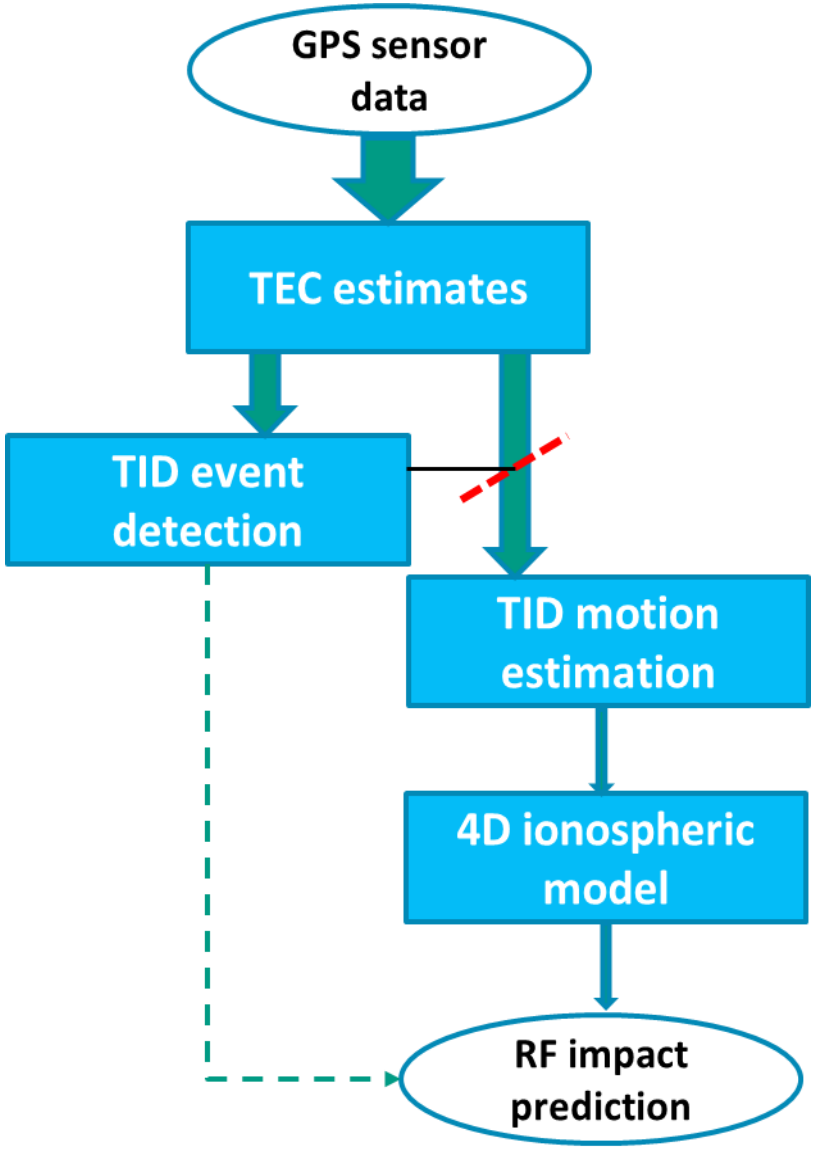
18th March – 20:19 UT Heater on 3/1 pulse



18th March – 20:31 UT Heater on 3/1 pulse



GNSS Network



Ionospheric heating and GNSS systems

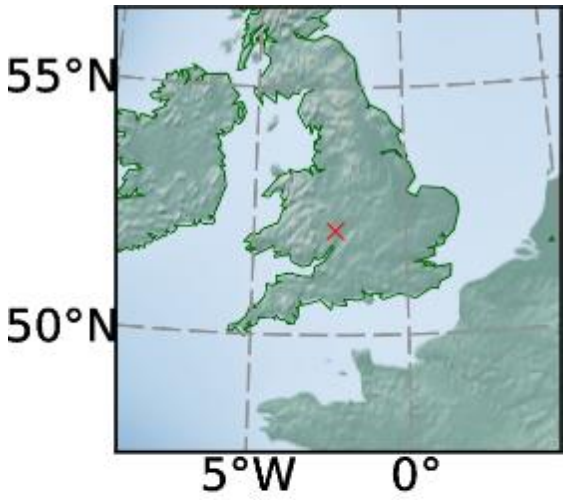
- **Ionospheric heating could create disturbances that might affect satellite systems such as GPS**
  - Bulk changes in electron density, and spatio-temporal variations may delay or refract GNSS signals
  - Variability in heating intensity or environmental factors may create scintillation
  - Physical mechanisms are not currently well understood

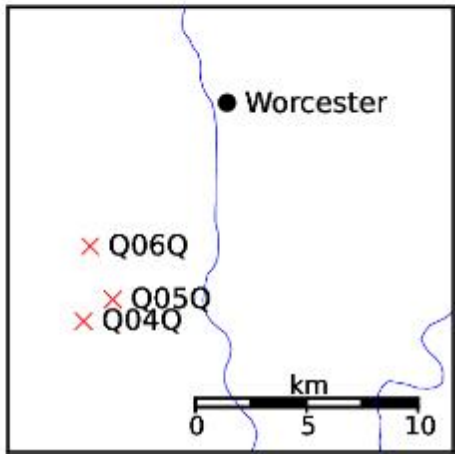
- **A network of 3 multi-constellation GNSS receivers has been deployed to monitor ionospheric effects on RF signals around 1-2 GHz**
  - Provides dual-frequency monitoring of GPS, GLONASS, Galileo and BeiDou at 10Hz sample-rate

- **GNSS time-series data allows monitoring of ionospheric scintillation (S4) and travelling ionospheric disturbances (TIDs)**
  - Short timescale (<60 s) fluctuations in received signal power allow computation of S4
  - Medium timescale (~1 hr) fluctuations in TEC give indication of TID presence
  - Time-delay between TEC waveforms on different receivers gives indication of TID motion

