Wind Monitoring Using 2nd Generation Wind Lidars

Peter Clive

Technical Development Consultant

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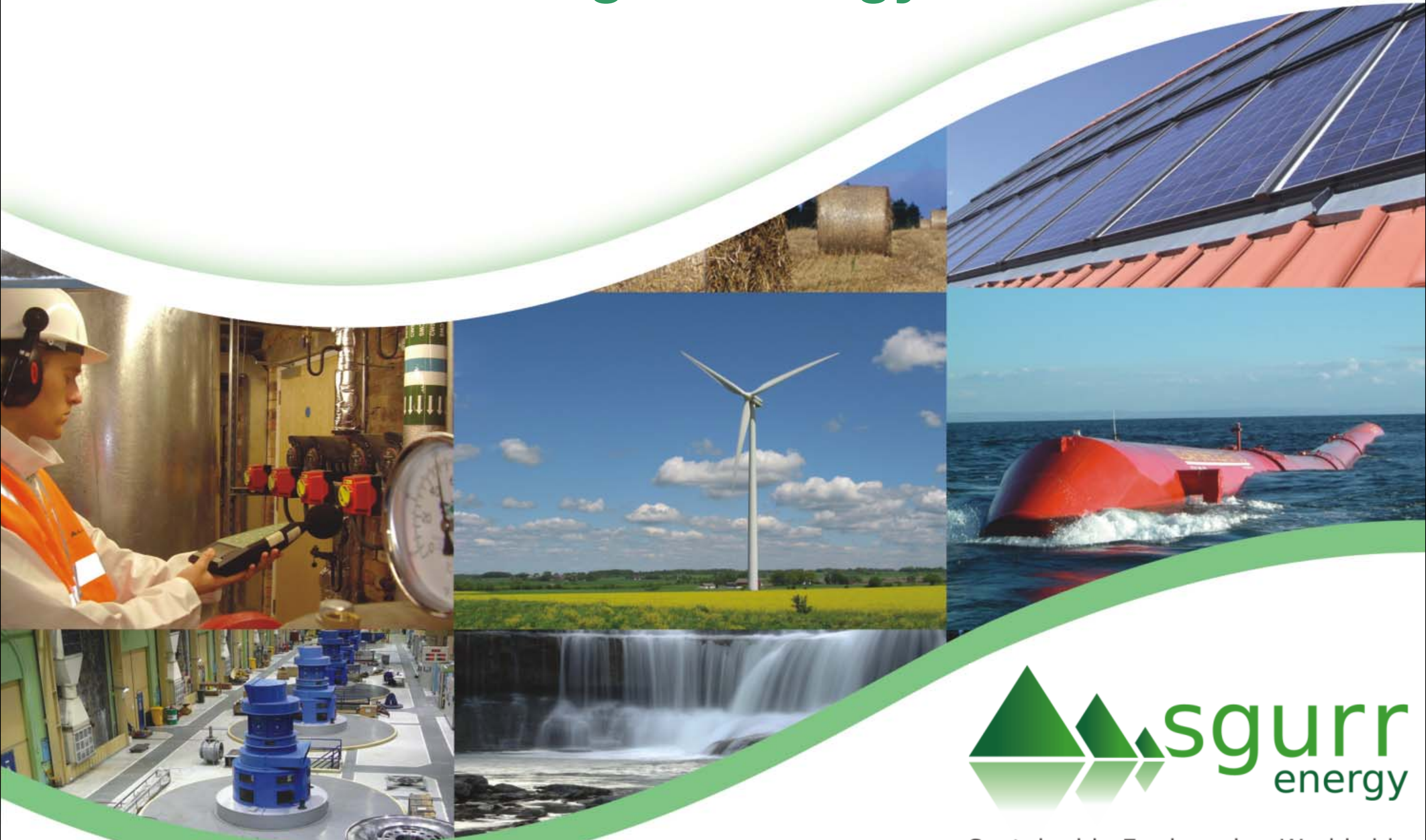
Introduction to SgurrEnergy



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SgurrEnergy today

- Leading independent engineering consultancy
- International
  - Glasgow (Head Office)
  - Beijing
  - Pune
  - Wexford
  - Vancouver
  - Scottish Highlands
  - Paris
  - Boston
- Experienced
  - Over 100 responsive engineers and consultants

Triple certification

FS 85385

EMS 85386

OHS 538996

Leading position by experience

We have consulted on over 40,000 MW of renewable energy in over 30 countries covering both project development and due diligence

Europe

- Belgium
- Estonia
- France
- Germany
- Greece
- Republic of Ireland
- Italy
- Malta
- The Netherlands
- Poland
- Portugal
- Spain
- Sweden
- UK

Asia

- China
- India
- Korea
- Pakistan
- Philippines
- Russia
- Saudi Arabia
- Sri Lanka
- Turkey
- Vietnam

Africa

- Angola
- Kenya
- South Africa

Oceania

- New Zealand

North America

- Canada
- USA

South America

- Chile
- Galapagos Islands

What we do

SgurrEnergy personnel hold unparalleled knowledge to ensure successful project delivery.

