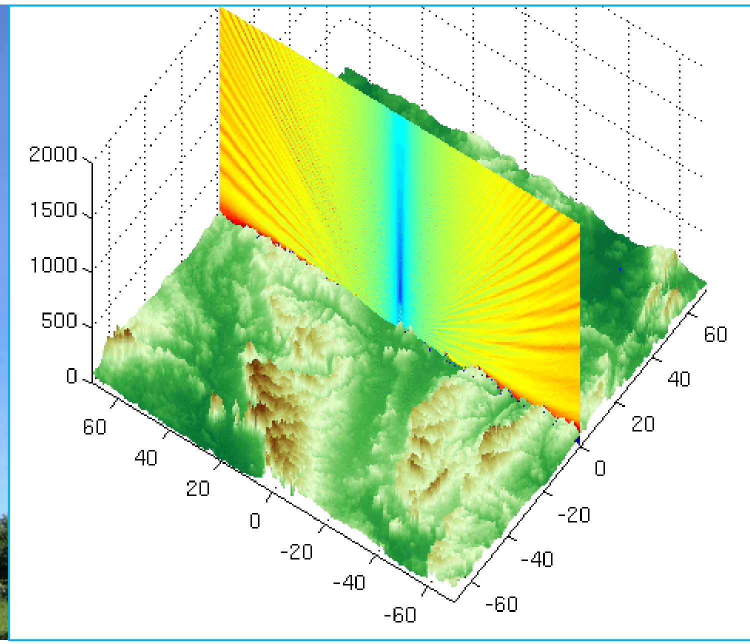
The use of Signals of Opportunity for the Measurement of Atmospheric Refractivity



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Outline

- ► Atmospheric refractivity measurements
- ► Signals of opportunity for remote sensing
  - ► Basic concepts
  - ► Example: DAB digital radio
- ► Modelling the availability of signals
  - ► Overview of Parabolic Equation approach
  - ► Example: propagation loss results Mendip-Bath
- ► Evidence of observed refractivity changes
- ► Summary

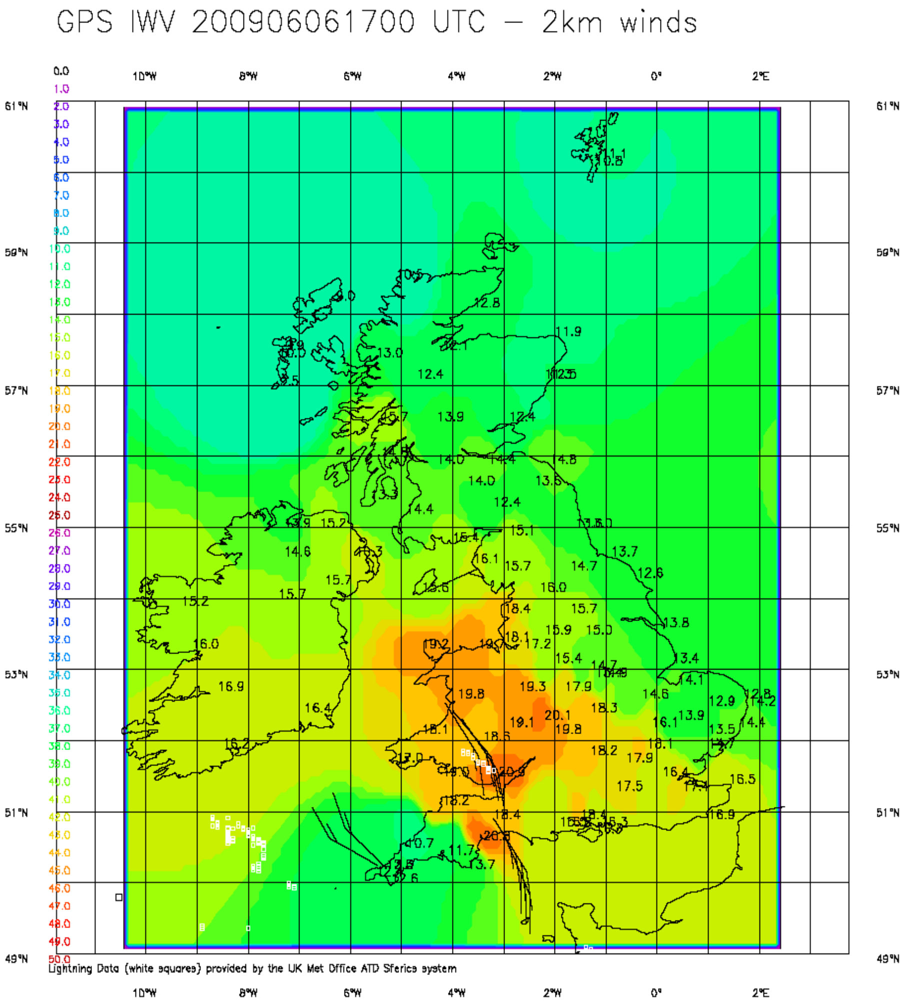
Atmospheric refractivity

Why are we interested in refractivity?

Why is refractivity so important?

- ►Numerical Weather Prediction models have improved enormously in recent years
  - ►Key to many advances has been significant increases in computational capacity
  - ►Reaching the point where the “skill” of the model is being limited by the available observation data
- ►The current Met Office “UK” model runs with ≈4 km grid (soon to be reduced down to ≈1.5 km)
- ►With current models predictability horizon for is estimated to be 1-2hrs for thunderstorm size features
  - ►To improve this wide-area, high-resolution observations of key parameters such as water vapour (refractivity) are required

Water vapour from GPS



- Water vapour derived from UK dual-frequency GPS network (*courtesy Jon Jones, UK Met Office*)
- Vertically integrated water vapour
- Routinely assimilated into UK NWP model
- Good, but resolution not good enough

Refractivity measurements

- Why is water vapour (refractivity) so important?
  - Small differences in boundary layer temperature ≈1K and moisture ≈ 1 g kg^{-1} can make the difference between severe and no convection – *Crook (1996)*
  - Forecasting of convective initiation requires information about moisture on scales of 2-5 km – *Deeter & Evans (1997)*
- Current sensor technologies e.g., satellite imagery, radiosondes, radiometers, surface measurements etc all have significant limitations.

- Is there a low-cost (passive) solution?

