Numerical Simulations of the Effects of a Tidal Turbine Array on Near-bed Velocity and Local Bed Shear Stress

Philip Gillibrand

Environmental Research Institute, North Highland College, University of the Highlands and Islands, Thurso, Caithness, KW14 8YD, U.K.

Outline

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  - Modelling Objectives
- Methods
  - RiCOM Model
  - Turbine Parameterisation
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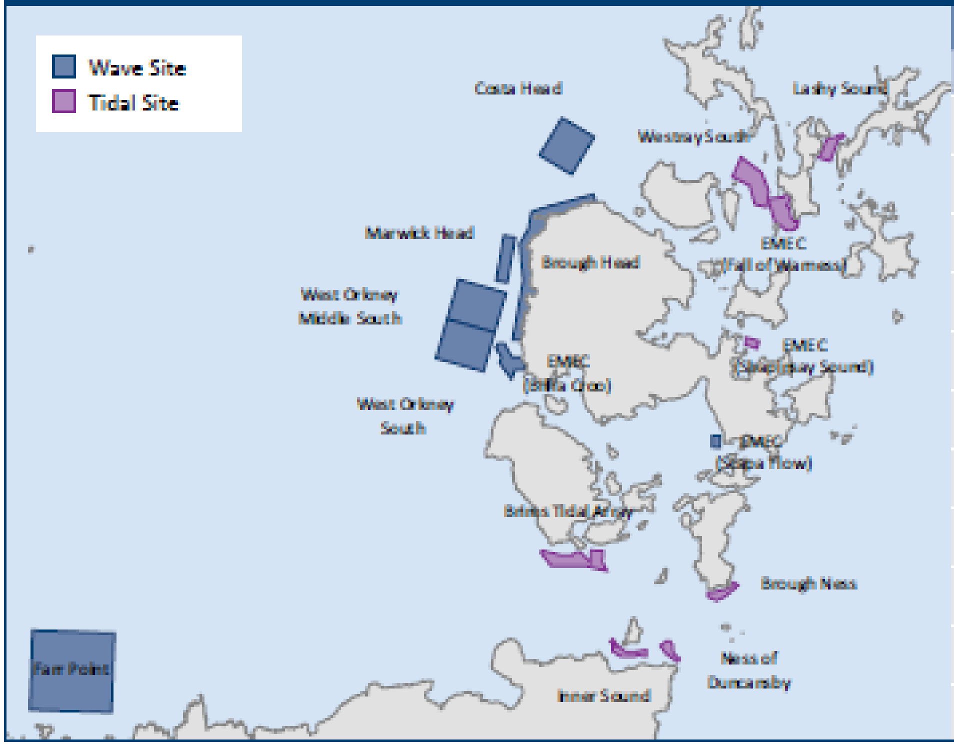
  - Velocity Profiles
  - Near-bed Velocity
  - Bed Shear Stress
- Conclusions
- Future Work

Introduction

- Pentland Firth Orkney Waters
  - Focus for UK marine energy development
  - Meygen deploying 4 x 1.5 MW turbines now ….. first of 268 ??
  - Meygen Phase 1: 6 MW (4 turbines)

    Phase 2: 86 MW (57 – 80 turbines)

Map of Pentland Firth and Orkney waters projects



Projects comprising the 2010 leasing round

Site Name	Capacity (MW)
Farr Point	50
West Orkney South	50
West Orkney Middle South	50
Marwick Head	50
Brough Head	200
Costa Head	200
Westray South	200
Brims Tidal Array	200
Brough Ness	100
Ness of Duncansby	100
Inner Sound	400

Modelling

- Objectives
  - To develop an accurate and robust hydrodynamic model of the region
  - To allow accurate resource assessment
  - To develop a tool capable of optimising the layout of tidal turbine arrays.
  - To predict potential effects on the ambient environment of tidal energy extraction prior to the deployment of large scale arrays.
  - To provide “operational” modelling of the Pentland Firth for the marine energy industry

Hydrodynamic Model Description

- The River and Coastal Ocean Model (RiCOM);
- Proprietory code developed at NOAA and NIWA;
- Basic finite element model using unstructured grids;
- Uses mixed finite element/finite volume methods to conserve mass;
- Solves the Reynold-averaged Navier-Stokes equations, using hydrostatic and Bousinesq approximations;
- Employs semi-implicit and semi-lagrangian techniques to solve the free surface and momentum equations;
- Model is fast, robust and accurate, ideal for use on desktop computers and small clusters;
- Previously applied to tsunami, storm surge and tidal modelling;
- Recently applied to tidal energy problems in Canada and New Zealand.

References

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Plew, D. R., & Stevens, C. L. (2013). Numerical modelling of the effect of turbines on currents in a tidal channel–Tory Channel, New Zealand. *Renewable Energy*, *57*, 269-282.

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Mathematical Framework

Hydrostatic and Boussinesq assumptions are made

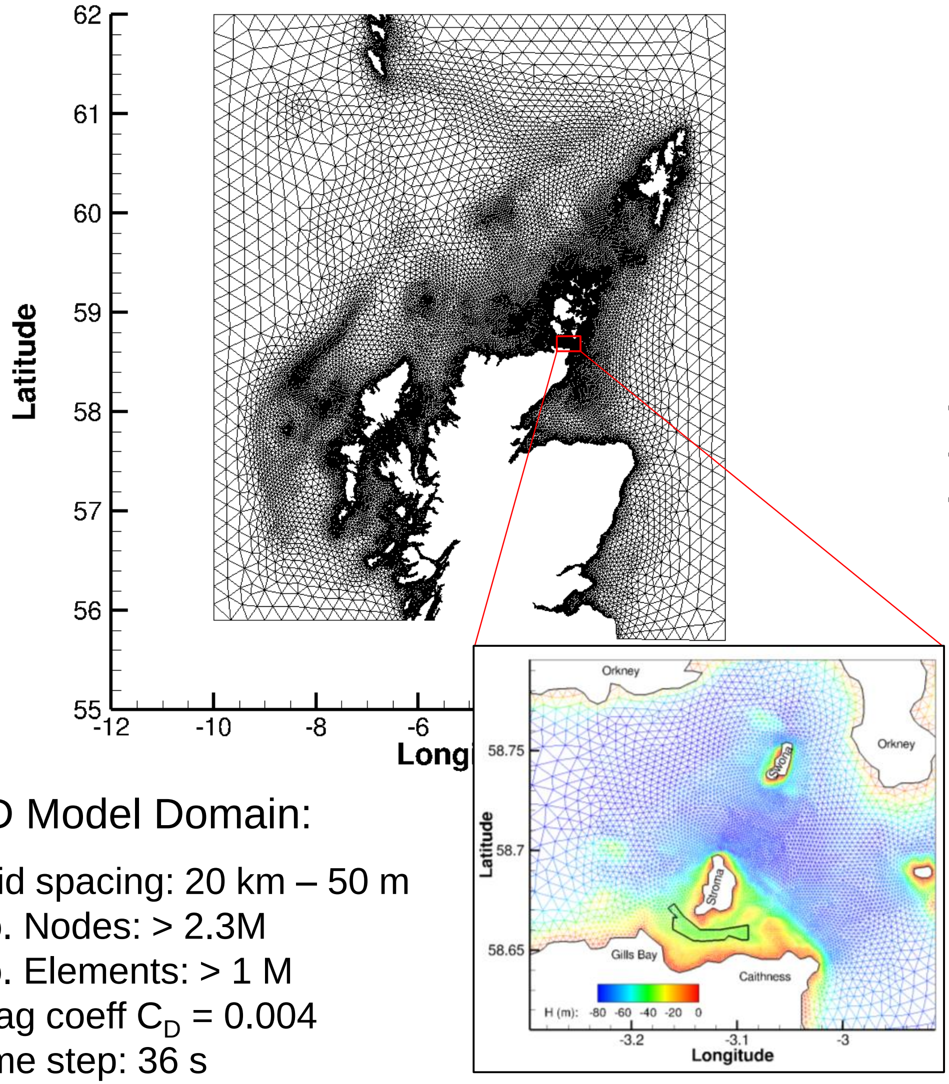
Continuity equation: $$\nabla \cdot \mathbf{u} + \frac{\partial w}{\partial z} = 0$$

Momentum balance: $$\frac{D\mathbf{u}}{Dt} + f\hat{\mathbf{z}} \times \mathbf{u} + g\nabla\eta - \frac{\partial}{\partial z}\left(A_V \frac{\partial \mathbf{u}}{\partial z}\right) - \nabla \cdot \left(A_h \nabla \mathbf{u}\right) + \mathbf{F} = 0$$

Free surface equation: $$\frac{\partial \eta}{\partial t} = \nabla \cdot \left(\int_h^\eta \mathbf{u}\, dz\right) = 0$$