Overview of capability

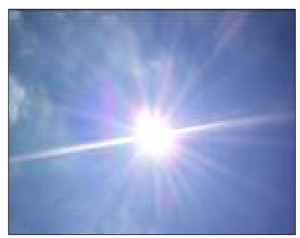
Wind

Wave & tidal

Hydro

Solar

Bio-energy



Micro-generation

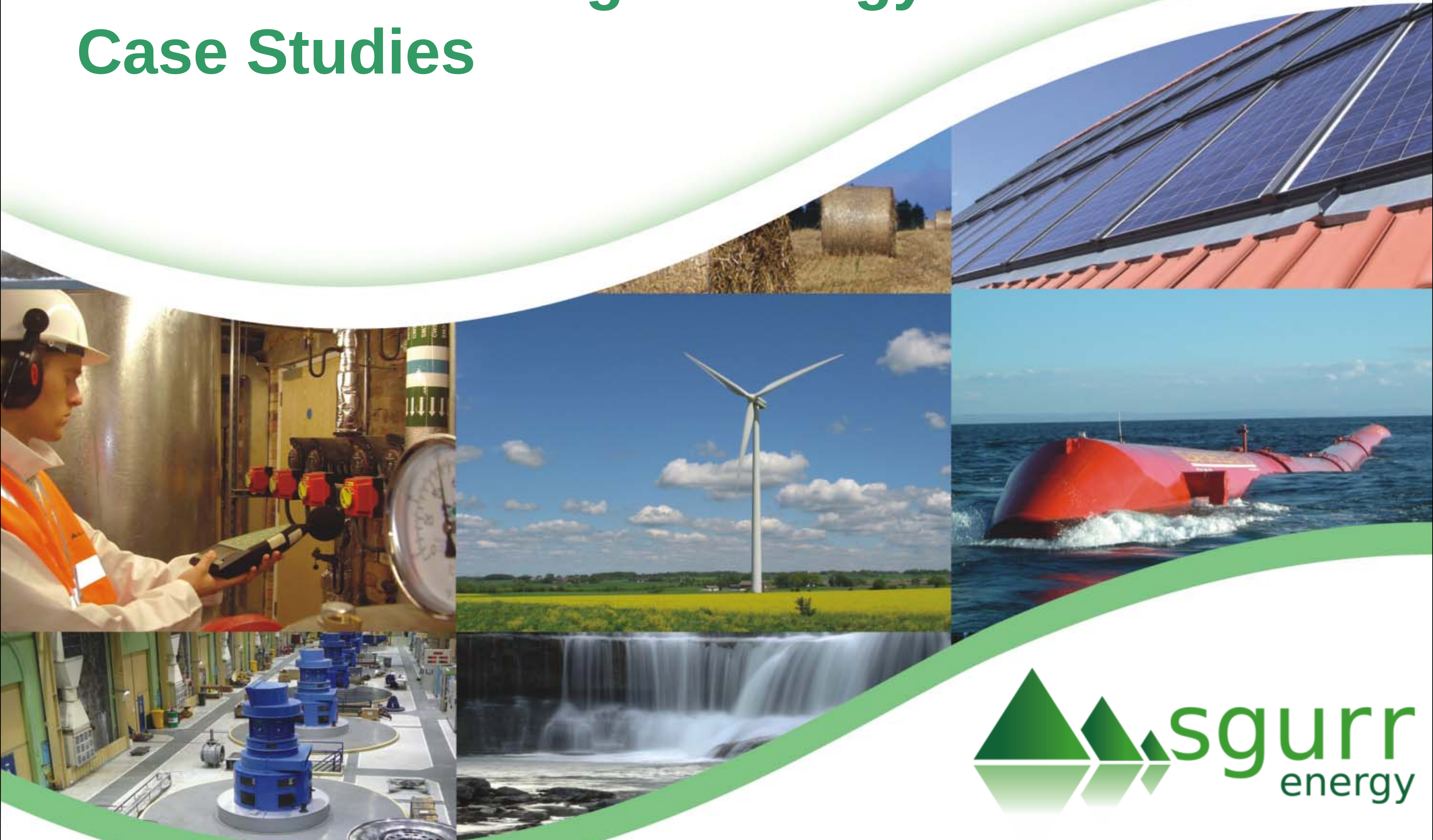
- Due diligence
- Lenders engineer
- Energy yields
- Technology audits & reviews
- Hybrid systems

Project management

Noise & vibration

- Technical advisor

Introduction to SgurrEnergy: Case Studies



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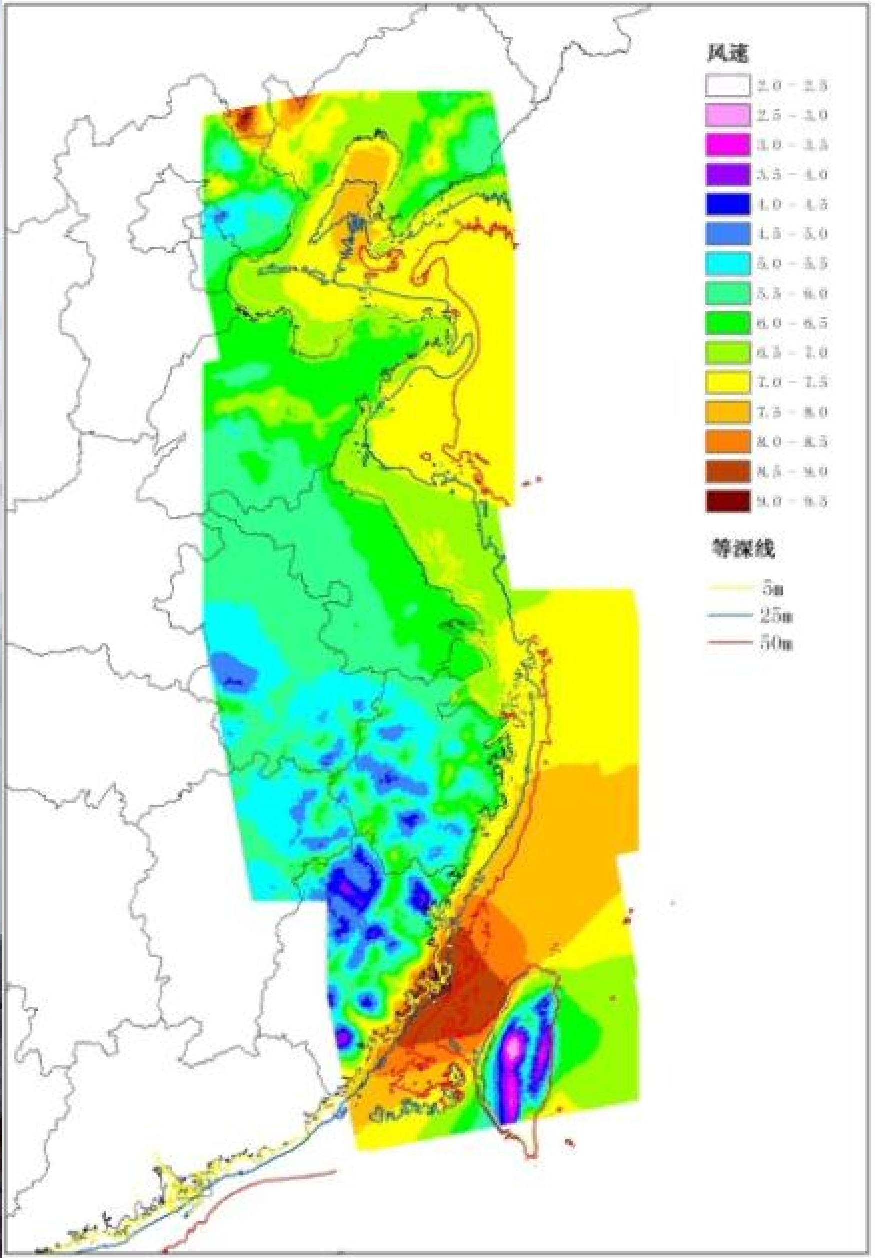
First Western designed wind farm in China