Signals of Opportunity

Indirect measurement of refractivity

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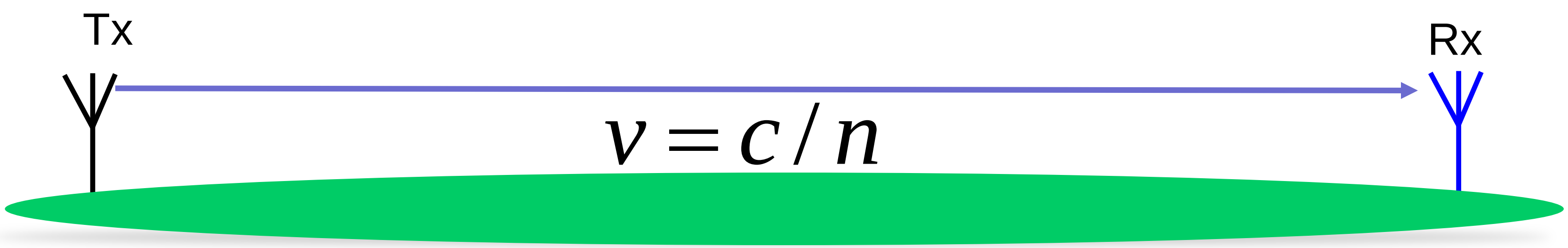
Sensing using signals of opportunity

- Use of signals for applications other than their original intended purpose e.g., digital radio (DAB) and television signals (DVB-T)
- Changes in refractivity, lead to changes in the propagation velocity



$$v = c / n$$

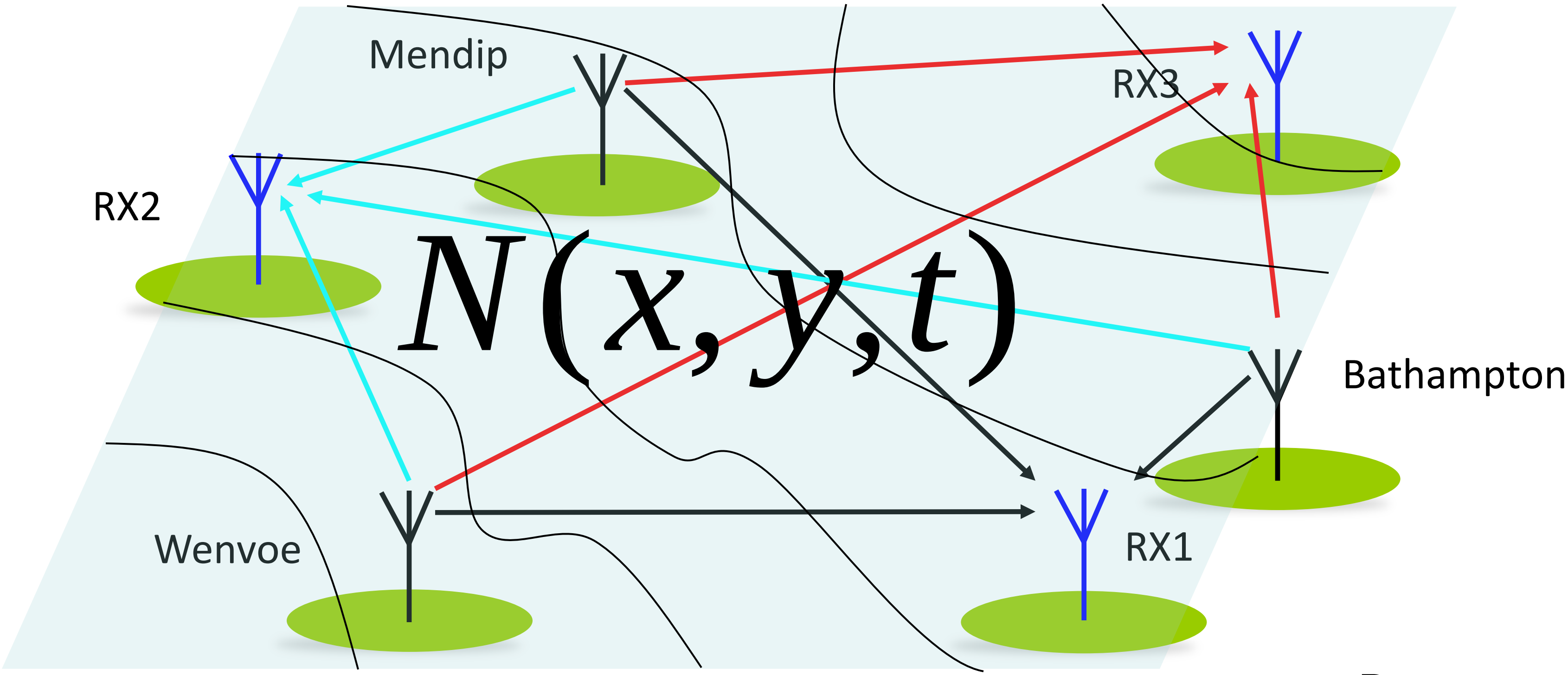
- Refractivity in N units can be written:

$$N = (n-1)\times 10^{6} = 77.6\frac{P}{T} + 3.73\times 10^{5}\frac{p}{T^{2}}$$

- Excess path delay (propagation path – geometric path)

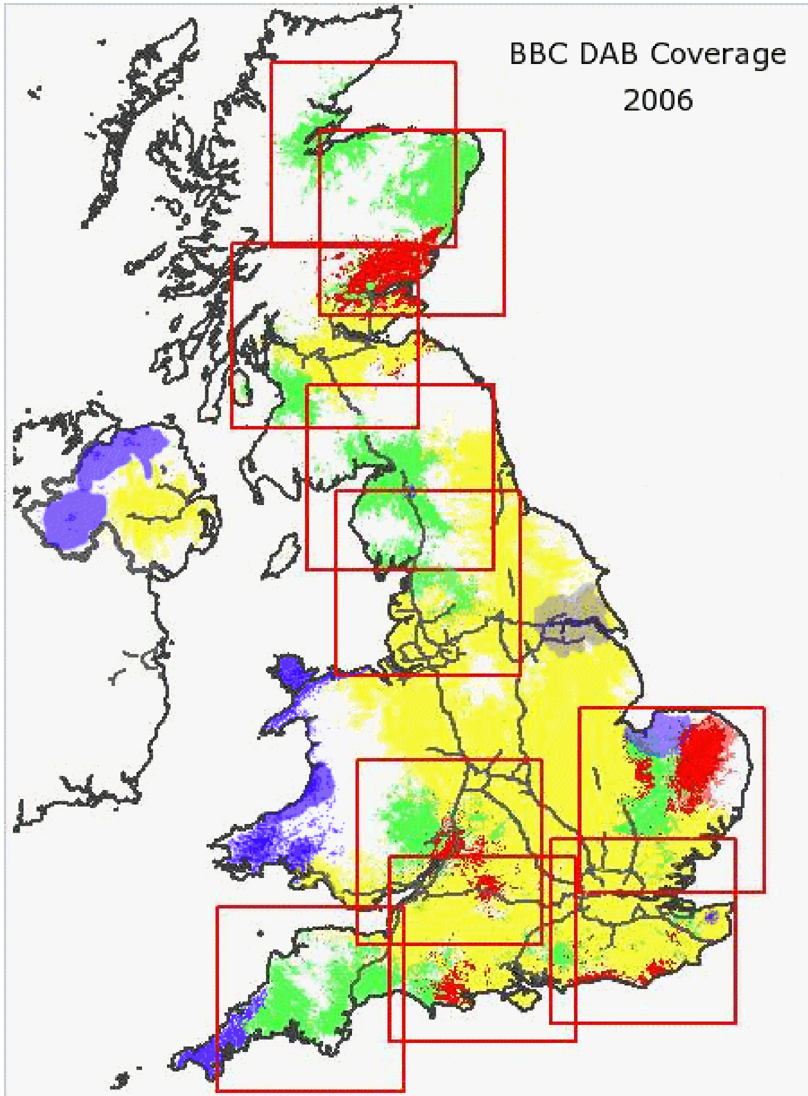
$$\Delta s = \int_{\mathrm{Tx}}^{\mathrm{Rx}} n(s)ds - \int_{\mathrm{Tx}}^{\mathrm{Rx}} ds = 10^{-6}\int_{\mathrm{Tx}}^{\mathrm{Rx}} N(s)ds$$