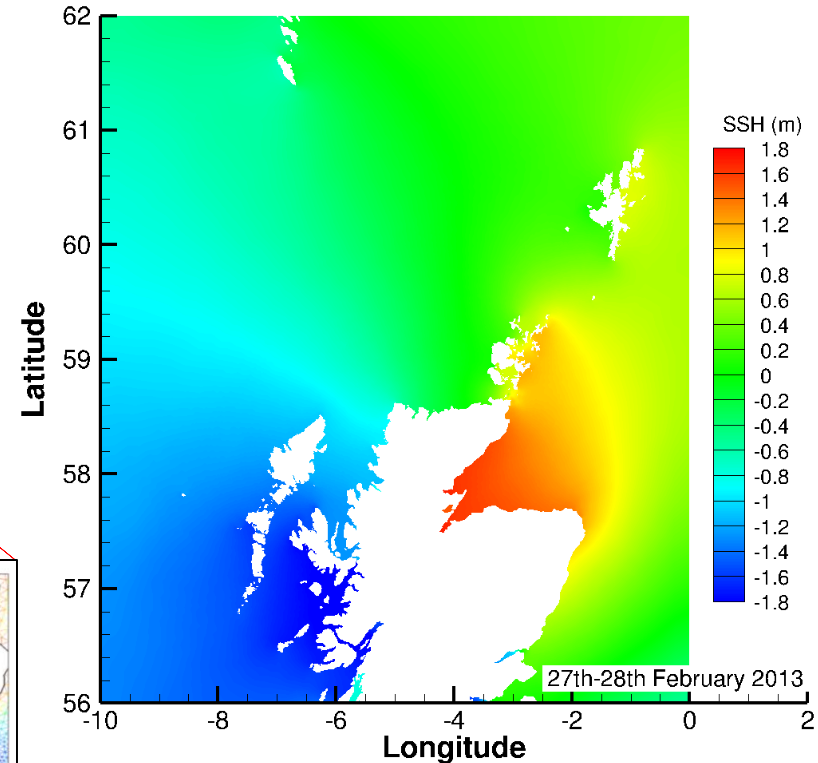
Bed stress: $$\boldsymbol{\tau}_\mathbf{b} = \rho C_D \mathbf{u}_\mathbf{b} \left|\mathbf{u}_\mathbf{b}\right|$$

Scottish Continental Shelf Grid



3D Model Domain:

Grid spacing: 20 km – 50 m
No. Nodes: > 2.3M
No. Elements: > 1 M
Drag coeff C_D = 0.004
Time step: 36 s
34 days takes: ~ 8 hours
(8 cores)



Boundary Forcing:
7 tidal constituents: M_2, S_2, N_2, O_1, K_1, Q_1, M_4
Reconstructed sea level along open boundary from OTPS (OSU)

15 sigma levels: σ = [0.00, −0.02, −0.05, −0.10, −0.15, −0.20, −0.30, −0.40, −0.50, −0.60, −0.70, −0.80, −0.90, −0.95, −1.00]

Turbine Parameterisation

- Turbines implemented through a form drag term in the momentum equation:

$$\mathbf{F}_\mathrm{D} = \frac{1}{2}\varrho A_\mathrm{T} C_\mathrm{T} |\mathbf{U}_\mathbf{R}| \mathbf{U}_\mathbf{R}$$

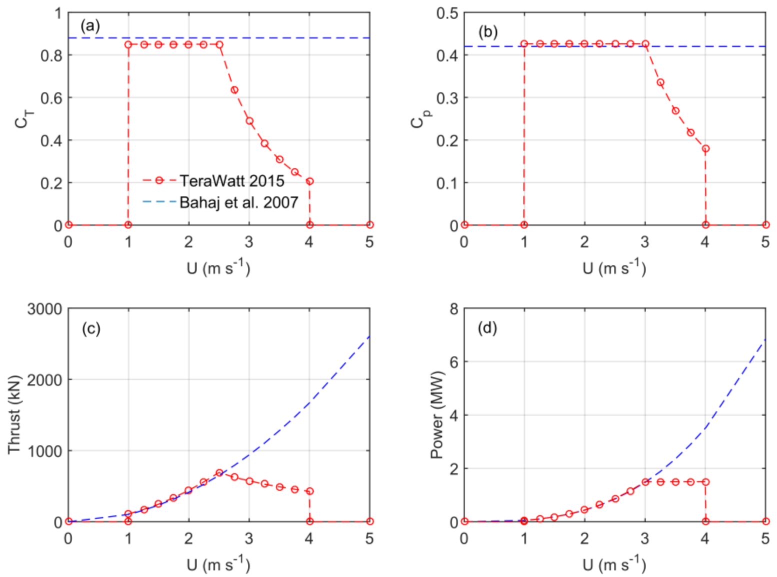
- In 3D, FD must be located in the appropriate vertical layers:

$$\mathbf{F}_\mathrm{K} = \frac{1}{2}\varrho A_\mathrm{K} C_\mathrm{K} |\mathbf{U}| \mathbf{u}_\mathrm{K}$$

- Power generated is calculated by:

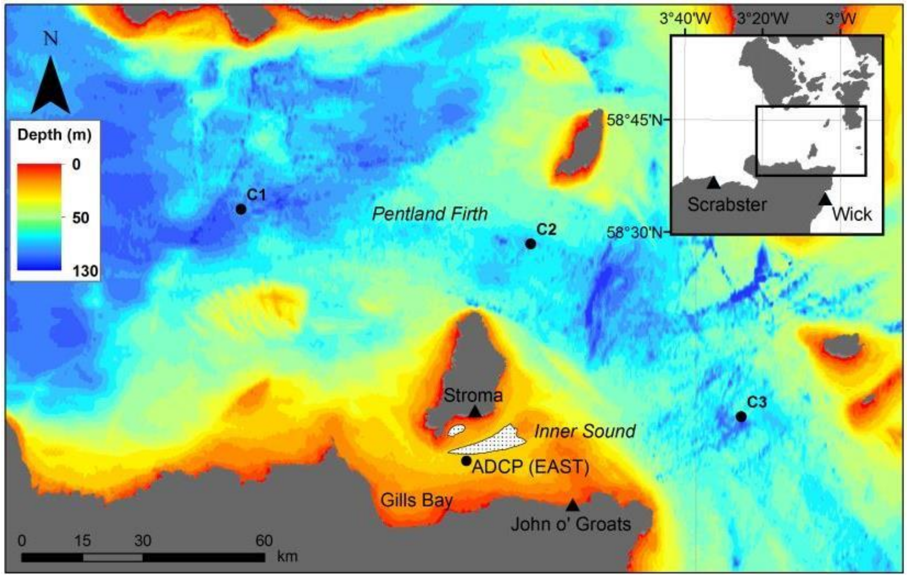
$$P = \frac{1}{2}\varrho A_\mathrm{T} C_\mathrm{P} U_\mathrm{R}^3$$

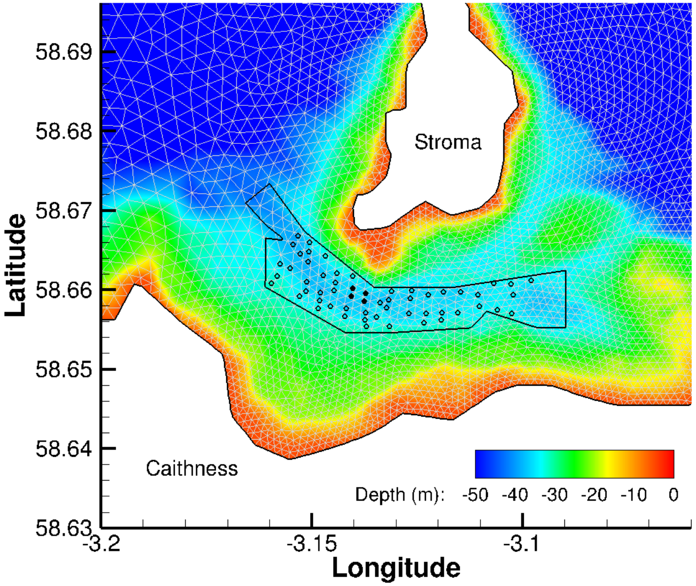
- C_T and C_P are taken from the TeraWatt project (Baston et al., 2015)



Simulations

Run	Period	No. of tidal turbines	Rated Power (MW)	Total Power (MW)	C_T and C_P
1	18/02/2013 – 24/03/2013	0	N/A	0	N/A
2	18/02/2013 – 24/03/2013	1	1.5	1.5	Constant
3	18/02/2013 – 24/03/2013	1	1.5	1.5	Variable
4	18/02/2013 – 24/03/2013	4	1.5	6	Constant
5	18/02/2013 – 24/03/2013	4	1.5	6	Variable
6	18/02/2013 – 24/03/2013	57	1.5	85.5	Constant
7	18/02/2013 – 24/03/2013	57	1.5	85.5	Variable