supporting Honiton Energy

Advising the Chinese government on offshore wind strategy

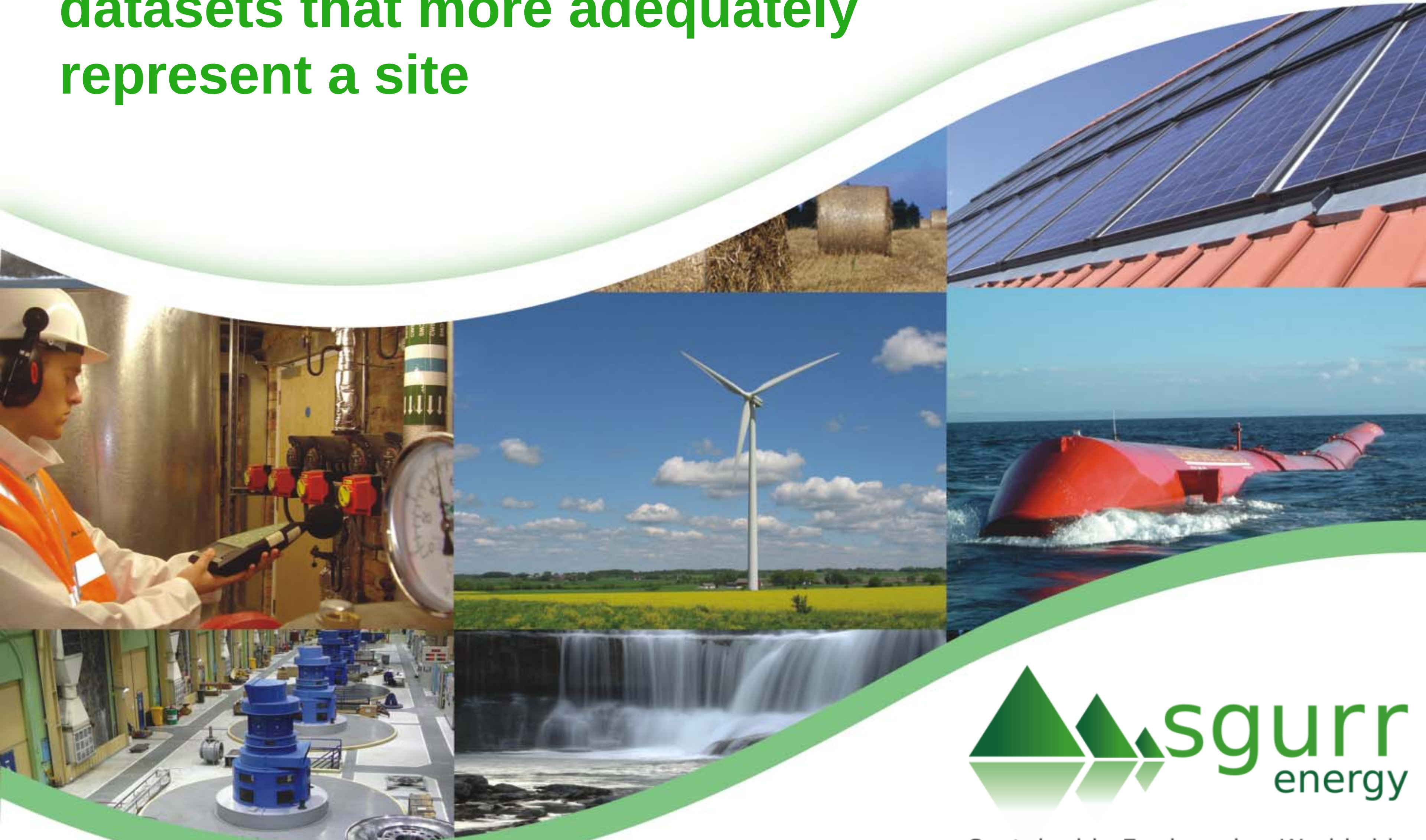


PV feasibility studies & outline design on 3 wind farms in India for Orb Energy

Advised SSE on £1.1bn acquisition of Airtricity's global portfolio across China and Europe

Global review of wave and tidal devices for a leading utility

Remote sensing: acquiring rich datasets that more adequately represent a site



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THE Sun

30p

STILL TIME TO JOIN IN

HOLS FROM £9.50

192 PARKS

3 OR 4 NIGHT BREAKS

COLLECT TOKEN PAGE 26

SAVE £5.50 OFF SHOPPING WITH Captain Crunch

VOUCHERS: SEE 4-PAGE PULLOUT

EXCLUSIVE

BEATRICE £15k CAR NICKED

SEE PAGE 7

MISSING BLADE RIDDLE

UFO HITS WIND TURBINE

4am prang at 300ft

A WIND turbine stood wrecked yesterday with one of its giant 65ft blades torn off — after it was hit by a UFO.