Network of sensors



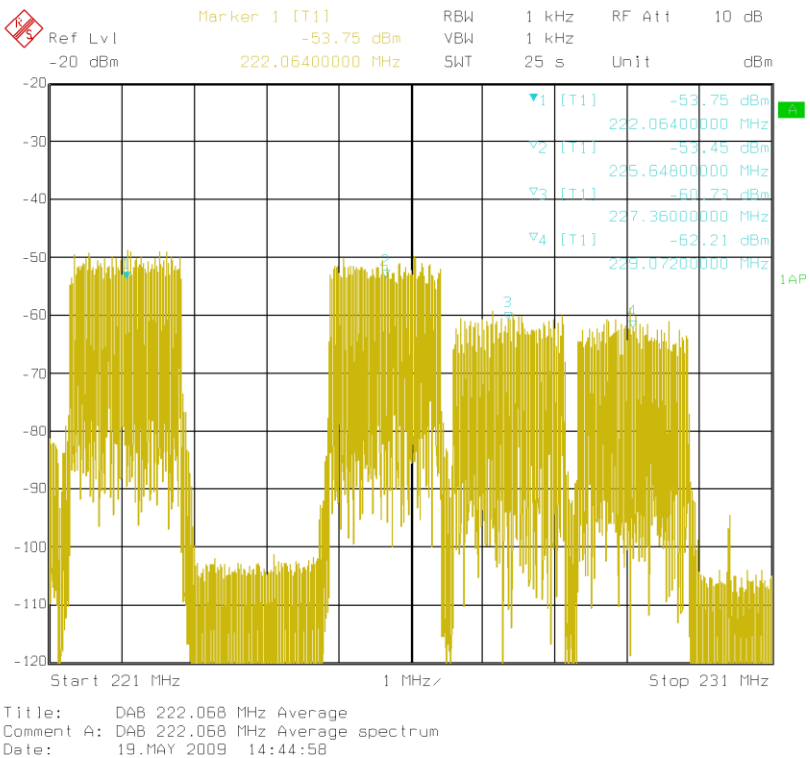
- Assuming direct path each link gives a delay $\Delta s_i(t) = \int_{\mathrm{Tx}}^{\mathrm{Rx}} N(s,t)ds$
- For real-time applications use inverse methods
- Challenging as delays/excess path is small – a few ns!
- For NWP application likely assimilate raw delay

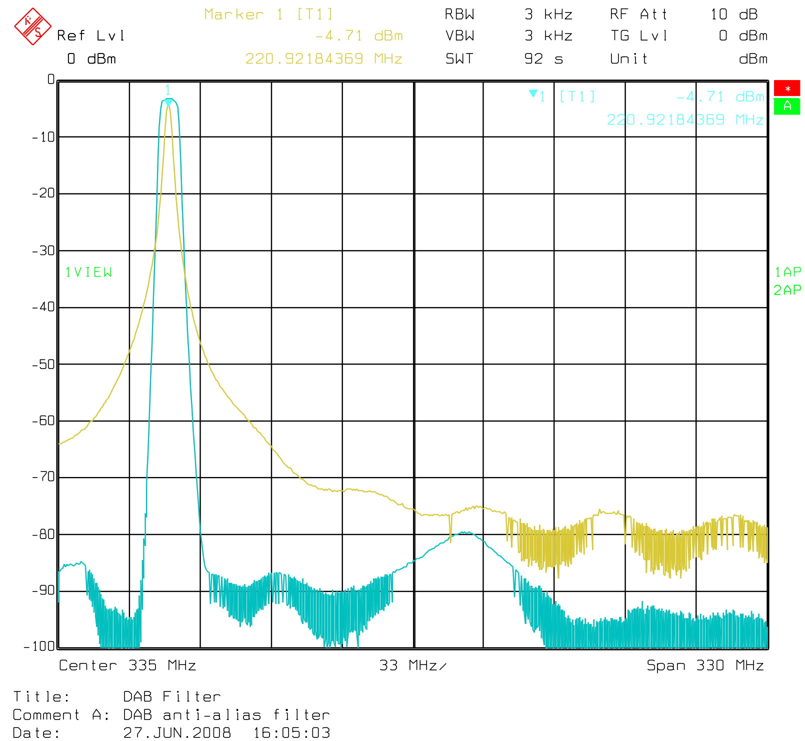
Digital radio (DAB) coverage in the UK

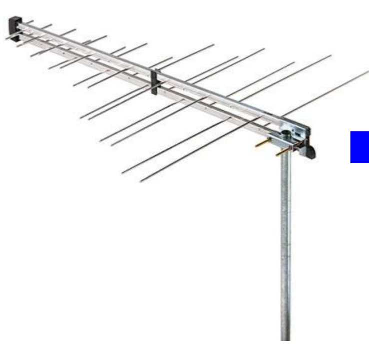


- 1.5MHz C-OFDM
- Single-Frequency Network
- National transmitters
  - 225.640 MHz BBC
  - 222.068 MHz DigitalOne
- Closest to Bath
  - Mendip 5 kW (30km)
  - Wenvoe 9 kW (70km)
  - Bathampton 2kW (300m)
  - Oxford 10 kW (90km)
  - Salisbury 2kW (50km)