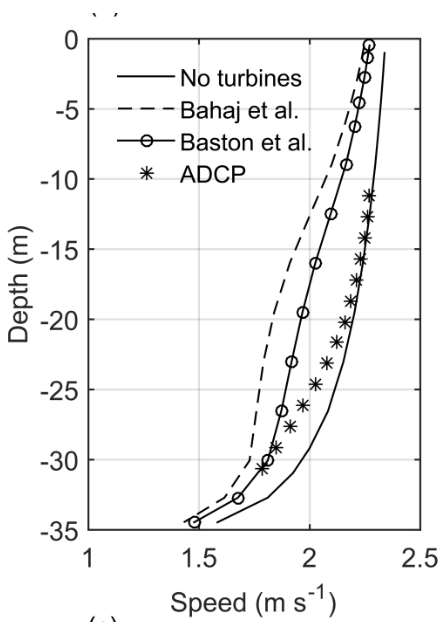


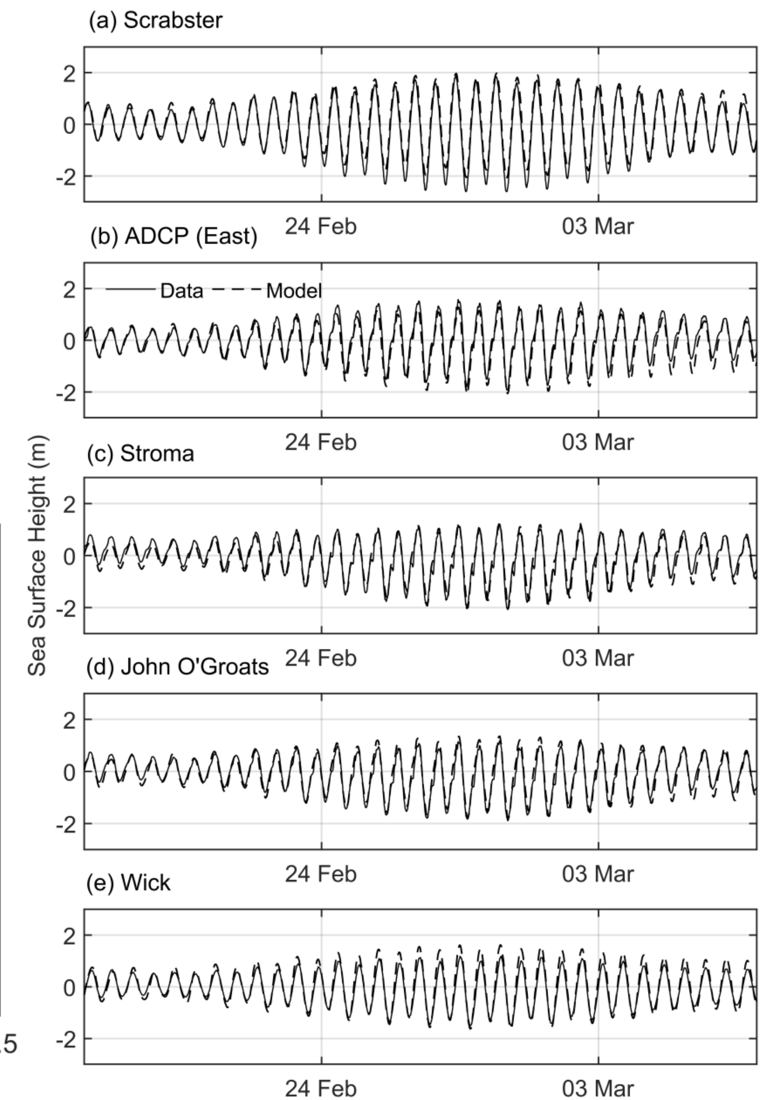
Calibration

- Model calibrated against sea surface height data
- Skill scores > 0.9
- M_2 tide amplitude error ~ 4 cm
- M_2 tide phase error ~ 3°
- Best fit with $C_D = 0.004$
- Comparison with ADCP data
- Errors:

M_2 East: 0.2 m s^{-1}

4°

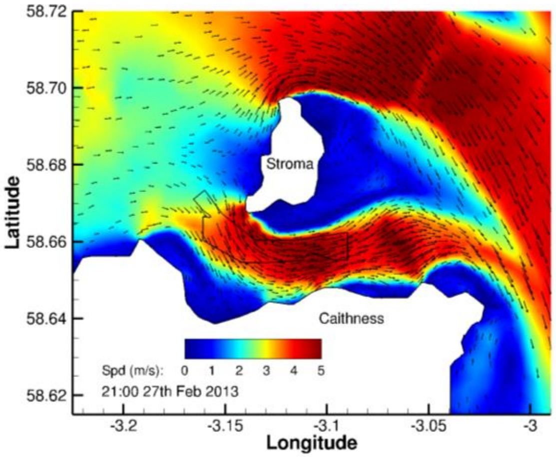




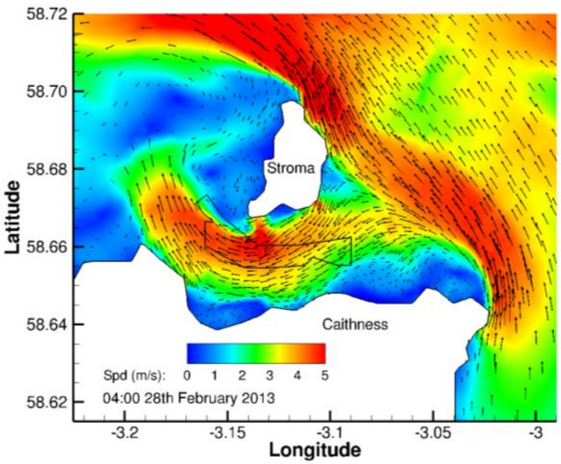
Results

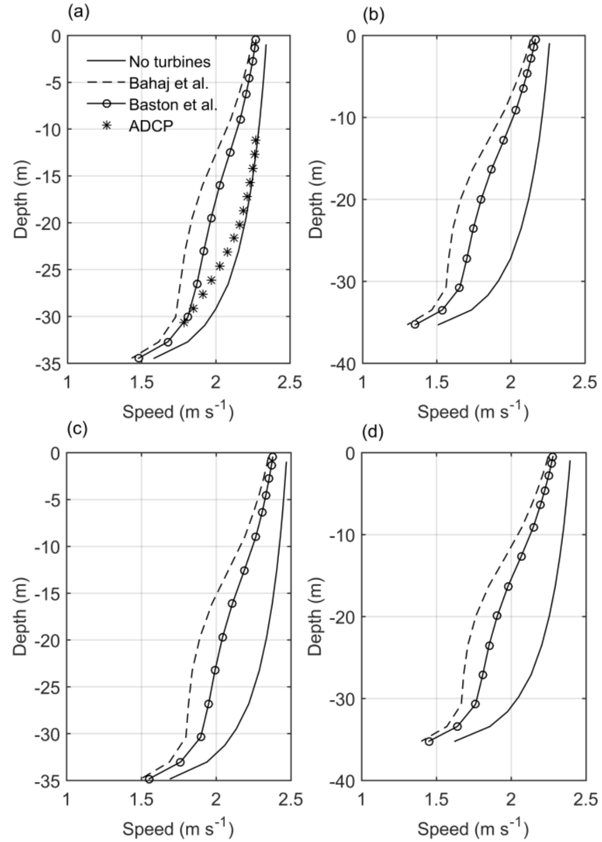
Near-bed velocity fields

Flood

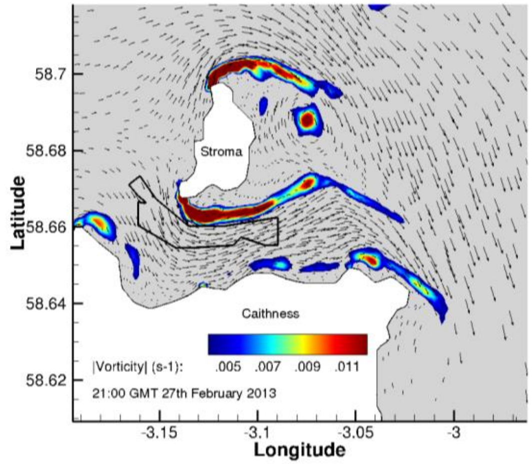


Ebb





Mean Speed profiles



Vorticity

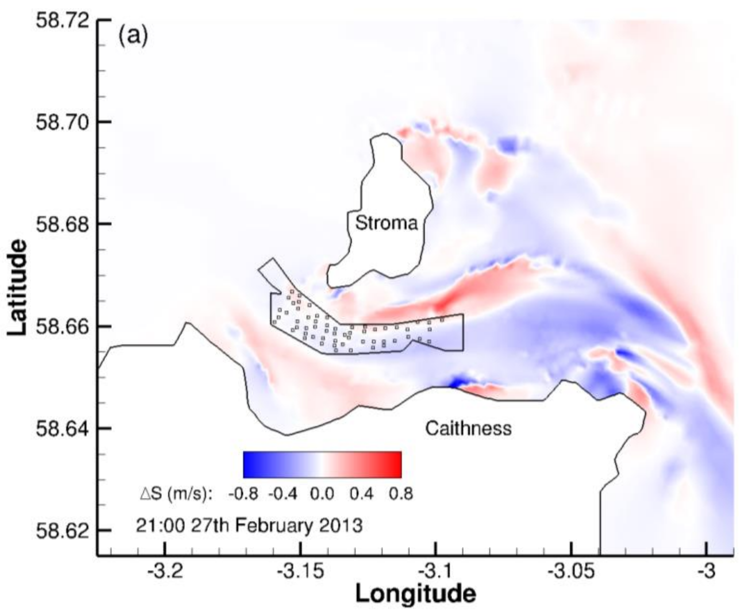
Effects of 86 MW turbine array

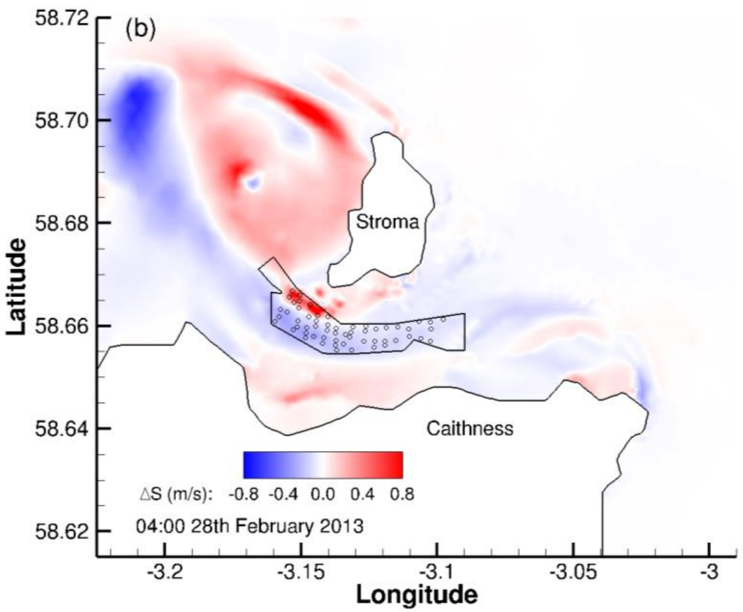
Near-bed velocity

Difference between 57 and no turbines

Flood

Ebb



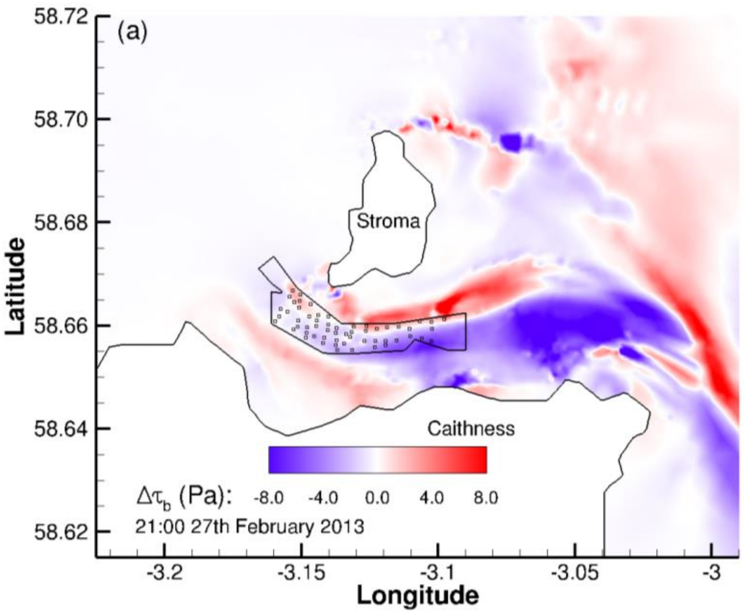


Effects of 86 MW turbine array

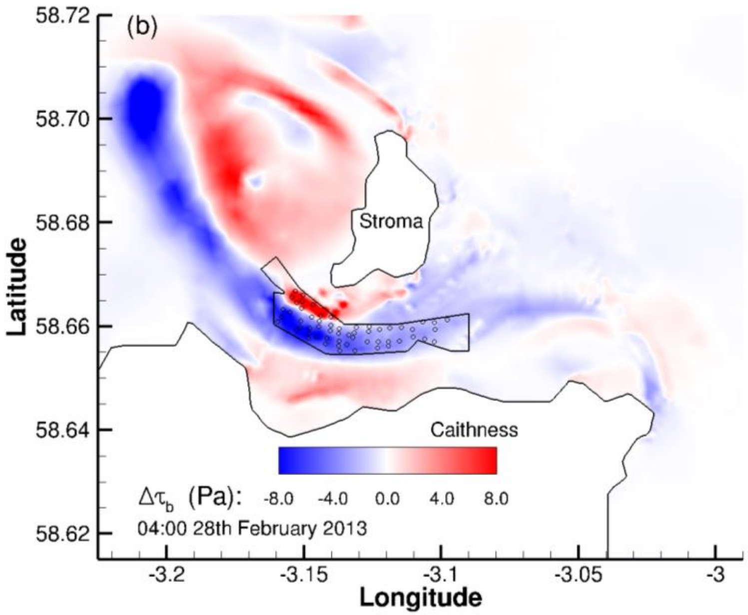
Bed shear stress

Difference between 57 and no turbines

Flood