Clobbered .. turbine yesterday


AUG 25 2007

Design life

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- Wind characteristics influence not just productivity but also longevity

- Wind characteristics that can actually damage your asset include
  - Excessive turbulence arising from complex terrain and adjacent turbines
  - Shear and veer stressing blades and causing unbalanced loads
  - Flow inclination
  - Extreme wind speeds

Lidar

Mature technology, new application

Compact and portable for rapid and easy deployment

Acquires wind speed, direction, shear, veer, TI, and inclination data

Measures at proposed turbine locations and operational assets

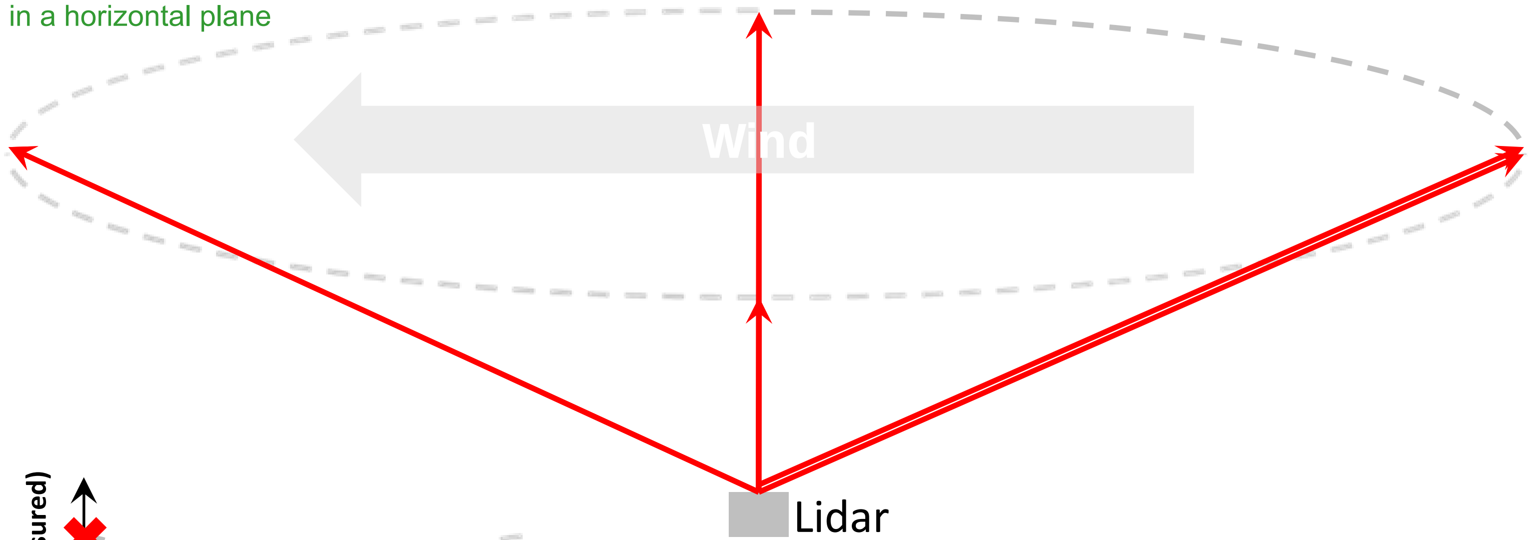
Wind resource assessment and model validation

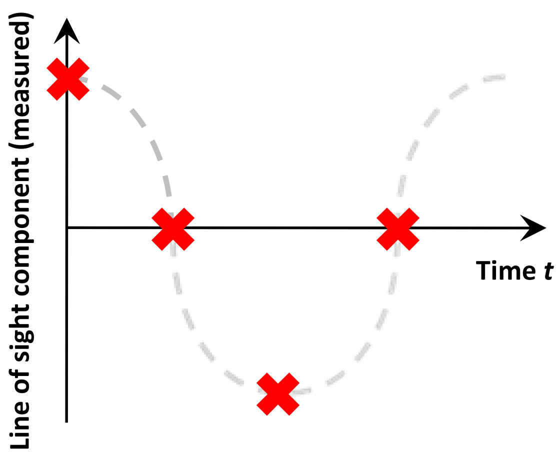
Performance monitoring and assessment of operational turbines