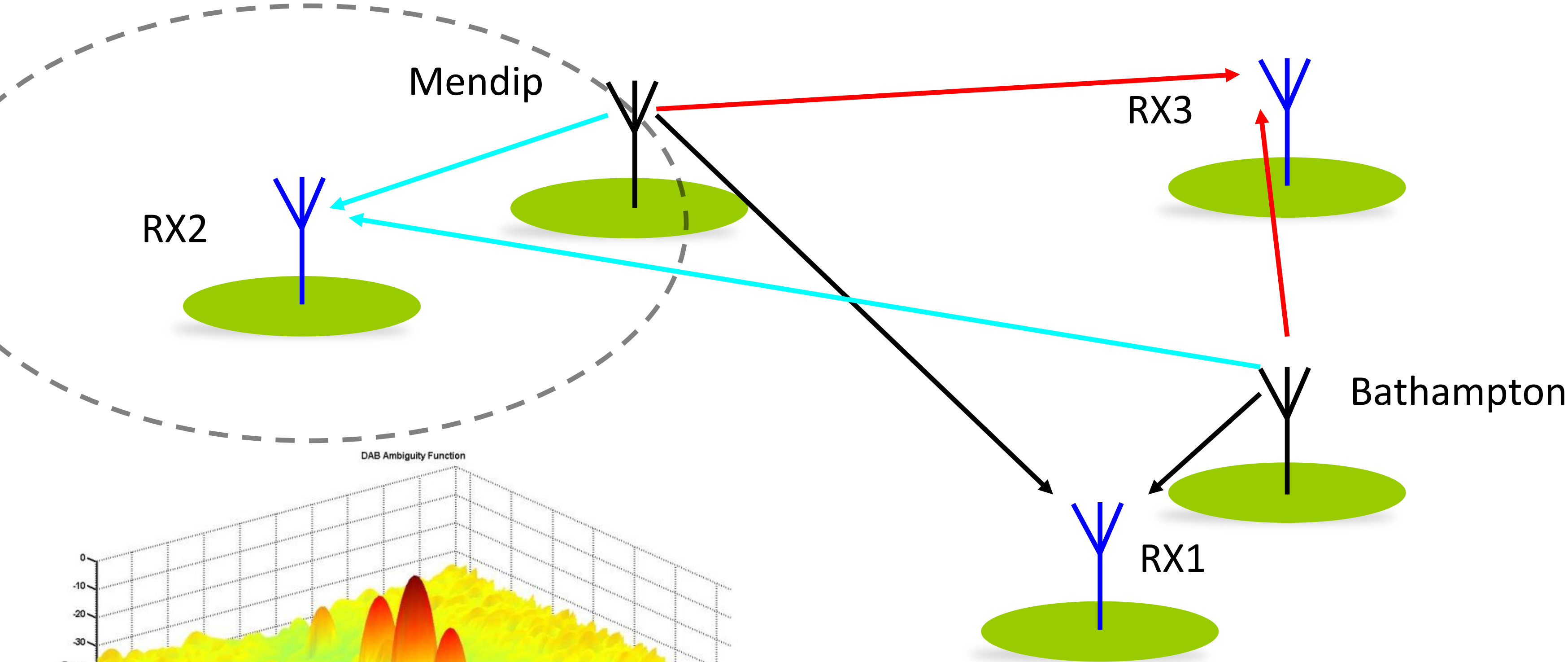
DAB signal sampling and processing

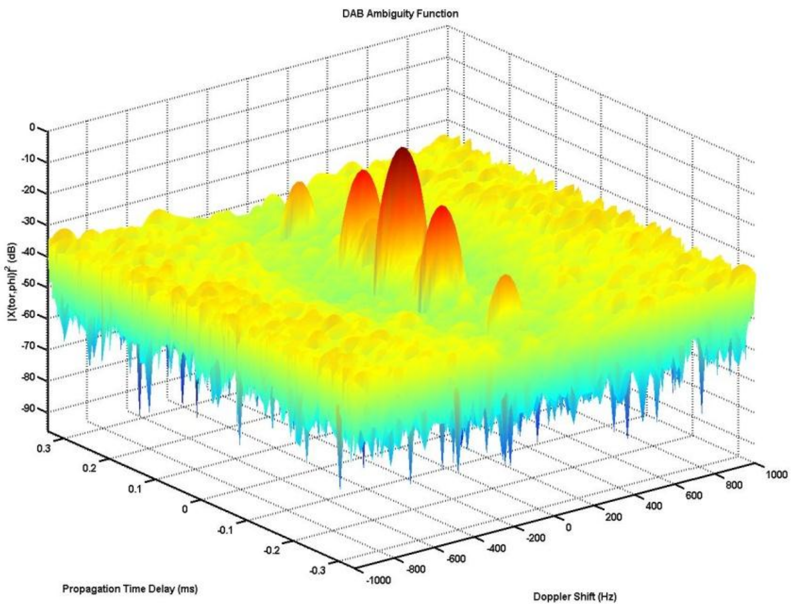






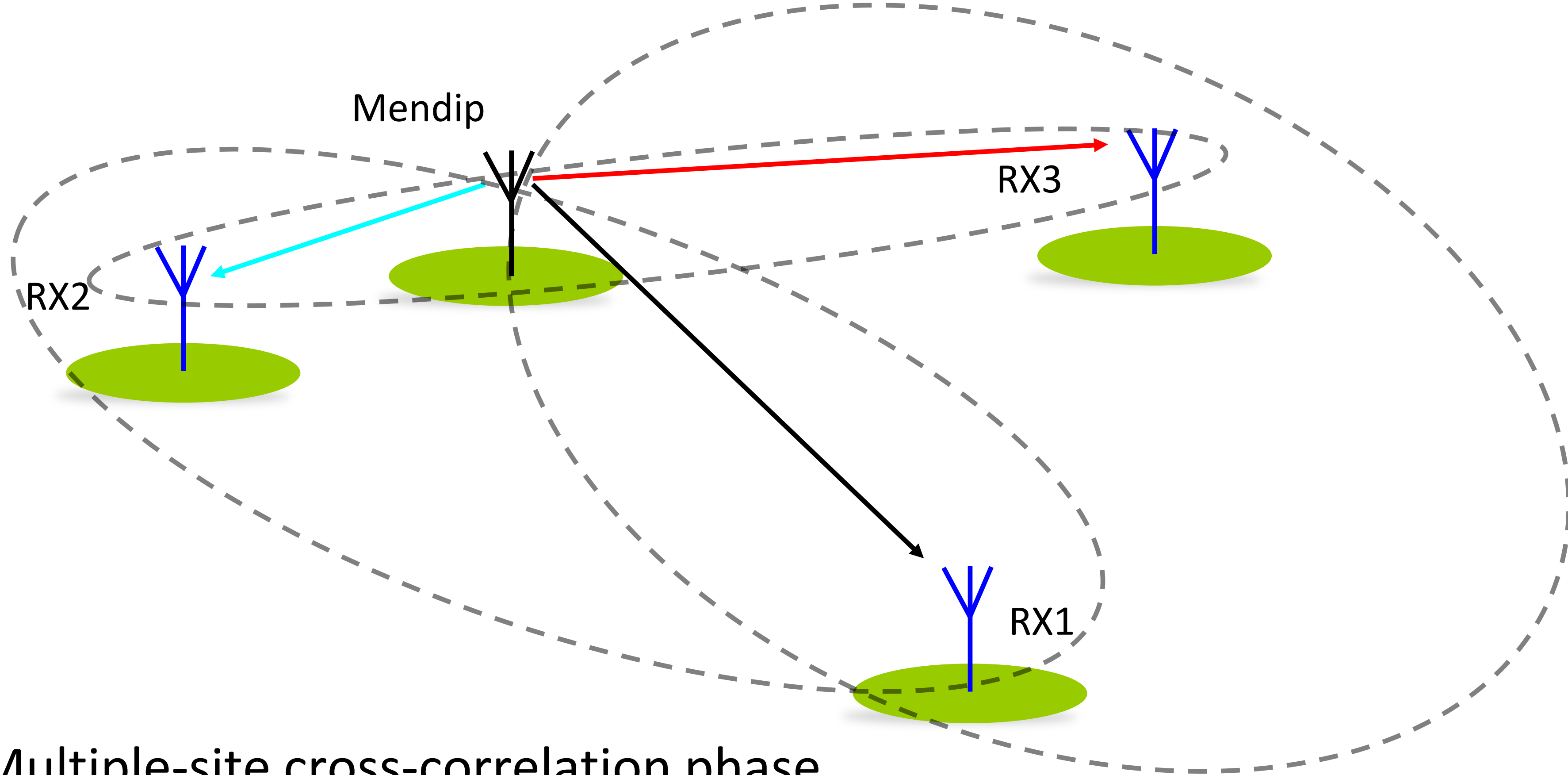
Phase estimation: single-site auto-correlation