“TEMPLAR” GPS network

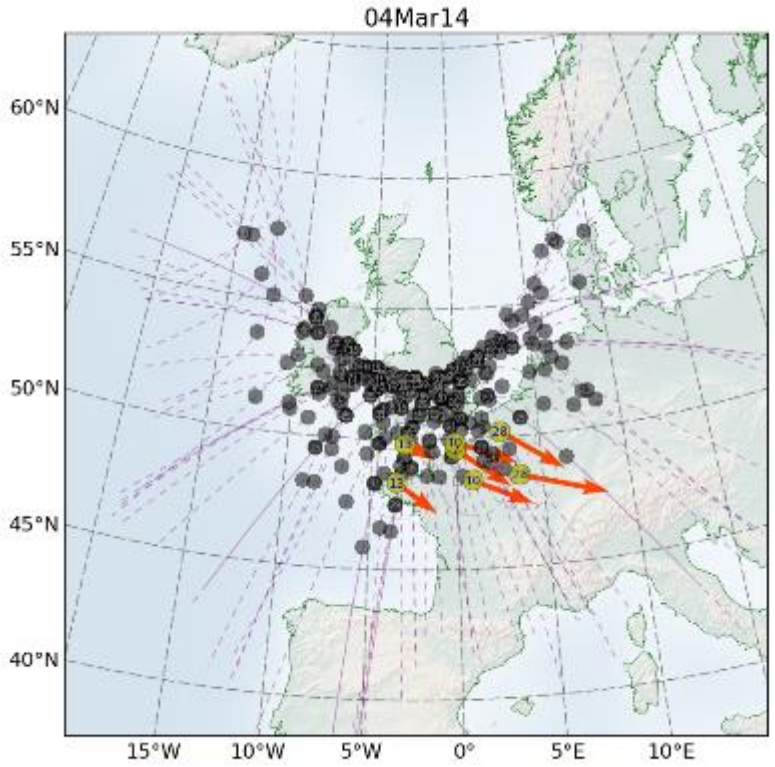
- **Project goals include:**
  - Live ionospheric monitoring from small dedicated GPS arrays
  - Detection and characterisation of TID activity over UK
  - R&D on TID analysis & forecasting techniques
- **Compact network of 3 GPS receivers deployed**
  - Semi-autonomous recording, with 3.4 km baseline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





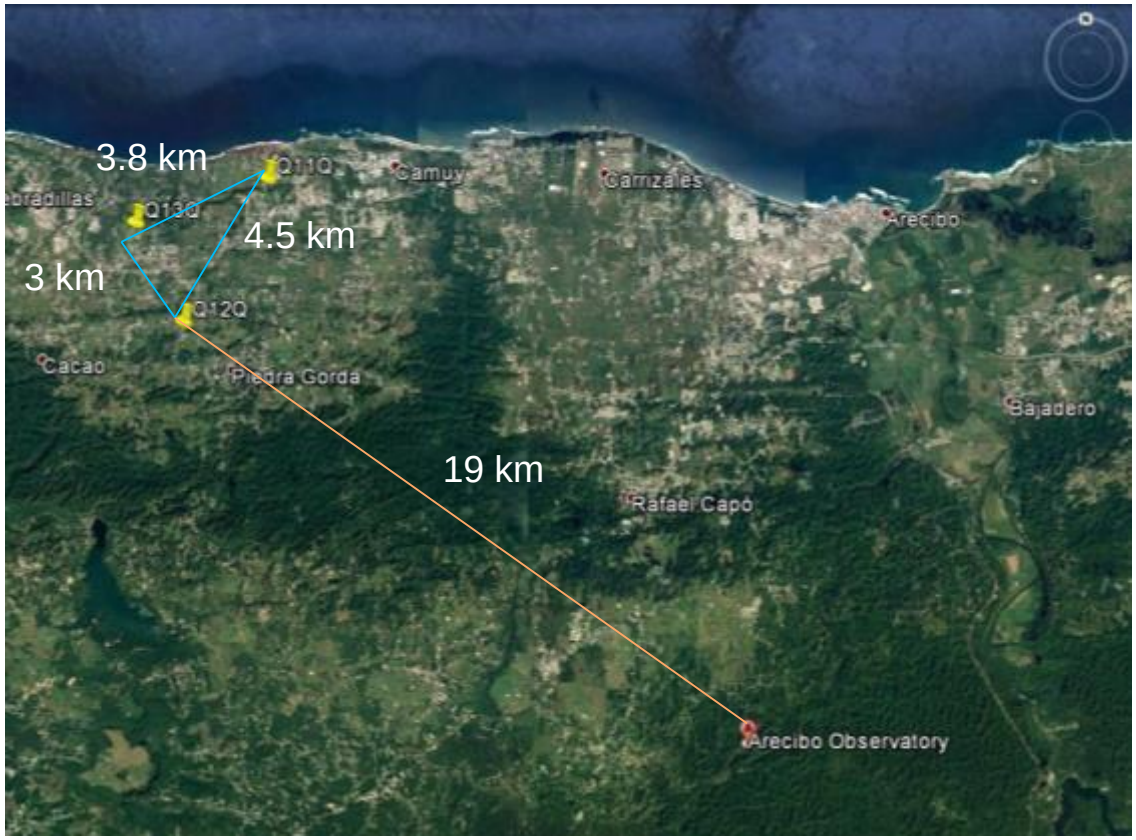
TID velocity estimates

- **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 ~150 m/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 ~500 km
- **[*Penney & Jackson-Booth*, R.Sci., 2015]**