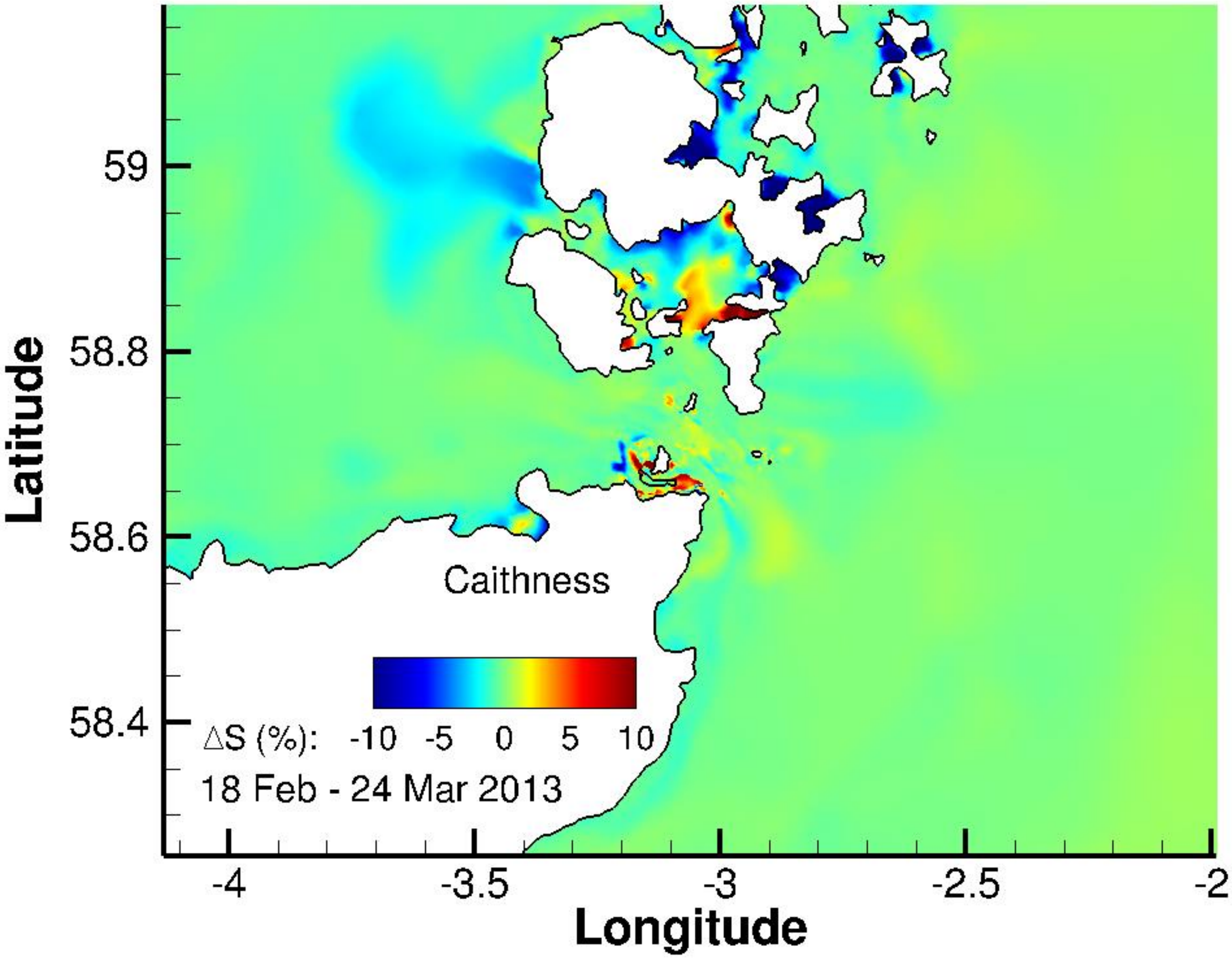


Ebb



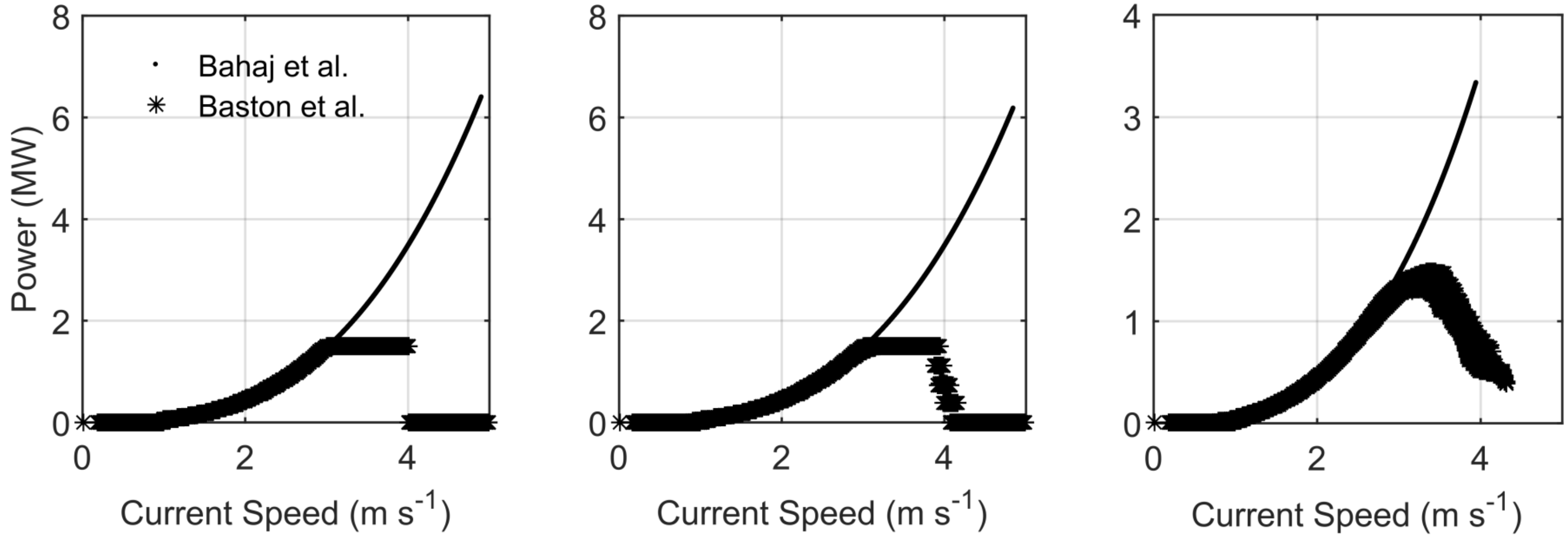
Far-field Effects of 86 MW turbine array

Maximum near-bed speed



Power Generation

No. turbines: 1 4 57

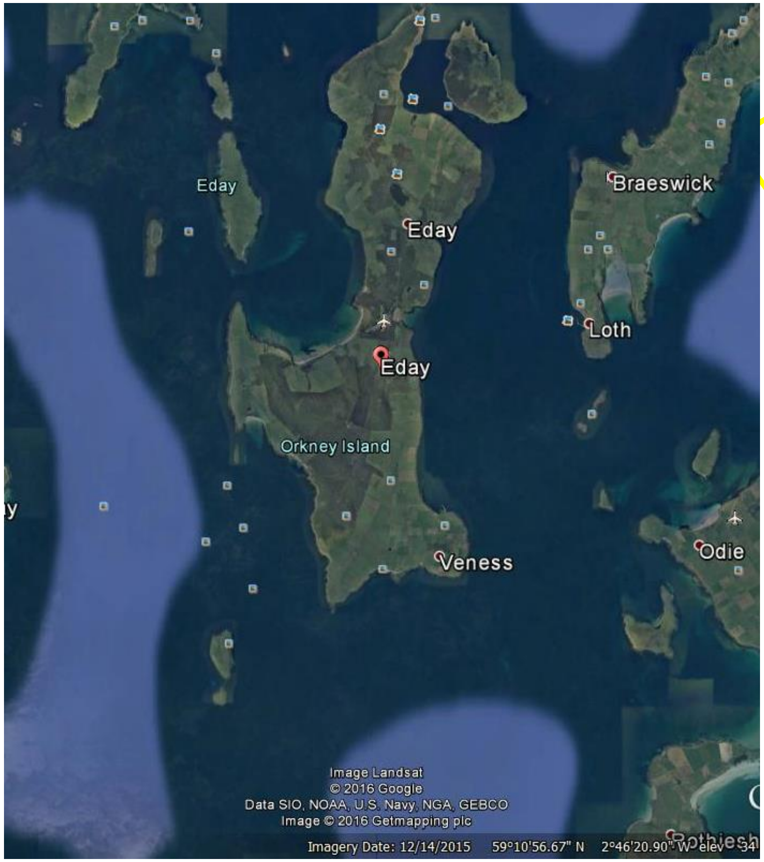


Preliminary Conclusions

- Model reproduces the tidal dynamics through the Pentland Firth and Inner Sound with acceptable accuracy.
- Deployment of 86 MW array likely to displace the location of the jet through the Inner Sound.
- Near-bed velocity modified by up to 0.8 m s^{-1}.
- Bed shear stress values modified by up to 8 Pa.
- Monitoring of nearby sand and shell banks could provide useful data for future modelling studies.