- Single-site autocorrelation phase
  - Change in phase with time (single difference)
  - Assumes stability of the transmitter phase

Phase estimation: multi-site cross-correlation



- ▶ Multiple-site cross-correlation phase
  - ▶ Change in phase with time between to sites (double-difference)
  - ▶ Need network “coherency” between receiver sites
  - ▶ Only one transmitter lies on ellipse – isolate Tx in time domain

Coverage area modelling

“Forward” modelling using parabolic equation method

Propagation path modelling

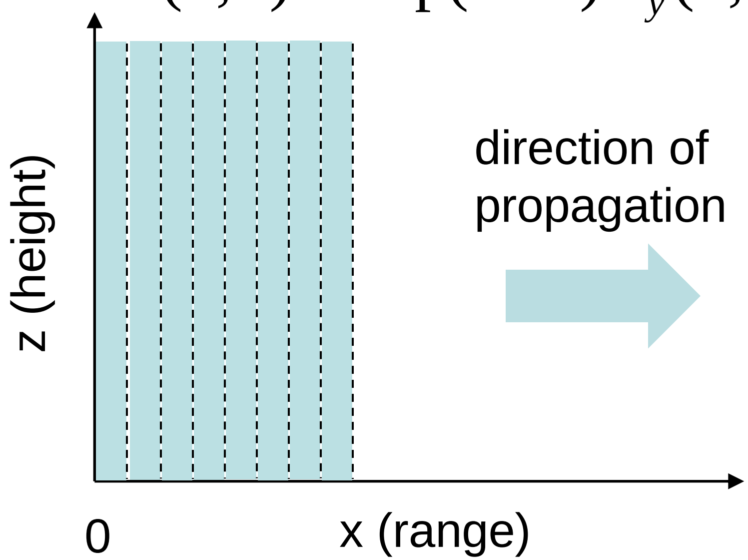
- Where should we site the receivers?

- This is a coupled problem:
  - SFN – multiple transmitters on same frequency – as we have seen we can isolate transmitters in time domain if:
    - Single site – only one transmitter on range circle
    - Multiple site – only one transmitter on range ellipse
  - Inversion of data depends on having “well conditioned” problem
    - Need many intersecting links
  - Manage dynamic range – different transmitter powers, radiation patterns, propagation conditions – need propagation model

Parabolic equation modelling

- Well described e.g., Levy (2000)
- Paraxial propagation, low elevation angles

$$u(x,z) = \exp(-ikx)E_y(x,z)$$



- Split-step method decouples:
  - Refractive effects
  - Diffractive effects
- Initial field $u(0,z)$ determined by transform of far-field antenna pattern
- Phase screens modulated by refractive index
- Operator **S** is the Fourier sine transform

$$u(x+\Delta x, z) = \exp\left(ik(n^2-1)\Delta x/2\right)\mathbf{S}^{-1}\left\{\exp(-i\pi^2 p^2 \Delta x/2k)\,\mathbf{S}\{u(x,z)\}\right\}$$