Receivers: 3x Septentrio

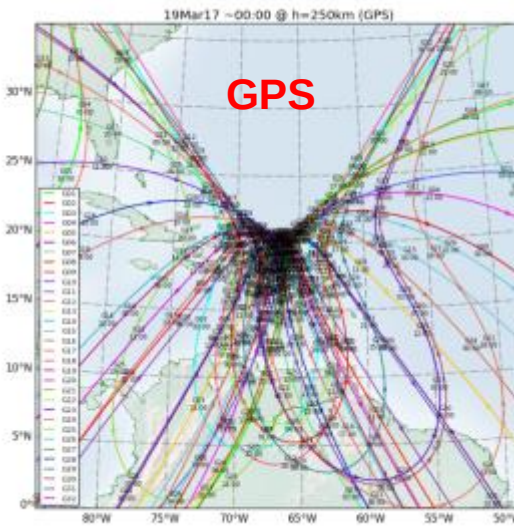
- **TID network to be set up round Arecibo**
- **3 x Septentrio PolaRx4Pro_SCI**

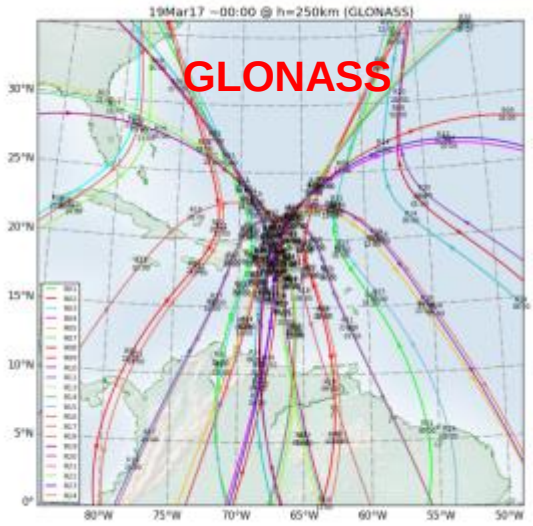


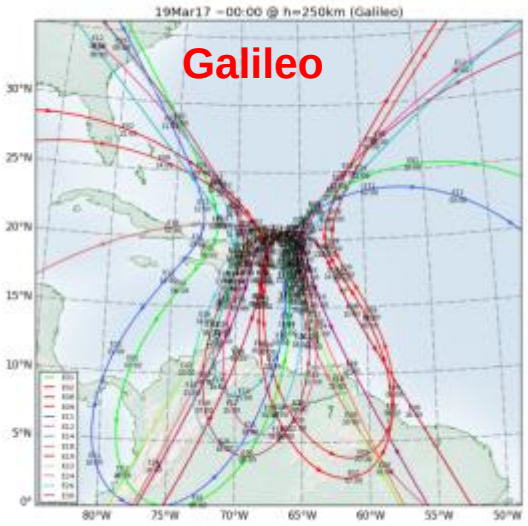
Satellite orbits

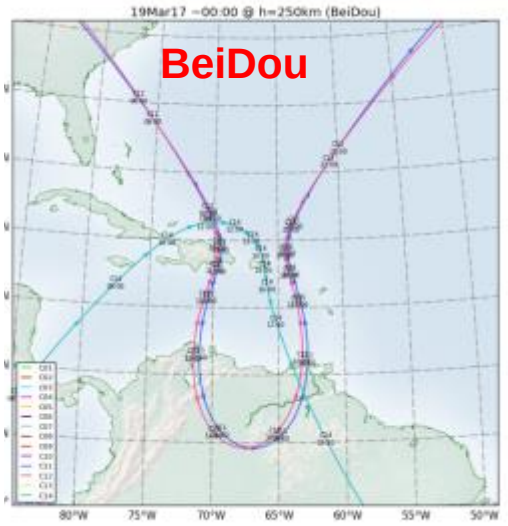
- All GNSS ionospheric measurements are constrained by the geometry of satellite orbits
- Combination of GPS+GLONASS+Galileo+BeiDou gives fairly good coverage around Puerto Rico
- All constellations have gaps in coverage due North of Arecibo

Plots show trajectories of ionospheric pierce-point at 250 km altitude around 18/19 March