X-Band Radar Deployments

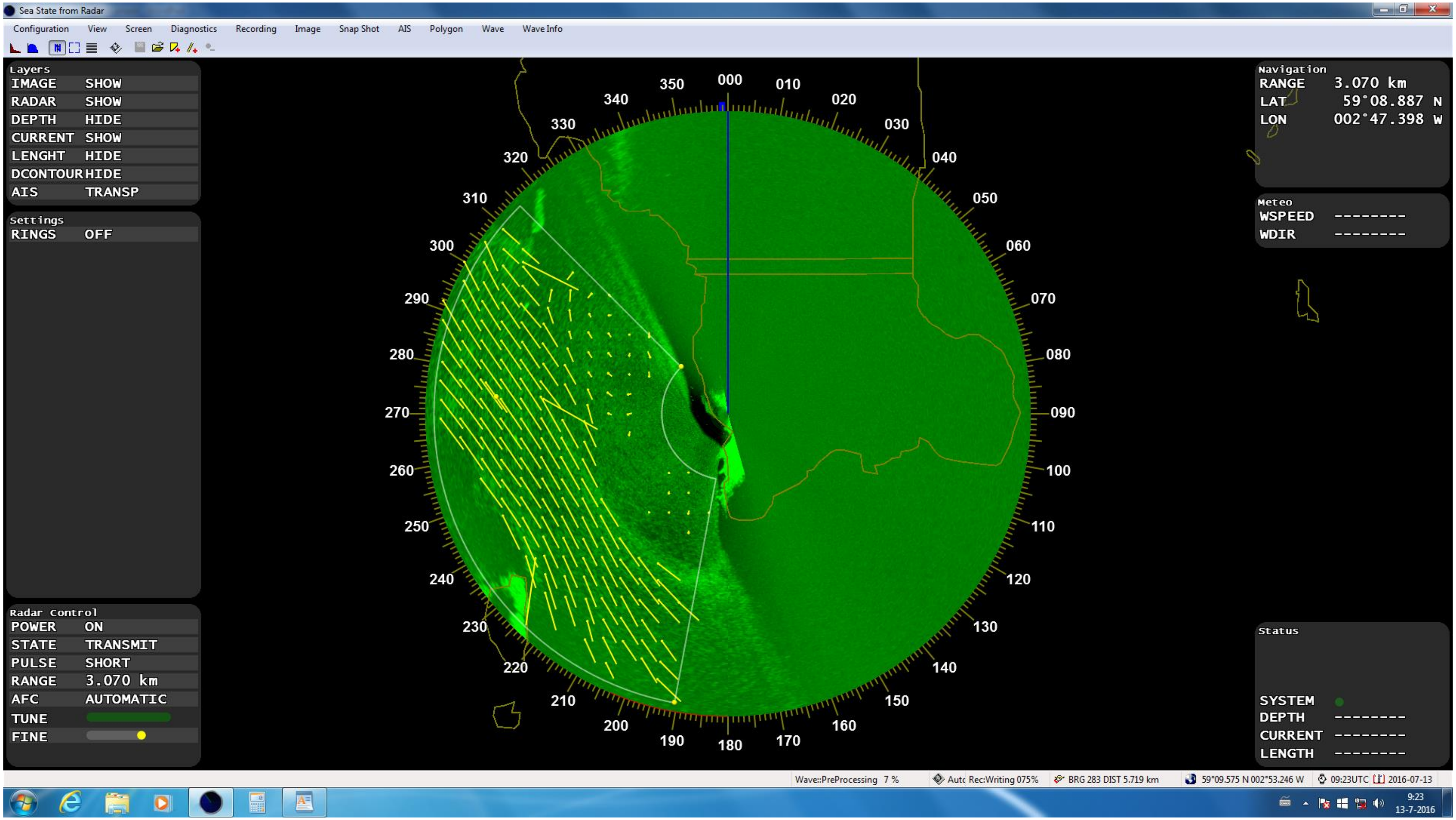
Falls of Warness, 8th – 12th July 2016



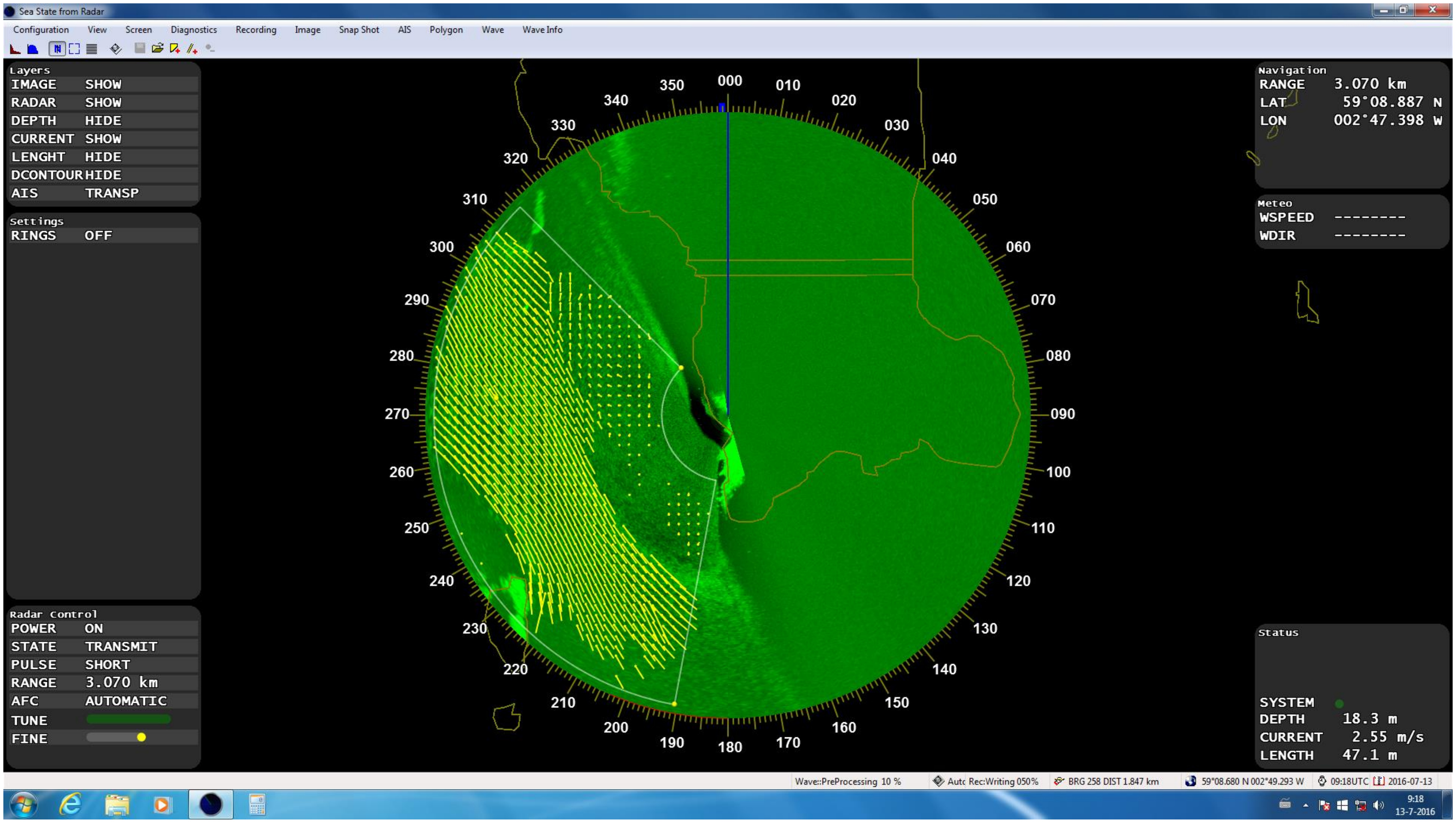
St Johns Point, Inner Sound

Falls of Warness, July 2016

Falls of Warness, July 2016



Falls of Warness, July 2016



Falls of Warness, July 2016

X-Band Radar Data Summary

- 4 days of continuous data (12 – 15 July)
- 239 data files
- 953 GB of data

Processing and analysis challenge !

- To extract gridded velocity fields throughout deployment period
- To analyse the data
- To develop methods to couple data with numerical model results

Future Work

- Further analysis of model results
  - Impacts of turbines on residual flows
  - Sediment transport pathways
  - Improve turbine parameterisation

- Wave-current interactions
  - Investigating wave-current interactions in highly dynamic areas
  - PhD student, Clare MacDowall, started 1st October
  - Observations (X-band radar) and modelling
  - Develop a predictive model

- "Operational" coupled hydrodynamic-wave model
  - Hydrodynamic model currently running "operationally"
  - Implement "operational" SWAN model
  - "Operational" wave-current forecasts

- Pentland Firth Observing System
  - Calibration/validation of modelling system

Thank You !

w. merikafp7.eu   e. merikafp7@uhi.ac.uk   @merikafp7

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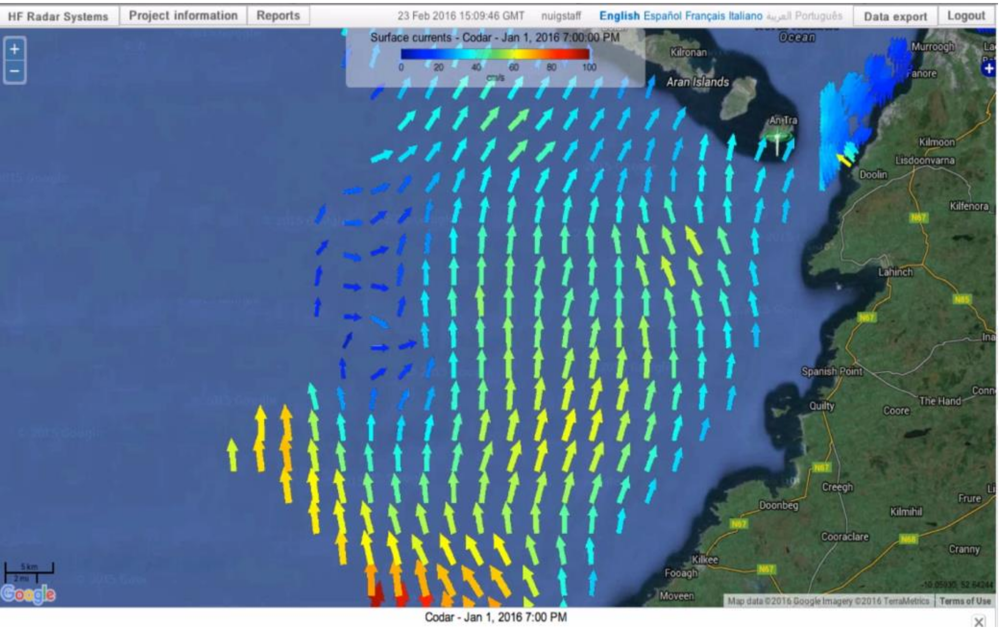
Pentland Firth Observing System

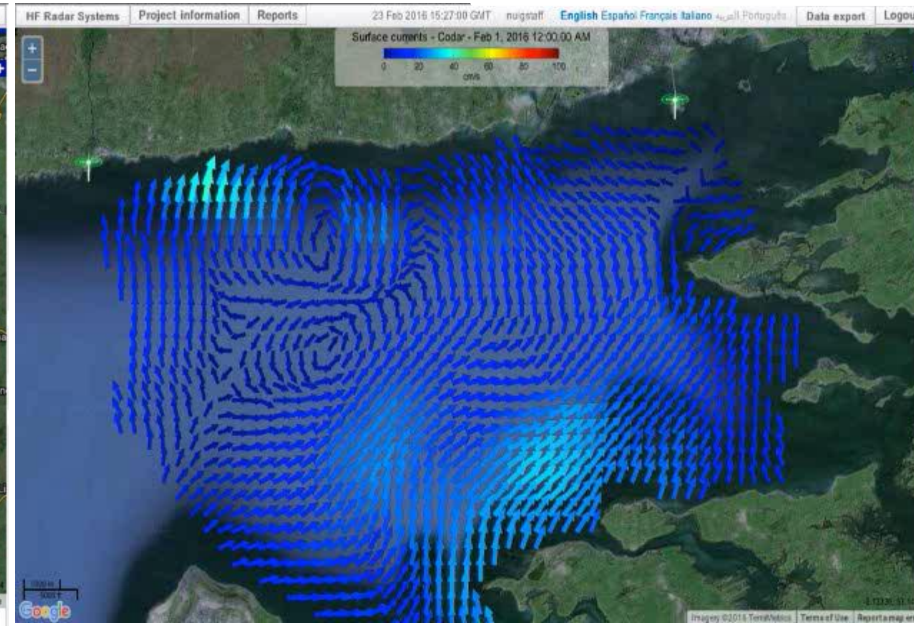
- Strategically important area over the next few years/decades
- Paucity of data
- Difficult working environment
- Data required for calibration/validation of models, including "operational" models
- Proposed system based on HF radar:
  - Avoids deployments of instruments in dynamic environment
  - Provides wide coverage
  - Discussions between UHI and HWU (David Woolf, Susanna Baston)
  - Options for CODAR installations considered with Jorge Sanchez (Qualitas Remos Ltd).