Next field — Refractive — Diffractive — Starting field

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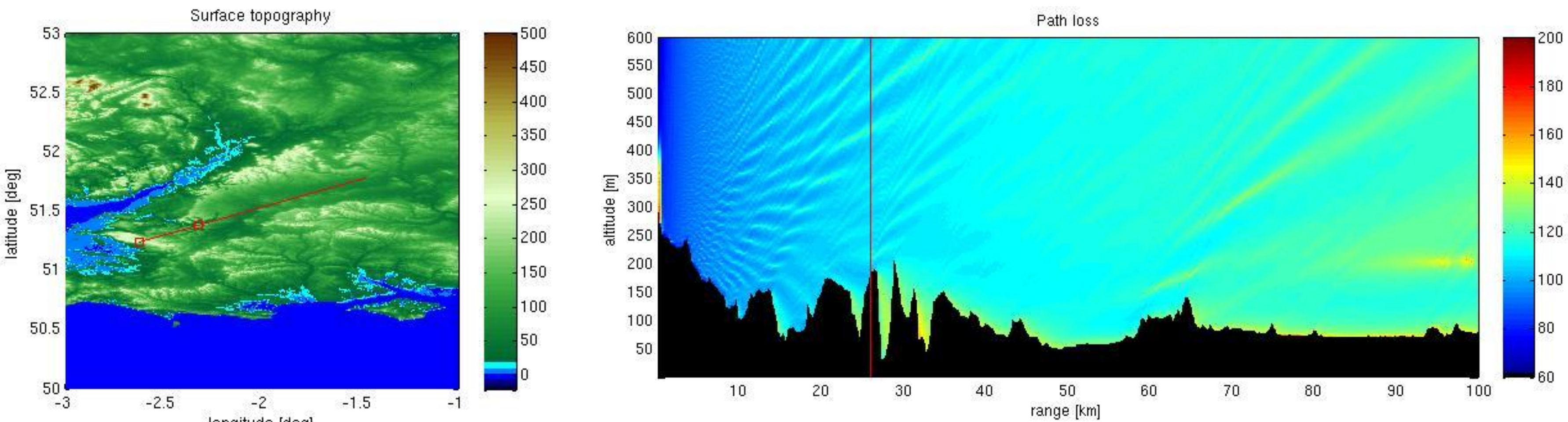
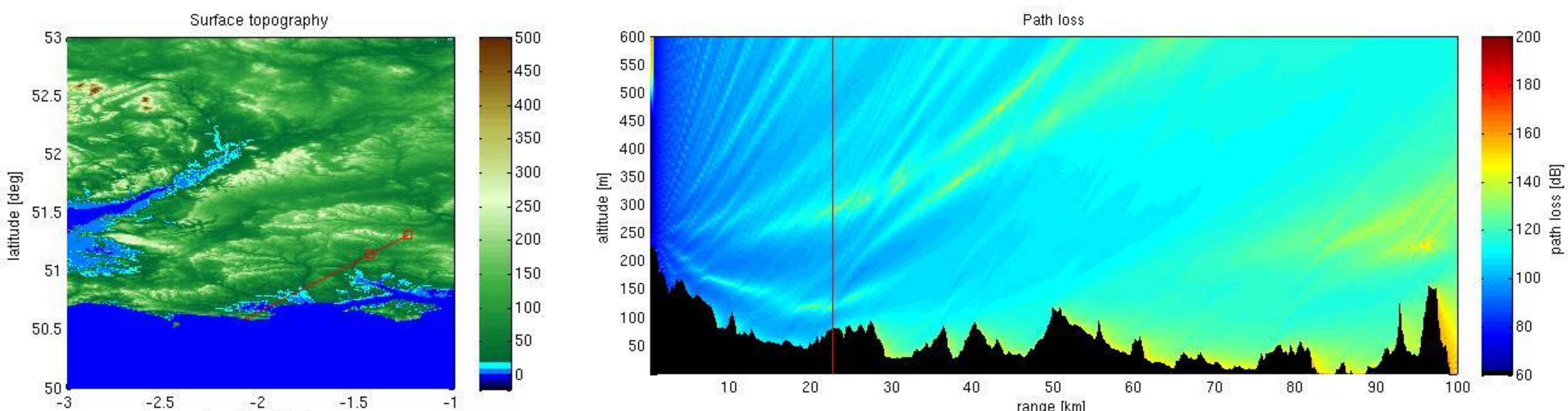
Propagation loss: Mendip & Hannington



Path: Mendip to University of Bath



Path: Hannington to STFC, Chilbolton observatory

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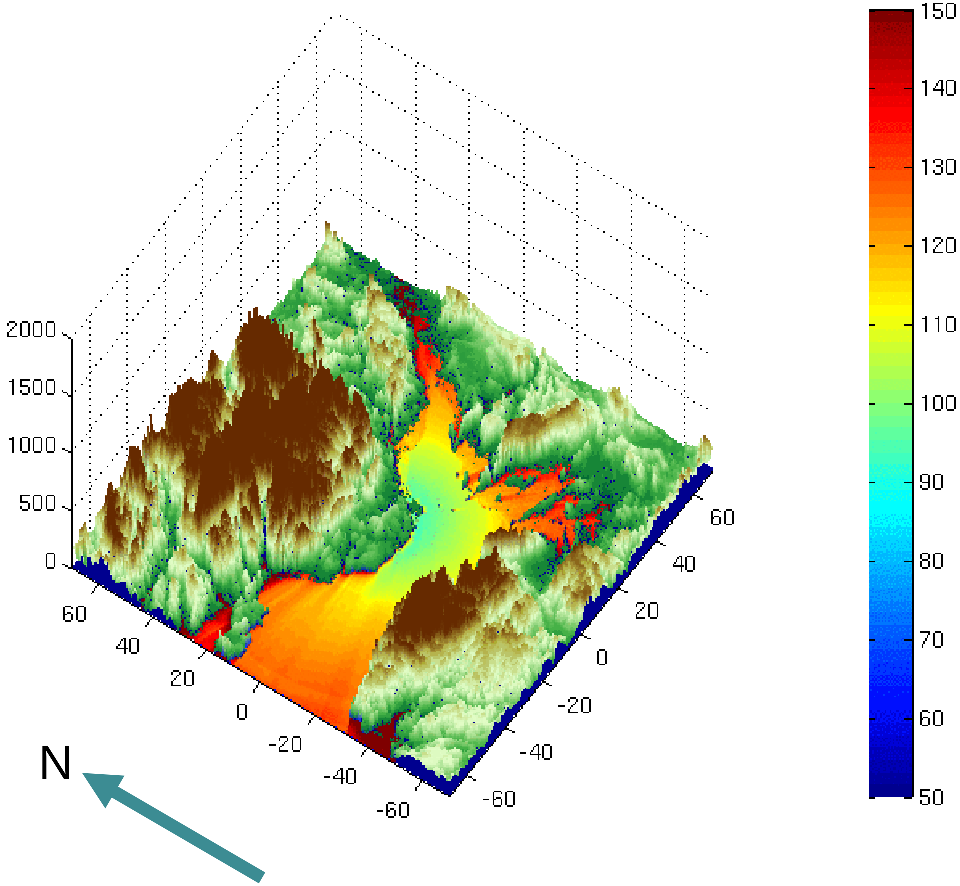
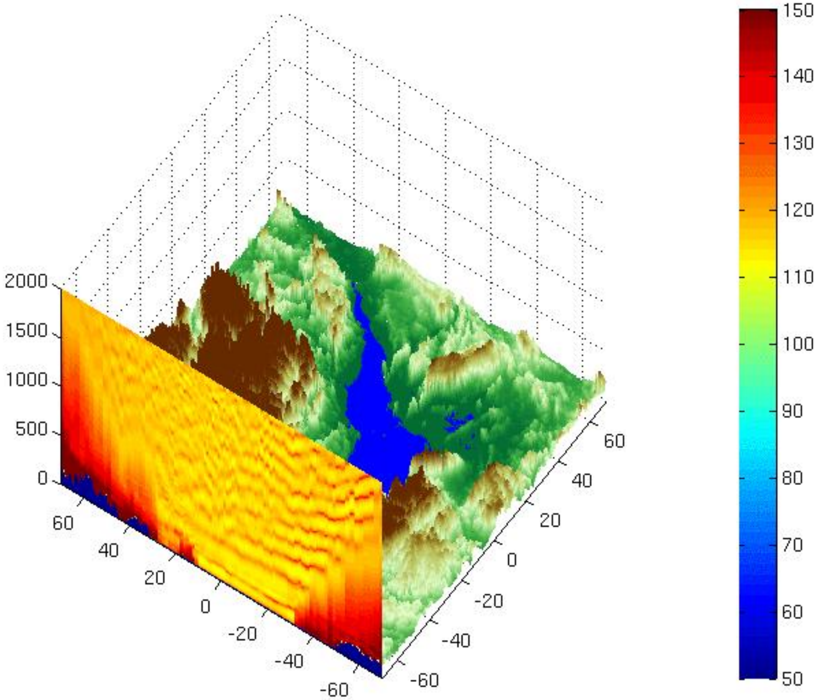
Parabolic equation modelling I: Wenvoe