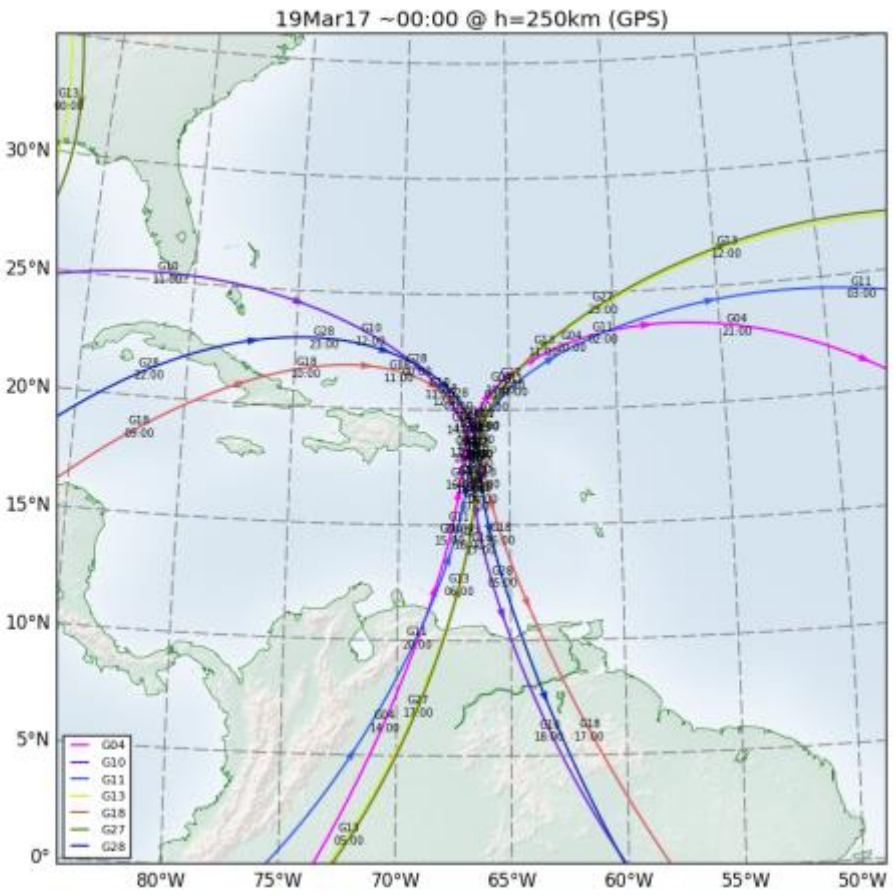






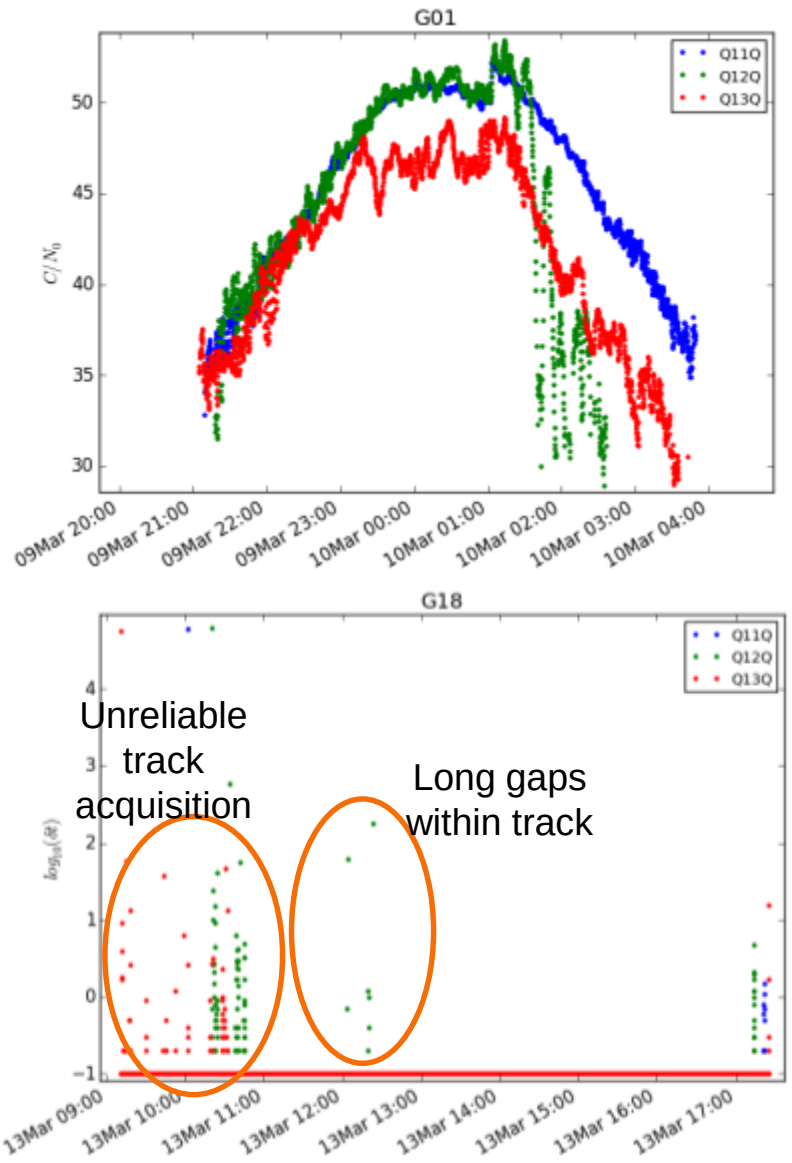
GPS orbits above Arecibo

- **HEX ionospheric effects may be quite localized over the Arecibo transmitter**
- **Most GNSS orbits do not pass immediately overhead**
- **Some satellites do fortuitously pass intermittently within 10° of boresight**
  - Around 20 minutes per day for small subset of satellites
  - e.g. G04, G10, G11, G13, G18, G27, G28
- **Tools have been developed to identify these "magic" time-windows**
  - May show clearest evidence of scintillation linked to heating