Ireland: Marine Renewables

West Coast

Galway Bay





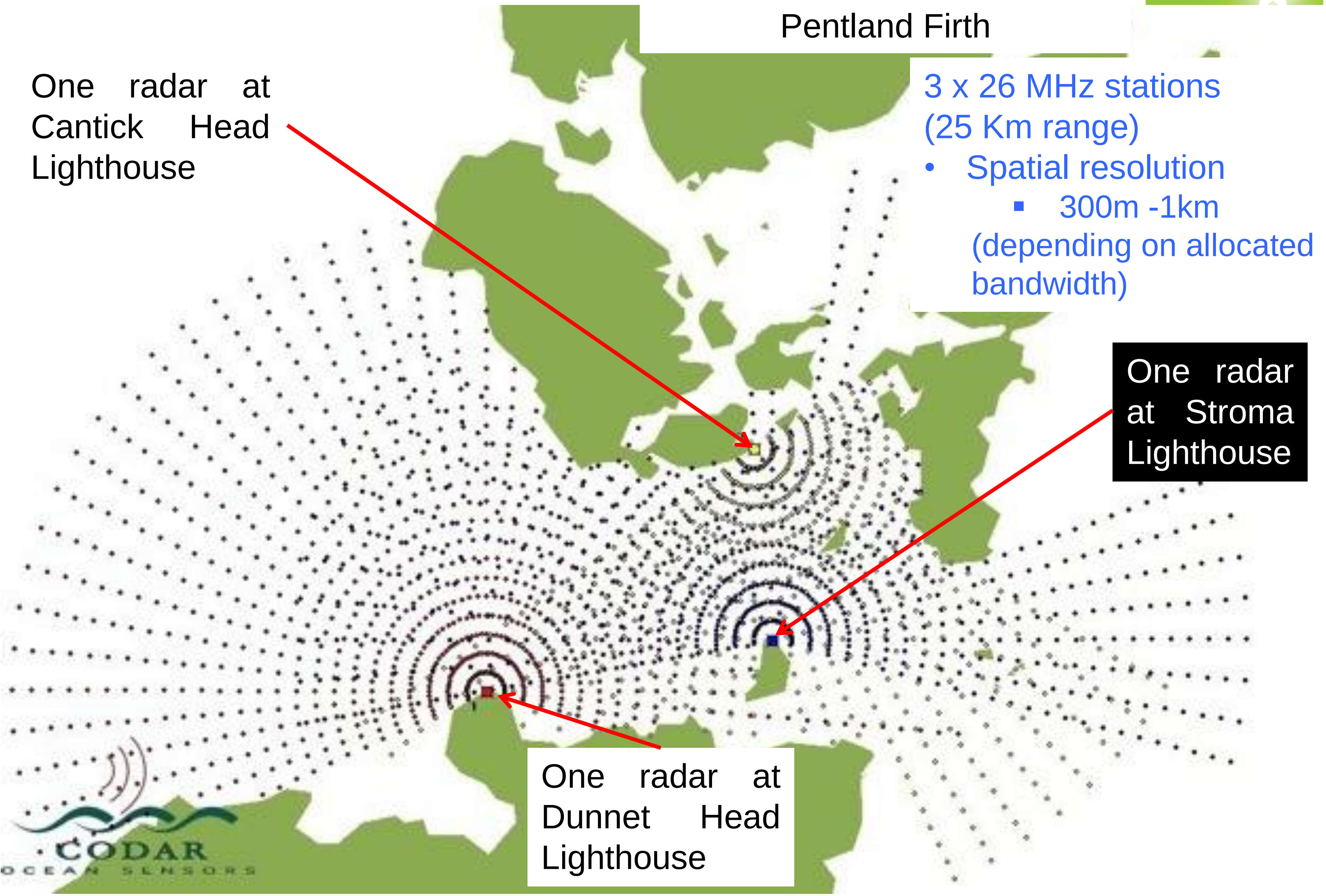
Monitoring most of the west coast south of Galway and up to 70 km offshore, including:

- Inner Galway Bay (High resolution 300m. 26 MHz systems)
- The West-wave National Test site
- Coastal waters West of Clare

Potential radial coverage (III). 26 MHz

3 x 26 MHz stations (25 Km range)

- Spatial resolution
  - 300m -1km (depending on allocated bandwidth)



Potential total coverage (III). 26 MHz

Pentland Firth

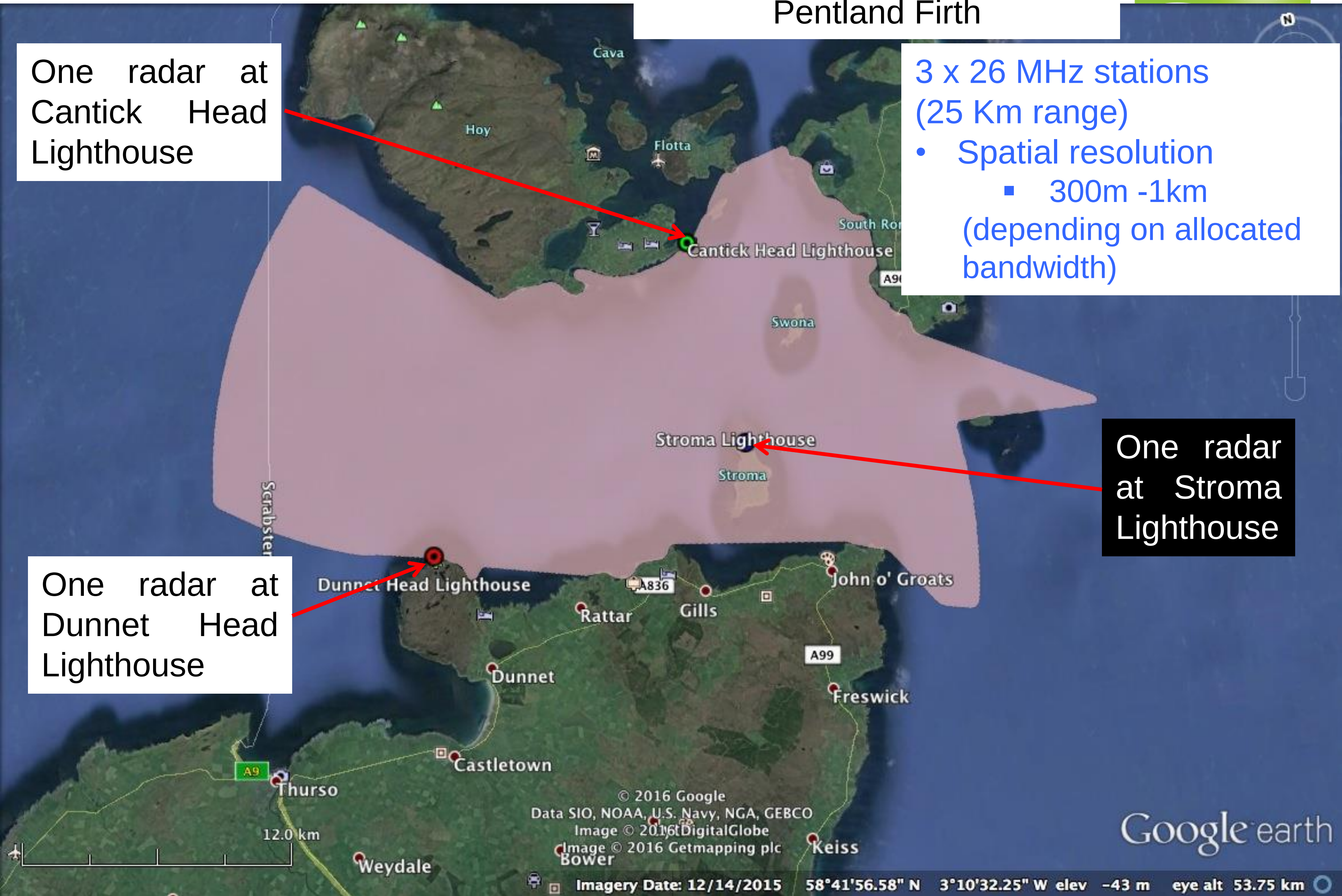
One radar at Cantick Head Lighthouse

3 x 26 MHz stations (25 Km range)