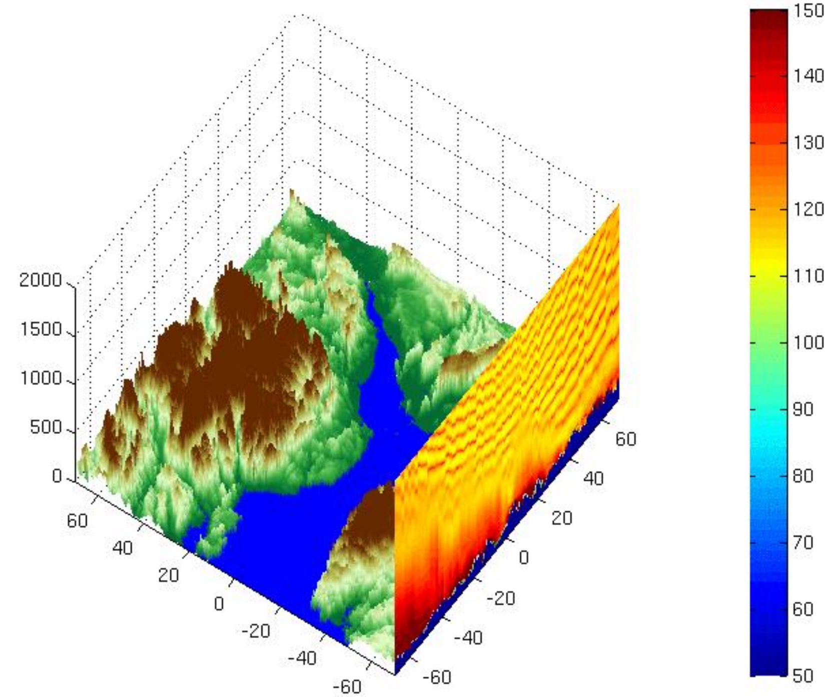


- Pseudo 3D propagation maps – generated from number of slices
- Vertical slices through propagation loss (dB)
- Wenvoe DAB transmitter in Wales located at origin

- Terrain data from SRTM (Shuttle SAR imagery)
- Refractivity data from WRF model output

Parabolic equation modelling II: Wenvoe





- ► N-S (left) and E-W (right) slices coloured by propagation loss (dB)
- ► Wenvoe DAB transmitter centred at origin
- ► Diffraction loss caused by Brecon Beacons and Exmoor easily visible

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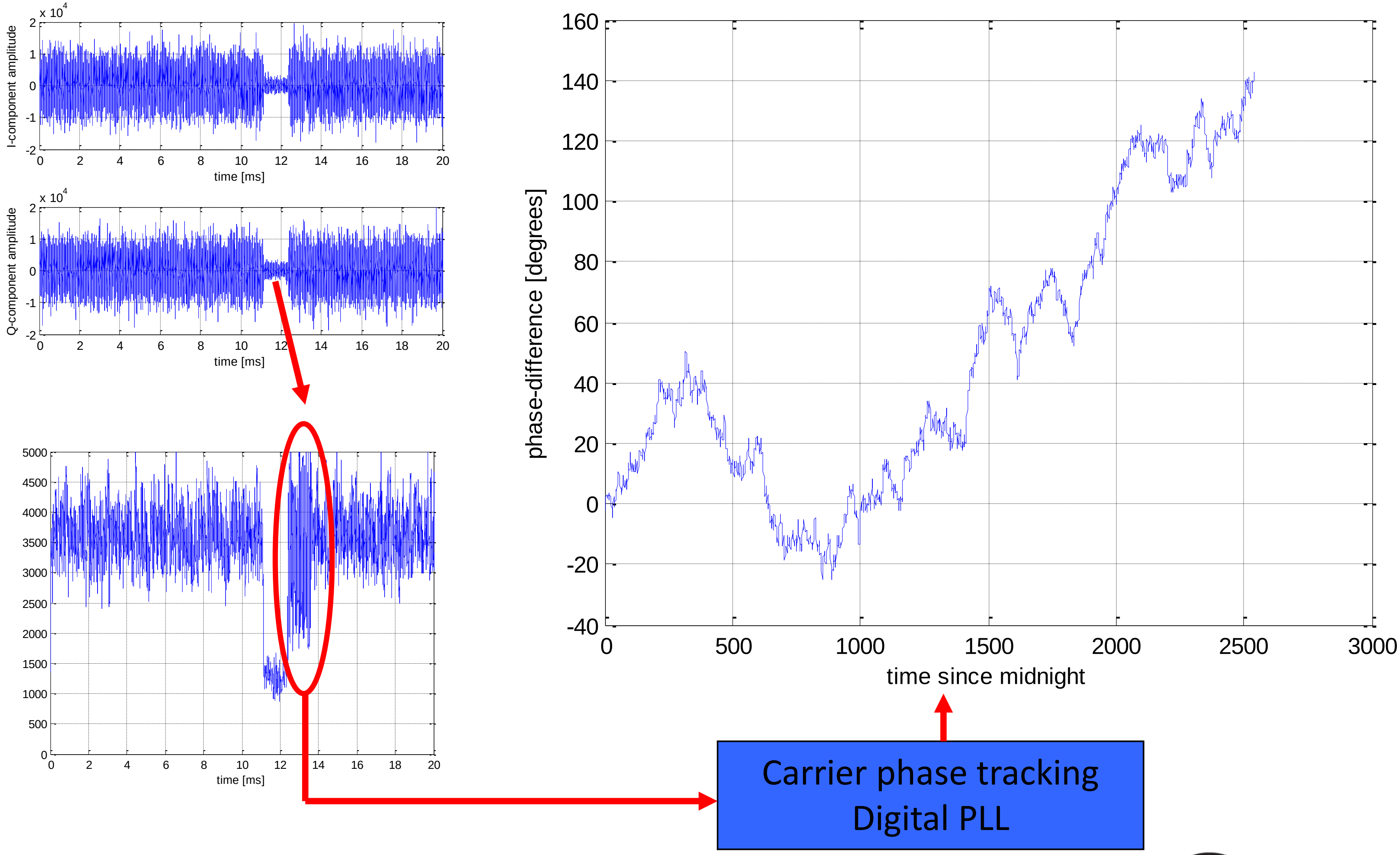
DAB signal analysis