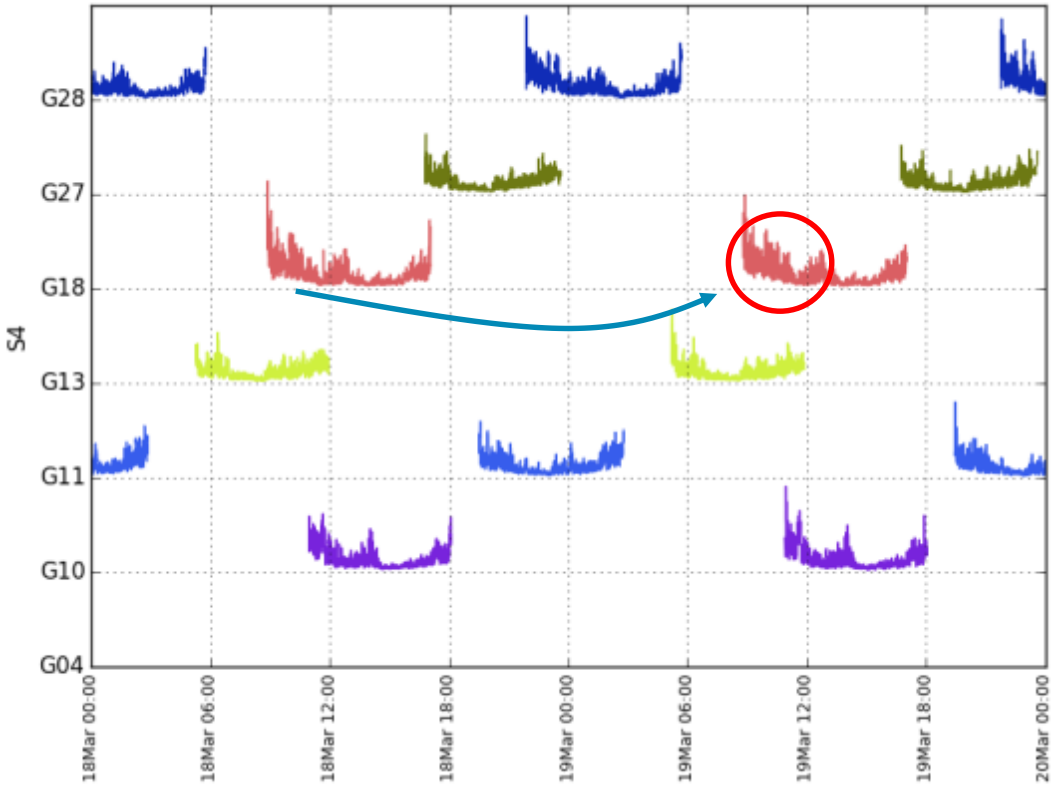
Environmental factors

- **All three GNSS receivers show much poorer data quality than observed in the UK**
  - Drop-outs are much more common
  - Maintaining satellite lock over >30 minutes is challenging
- **Significant differences in noise-levels are observed between the three sites**
  - Q12Q significantly worse, despite many equipment changes between sites
- **Inter-sample times frequently differ significantly from nominal 0.1 s, especially on Q12Q**
  - Gaps of 10 s are quite common
  - Effect is not limited to satellites at low-elevations

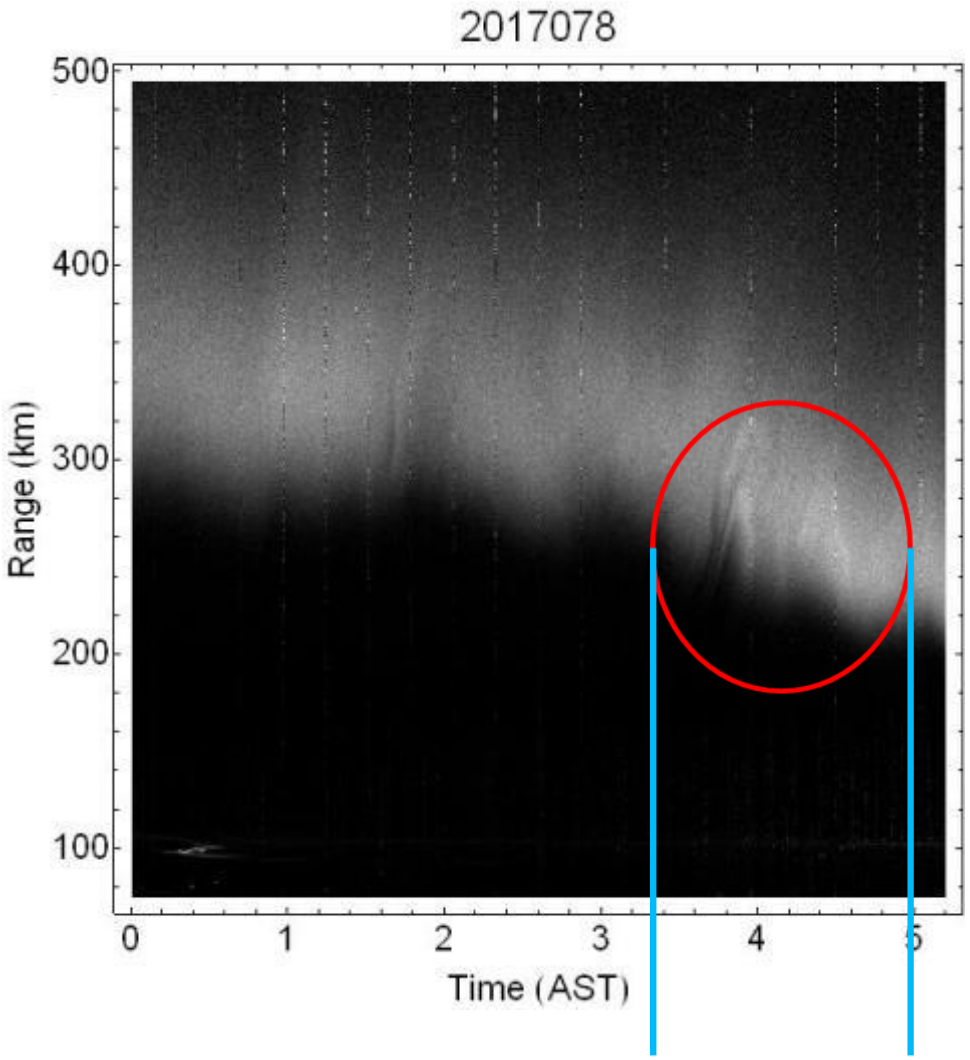


Scintillation for overhead GPS

- **Satellites that pass directly over Arecibo provide best chance of observing heating-induced scintillation**
  - Brief periods may not coincide with actual heating events
- **Possible weak effect seen on G18 around 8am 19th March (UTC)**
  - Not clear whether this is statistically significant