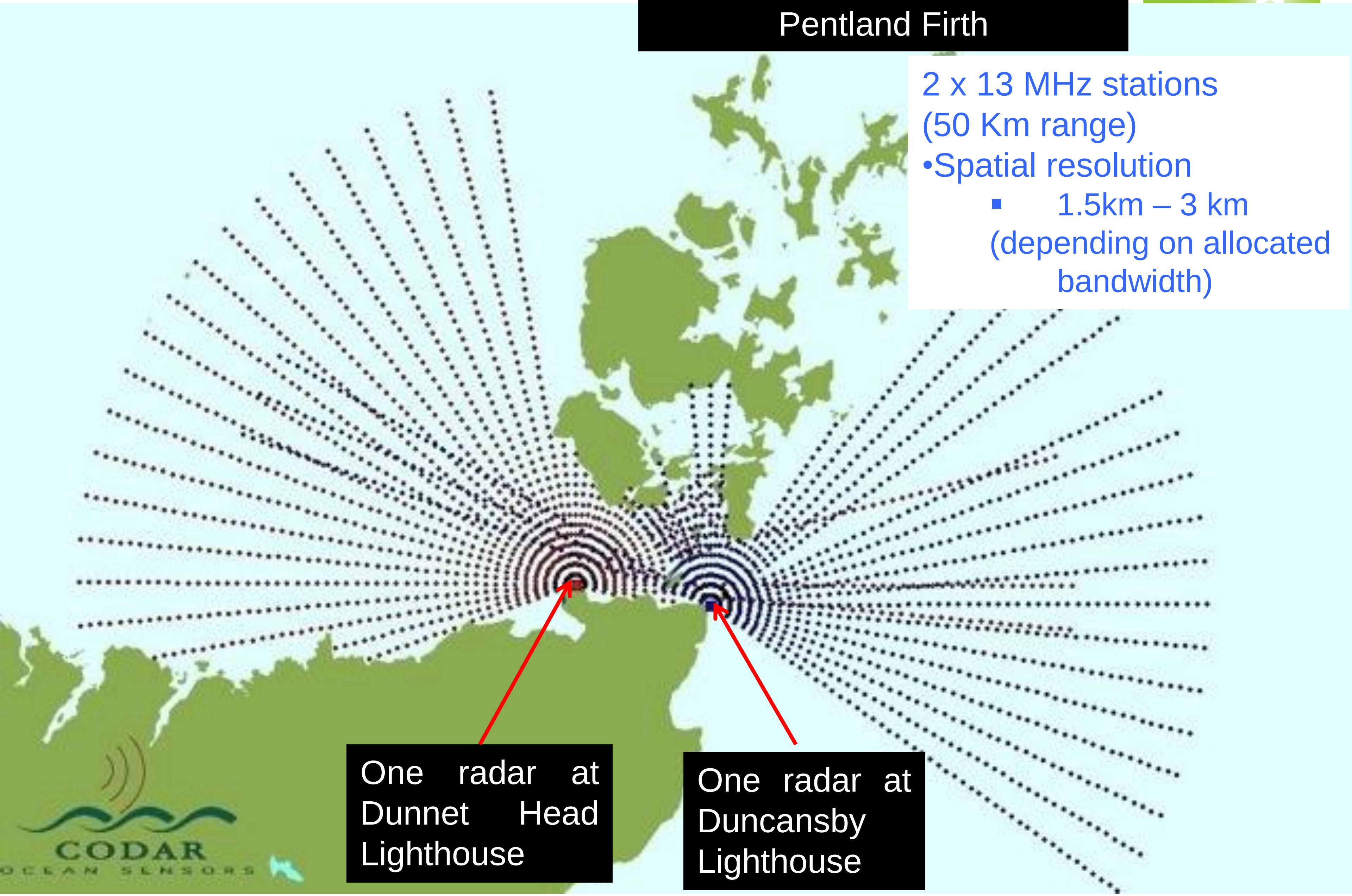
- Spatial resolution
  - 300m -1km (depending on allocated bandwidth)

One radar at Stroma Lighthouse

One radar at Dunnet Head Lighthouse



Potential radial coverage (III). 13 MHz



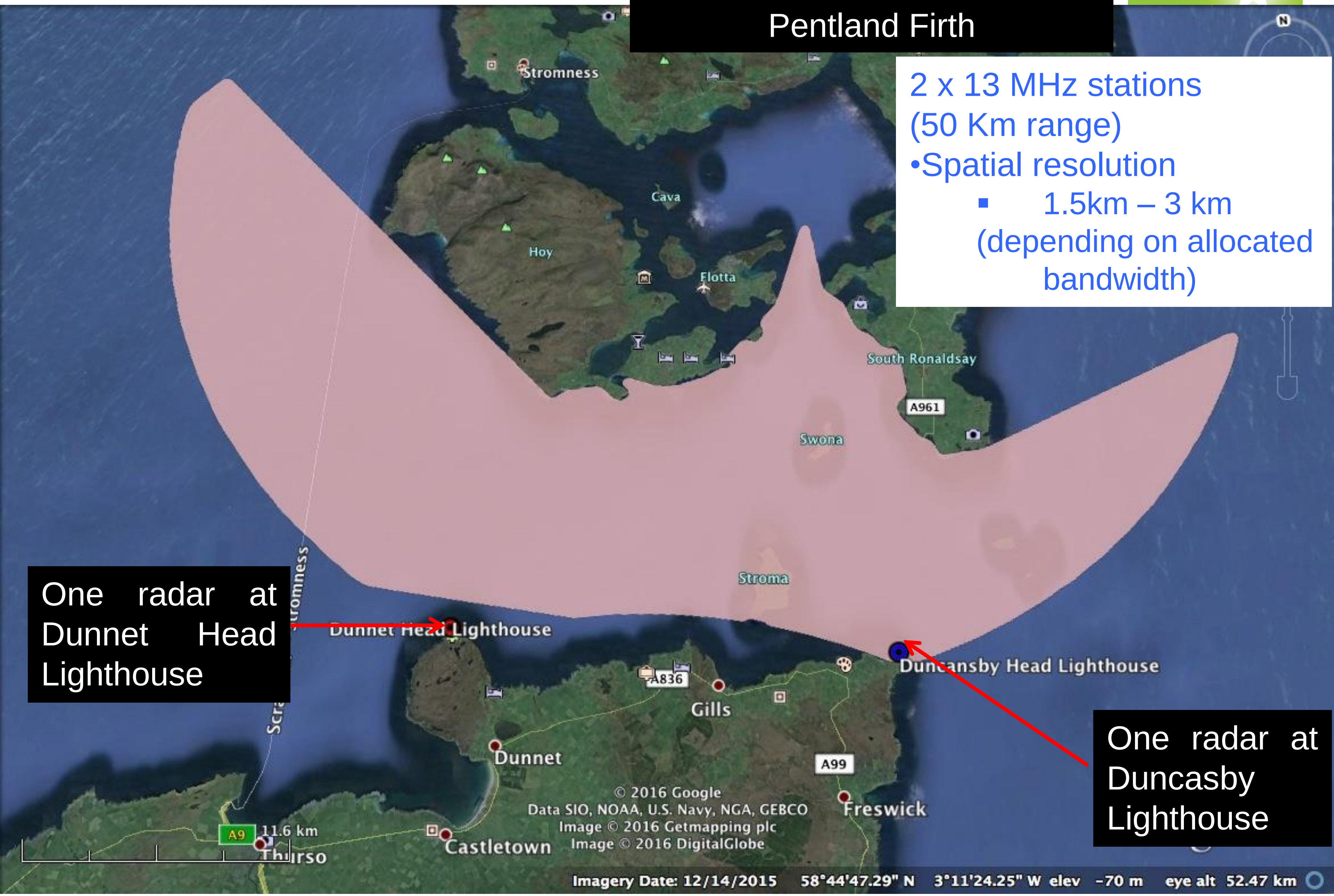
2 x 13 MHz stations
(50 Km range)
- Spatial resolution
  - 1.5km – 3 km (depending on allocated bandwidth)

Potential total coverage (III). 13 MHz

Pentland Firth

2 x 13 MHz stations
(50 Km range)

- Spatial resolution
  - 1.5km – 3 km (depending on allocated bandwidth)



One radar at Dunnet Head Lighthouse

One radar at Duncasby Lighthouse