Evidence of water vapour changes affecting propagation

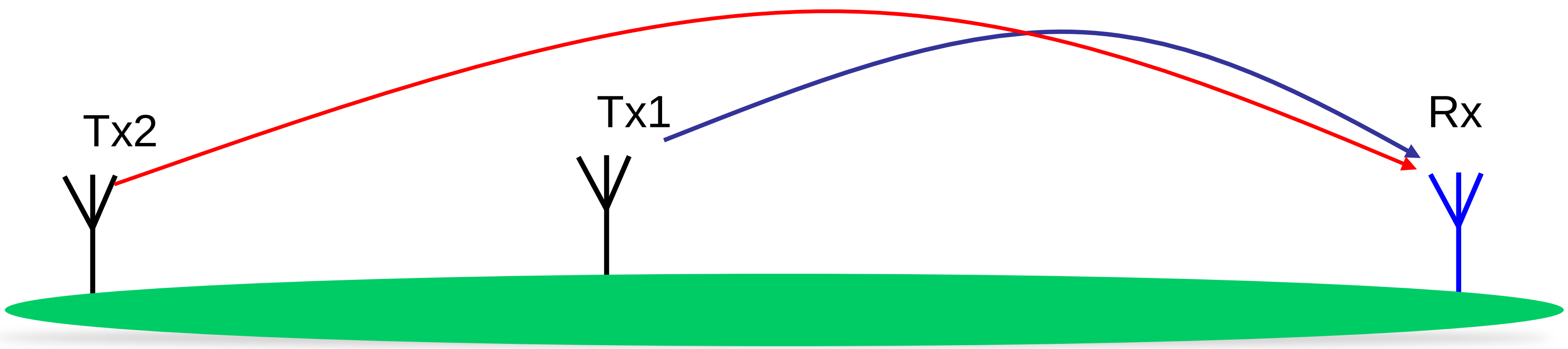
Phase estimation processing: pilot tracking



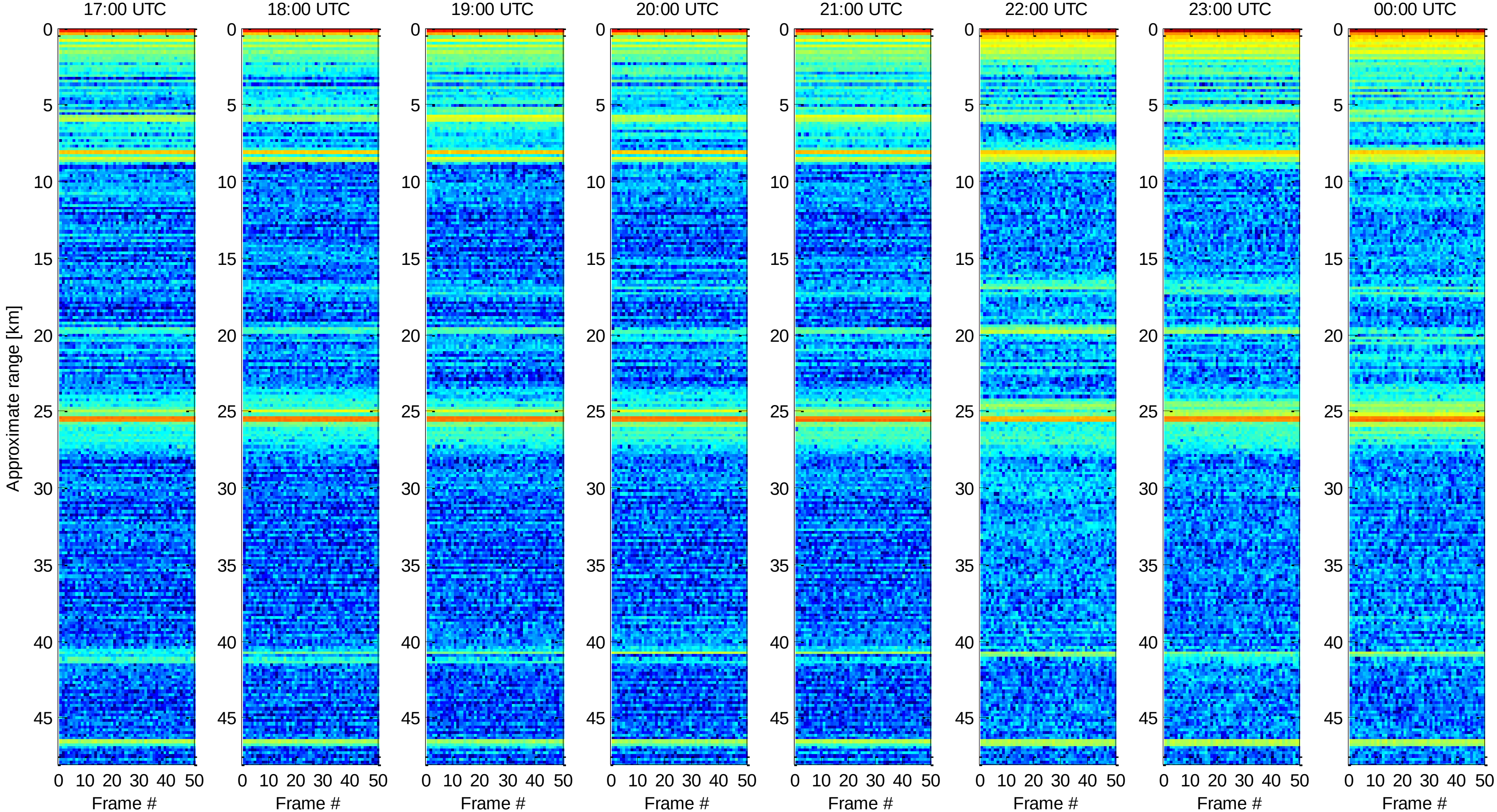
Vertical refractive index structure

- The distance VHF/UHF signals travel depends on the *vertical* refractive index profile

- The signal strength will vary depending on the profile and transmitters e.g., Tx2 only visible under certain refractive conditions



Single-site autocorrelation magnitude



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Summary

- Techniques show potential but need further development
- Many technical challenges e.g., receiver synchronisation
- Cost of DAB receiver sensor nodes will be low
  - A simple passive receiver with embedded processor
  - Integration with existing present weather sensor systems
- Receiver locations need to be optimised
  - Parabolic equation approach predicts well the path loss (PE can also estimate phase –not shown here)

- Acknowledgements: Met Office