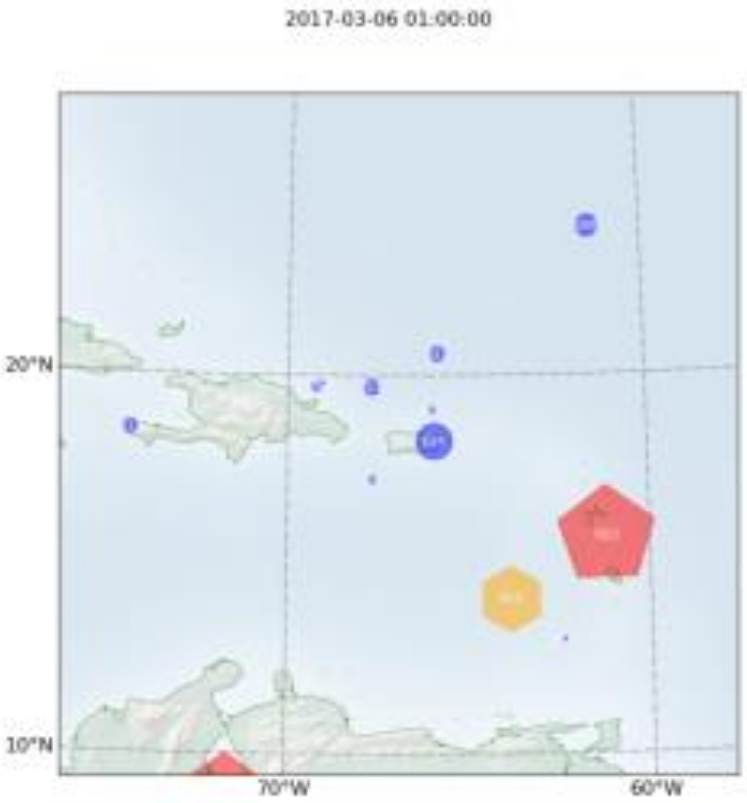
Ion Line Data Over Arecibo, 19 March 2017



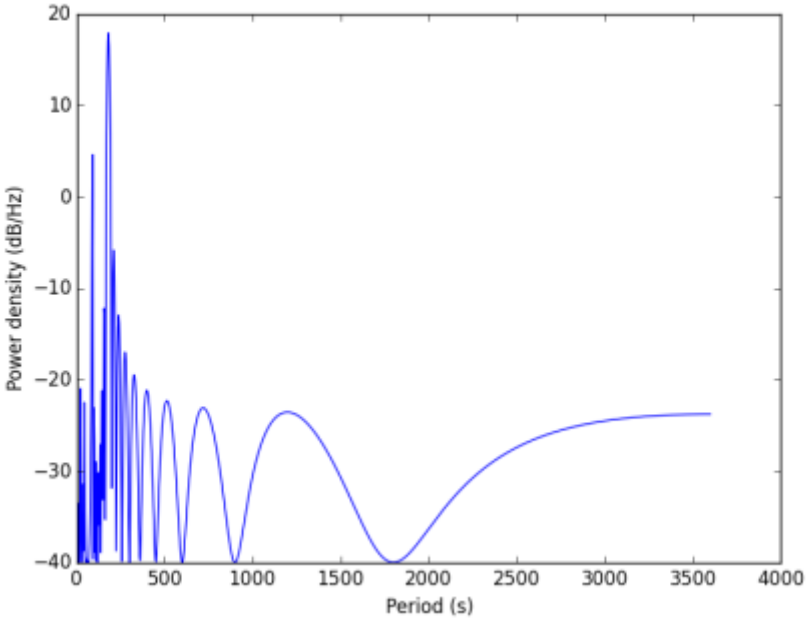
Time coincides with activity seen in G18

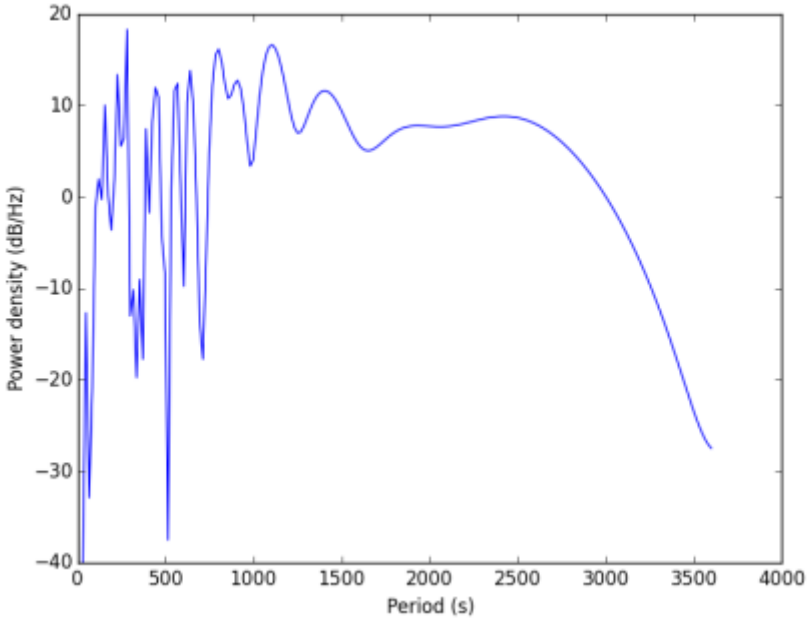
Travelling Ionospheric Disturbances (TIDs) - March

- **TEC time-series have been analysed to find evidence of wave-like ionospheric disturbances**
  - Oscillatory deviations from background trend give indication of presence of TID
  - TID amplitudes typically largest around midday local-time
- **TID activity is significantly larger than observed over the UK**
- **Again, little obvious signs of effects from Arecibo heater from first campaign**