Conventional scan geometry

VAD scan geometry

Locus of measurement sites is
a circle in a horizontal plane

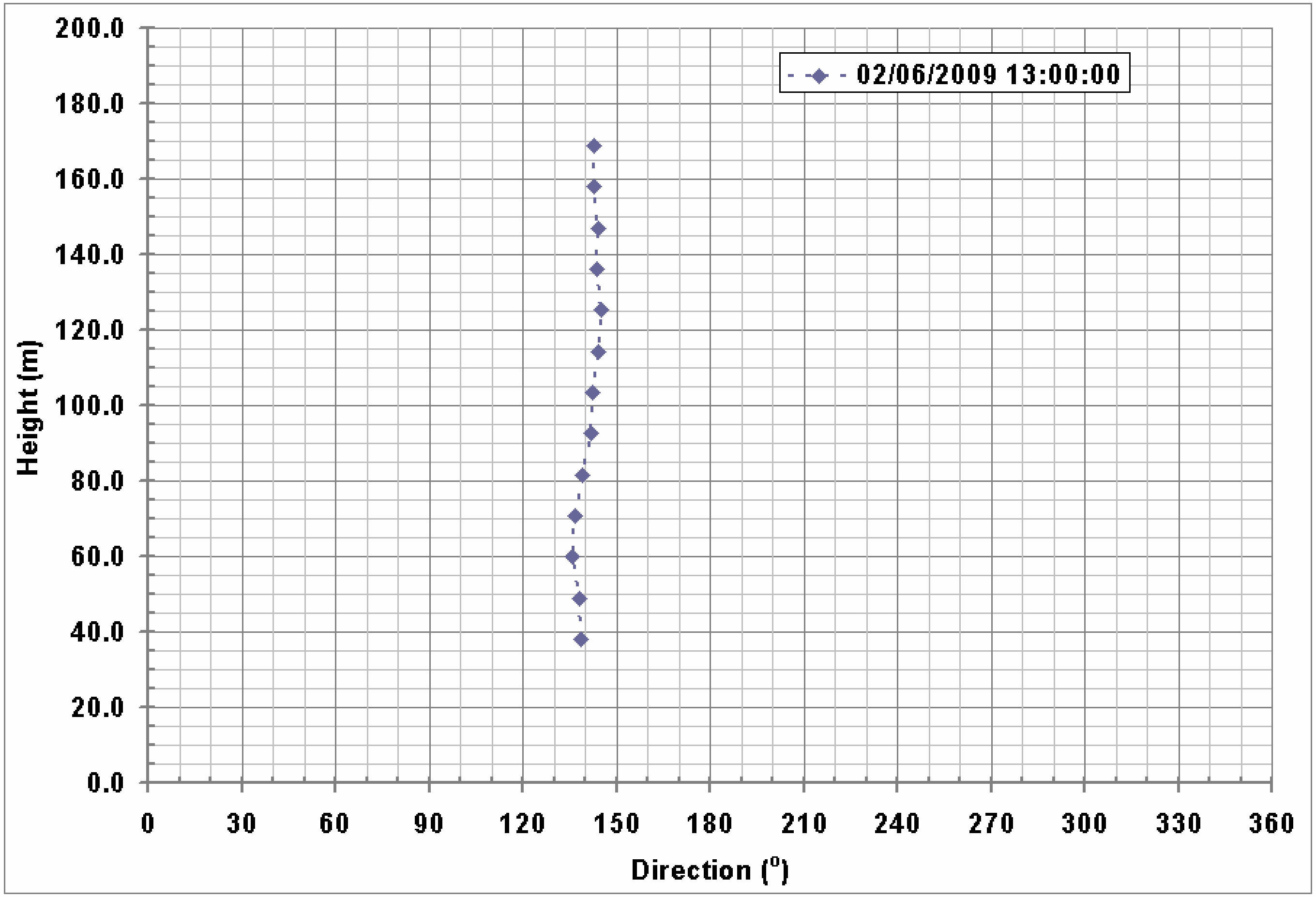




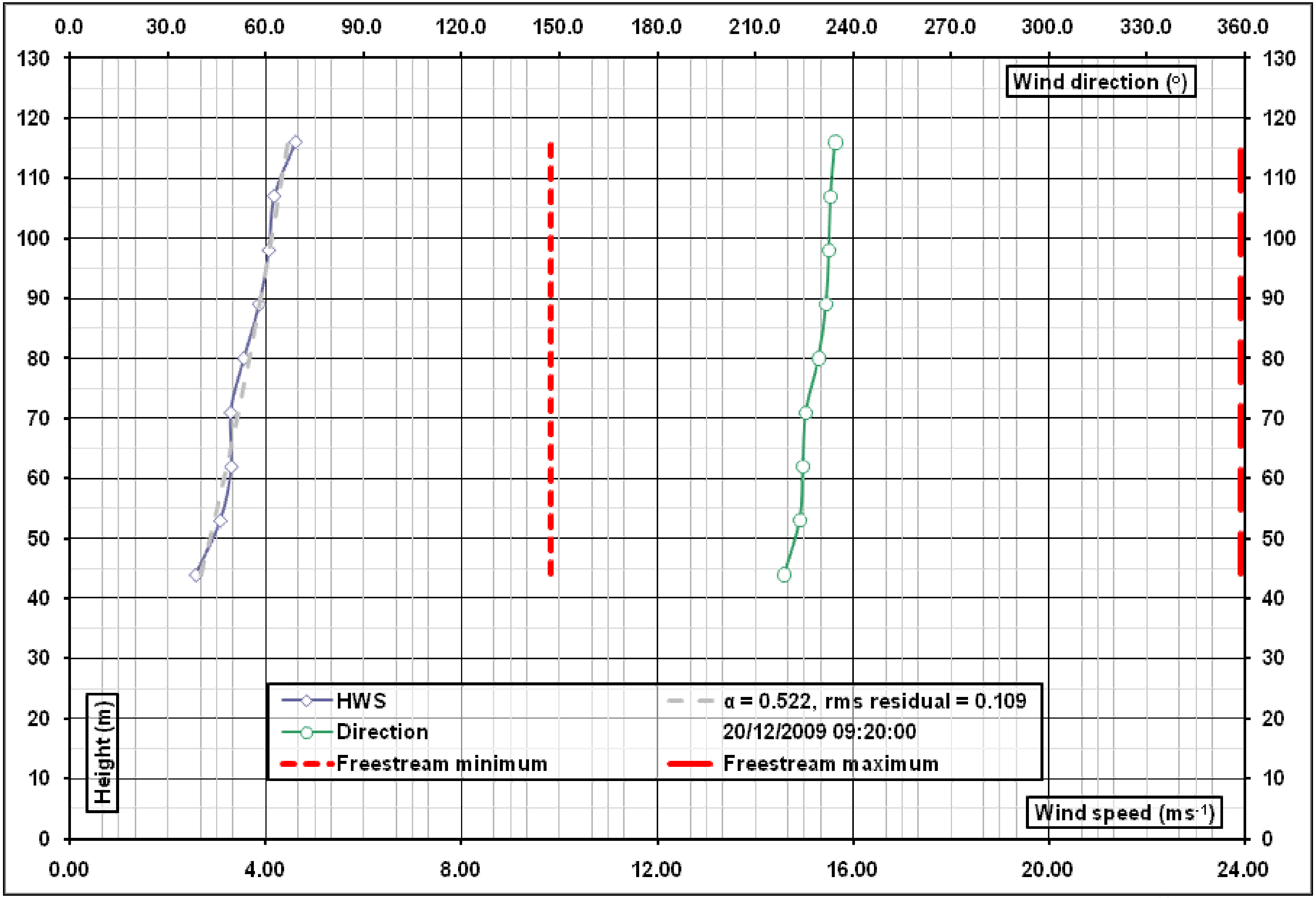
$$x = A \sin(\omega t + B) + C$$

A gives horizontal wind speed
B gives wind direction
C gives vertical wind speed

VAD - wind veer profiling

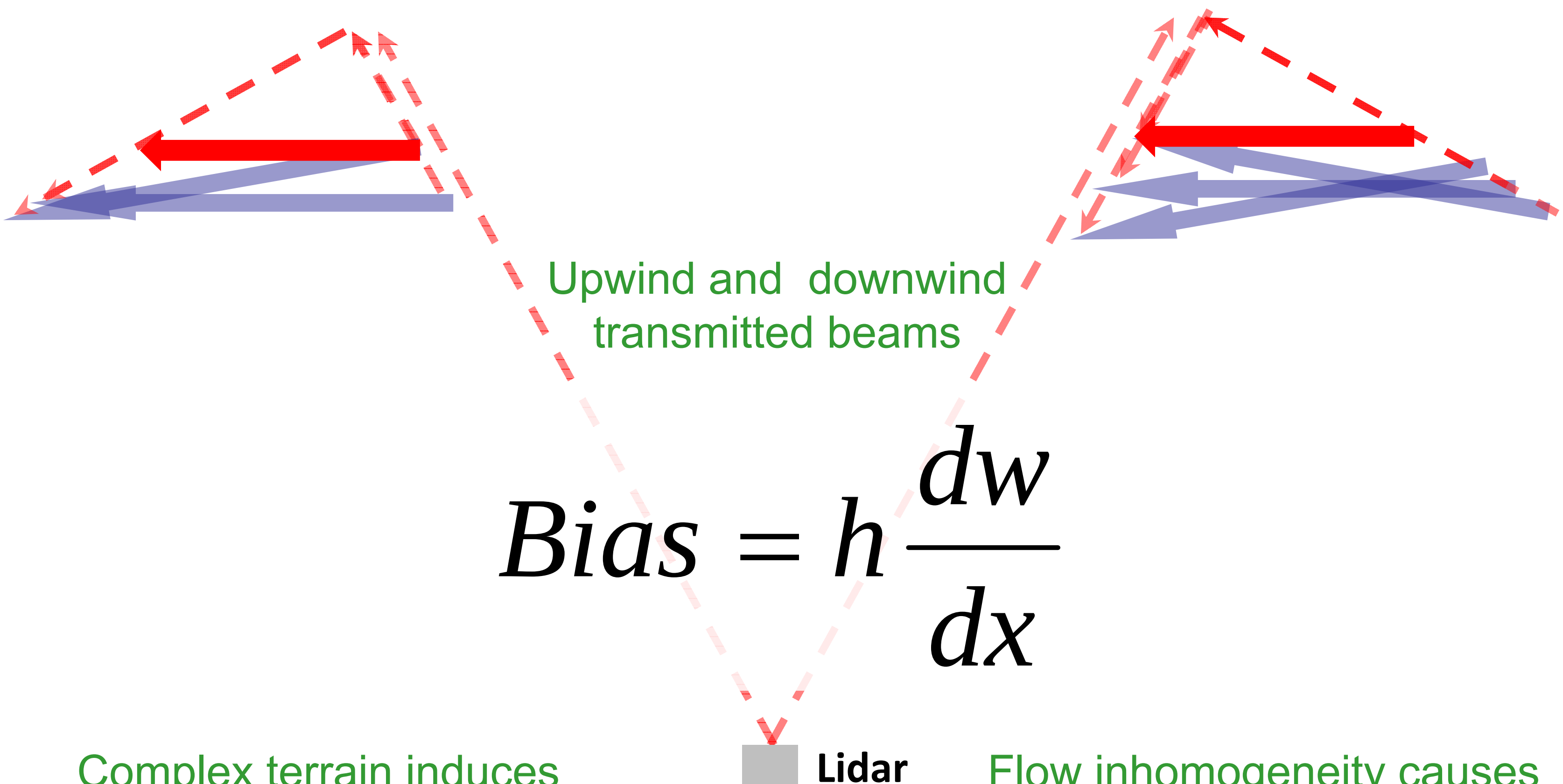


Wind Profiling



Complex terrain

Variable flow inclination



$$Bias = h\frac{dw}{dx}$$

Complex terrain induces flow inhomogeneity

Flow inhomogeneity causes bias in VAD results

2nd Generation Lidars

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- **Must implement scan geometries that mitigate issues that arise in complex terrain;**

- **2 degrees of scan freedom:**
  - **Arbitrary scan geometry;**
  - **Measurement volume not necessarily above the device;**
  - **Long range applications possible;**
  - **Pulsed beam necessary.**