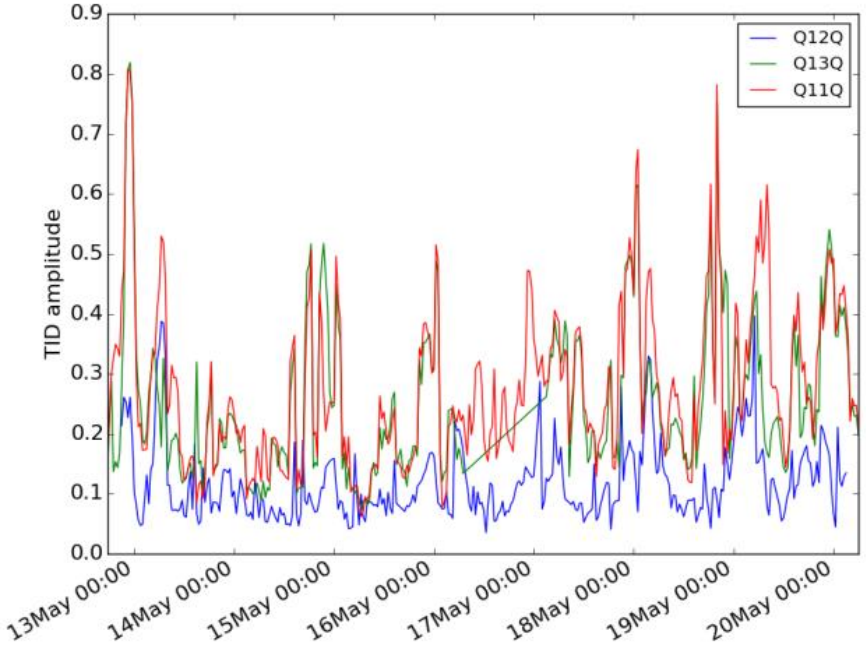
HEX waveform optimization

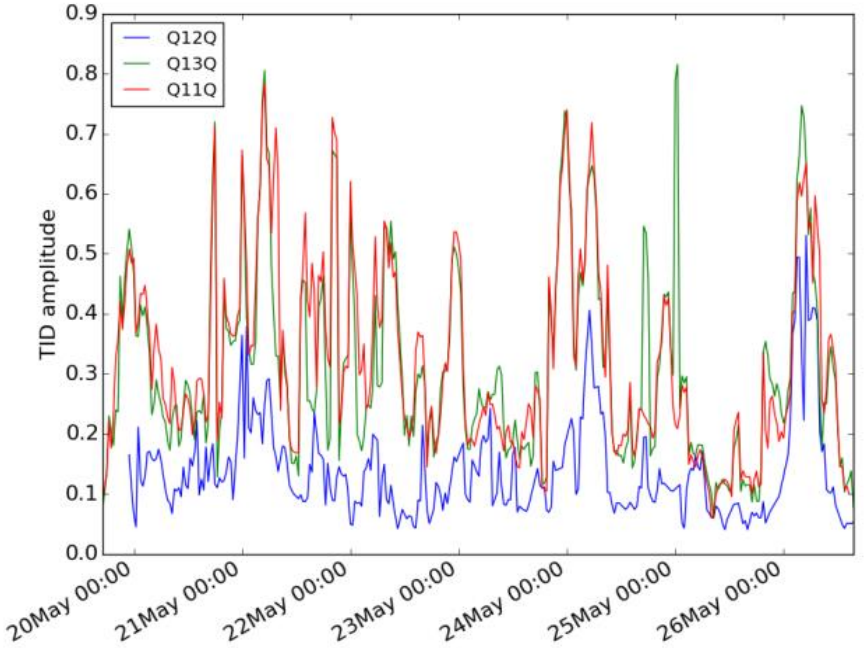




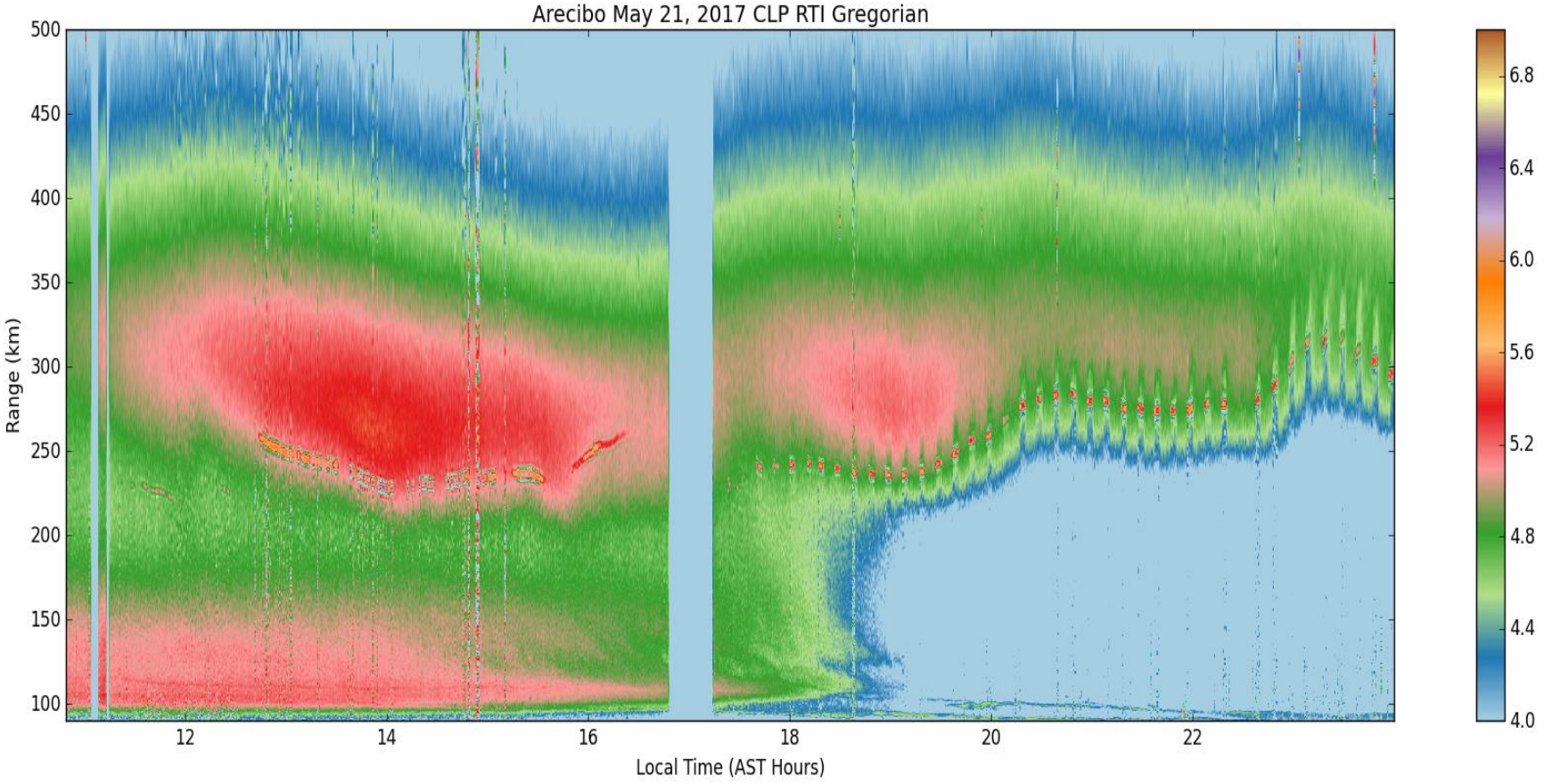
- **Initial analysis shows little sign of enhanced TID activity from first set of HEX trials**
- **Original HEX heating waveform has most energy around 1-minute periods**
- **Optimal pseudo-random waveform has been designed which is more likely to excite TIDs**
  - Orders of magnitude more energy around periods of 10s of minutes