Galion

Galion

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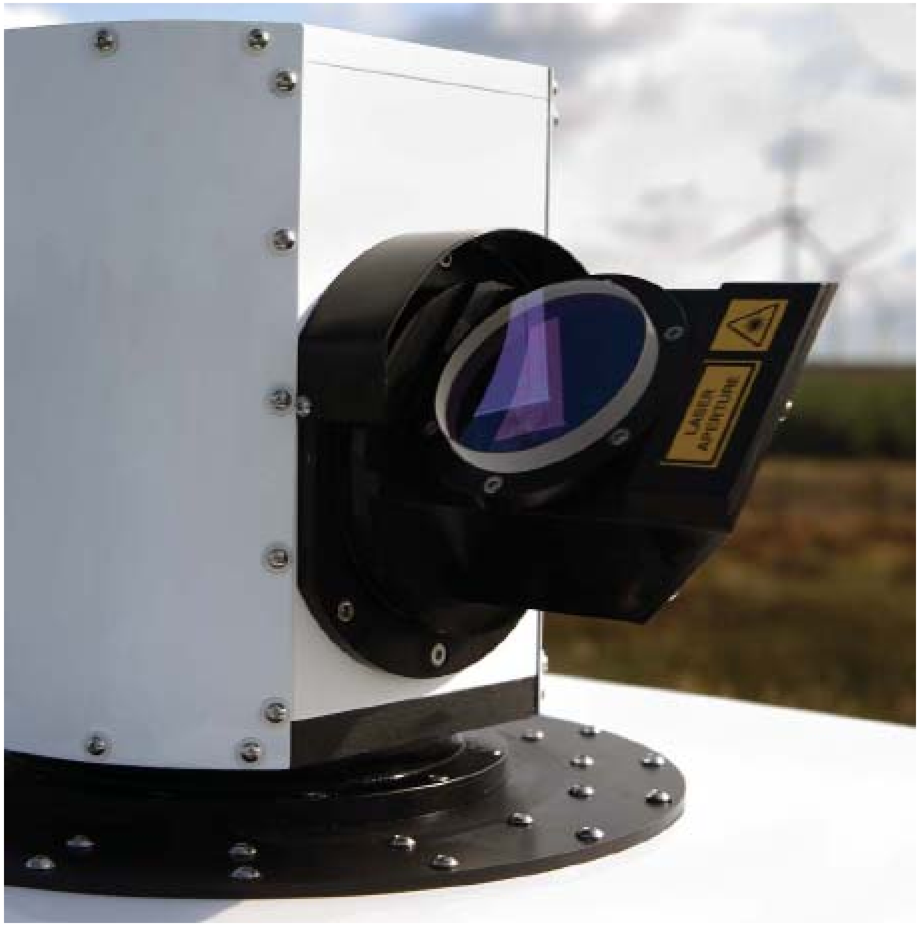
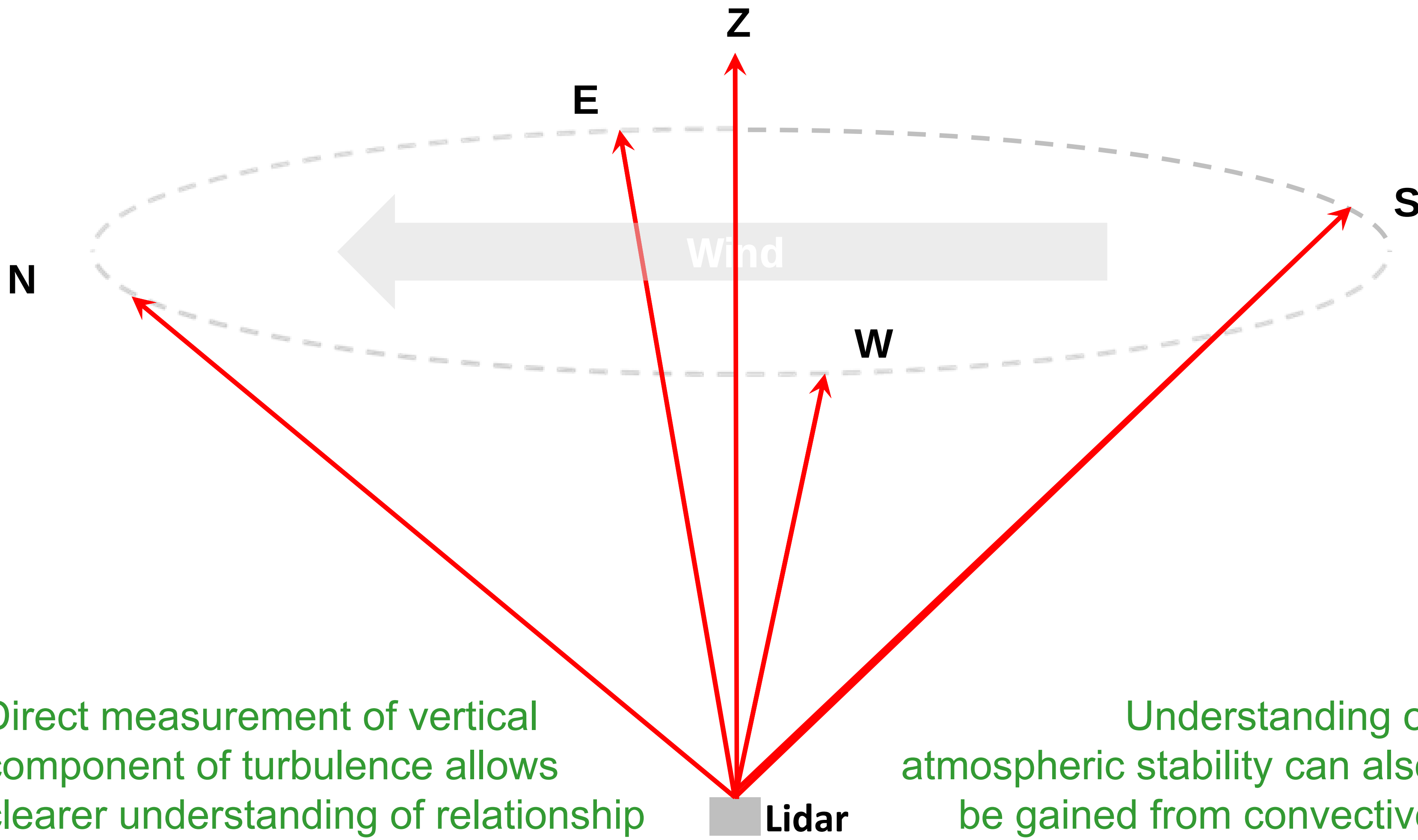
Galion™




Galion


5-Beam scan



Direct measurement of vertical component of turbulence allows clearer understanding of relationship between cup and Lidar TI measurements

Understanding of atmospheric stability can also be gained from convective structures and variance in w at multiple heights