TID activity week before and week of May campaign





21st May 2017



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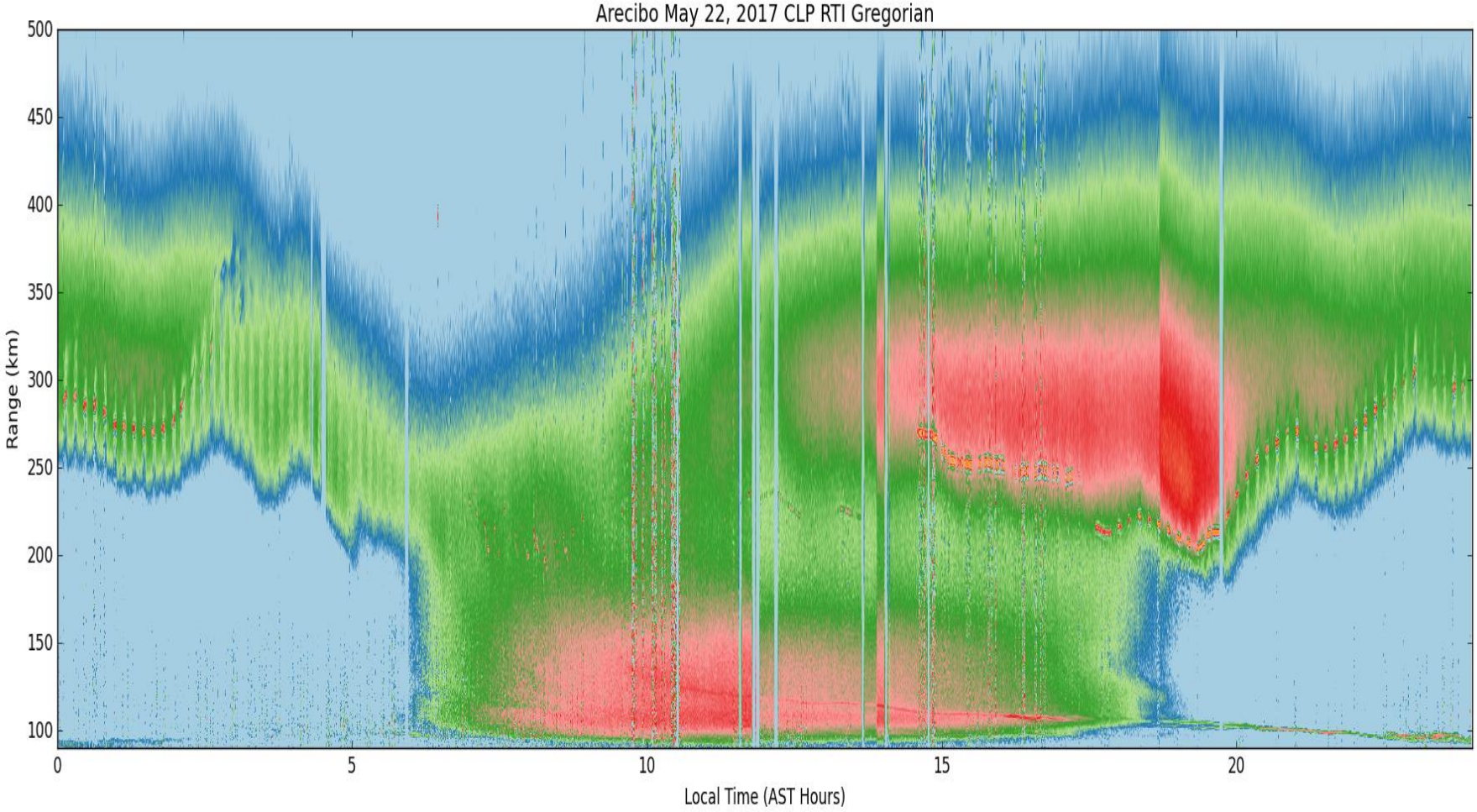

Conclusions

- **Initial results shows correlation with heating and new HF links**
- **Large volumes of multi-constellation GNSS data has been analysed for signs of ionospheric disturbances relevant to GPS or similar satellite systems**
  - ~300 GB of data in ~2500 files covering ~66 satellites
- **Scintillation and TEC oscillations have been analysed for "gross" indicators of the effects of ionospheric heating**
- **New waveform may be generating disturbances observable with GNSS**

Questions?