Compound scan

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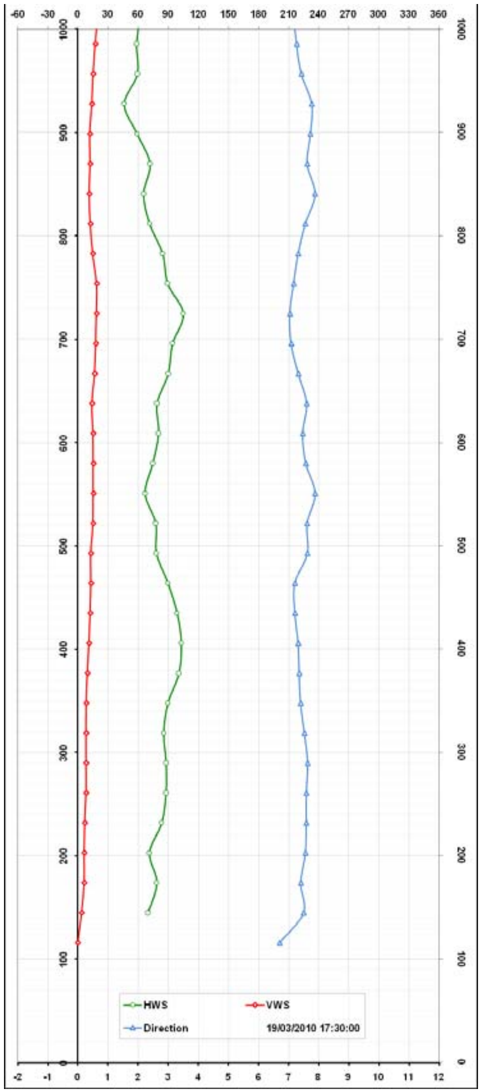
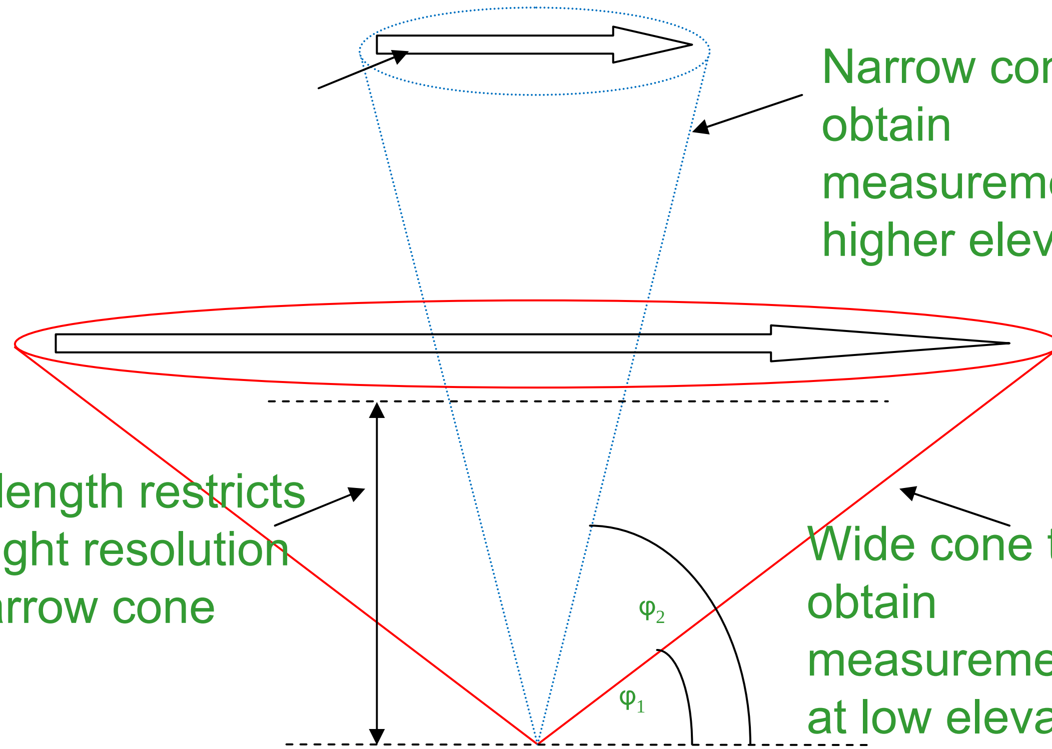




Narrow cone to obtain measurements at higher elevations

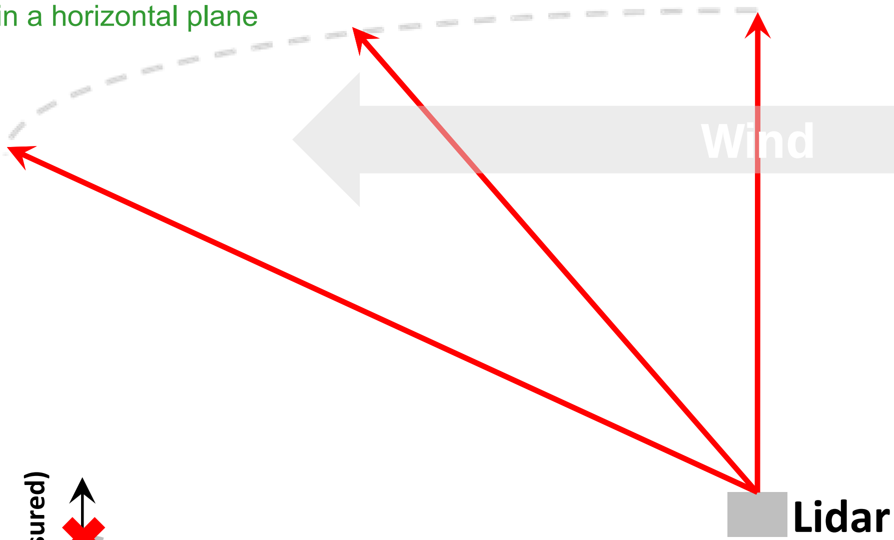
Probe length restricts low height resolution with narrow cone

Wide cone to obtain measurements at low elevations

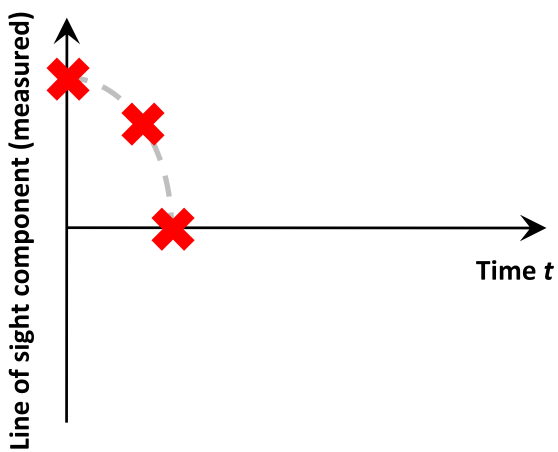
Arc scanning

Arc scan geometry

Locus of measurement sites is
an arc in a horizontal plane



You don't need 360° of azimuth to fit a sinusoid



$$x = A \sin(\omega t + B) + C$$

A gives horizontal wind speed
B gives wind direction
C gives vertical wind speed

Arc scanning

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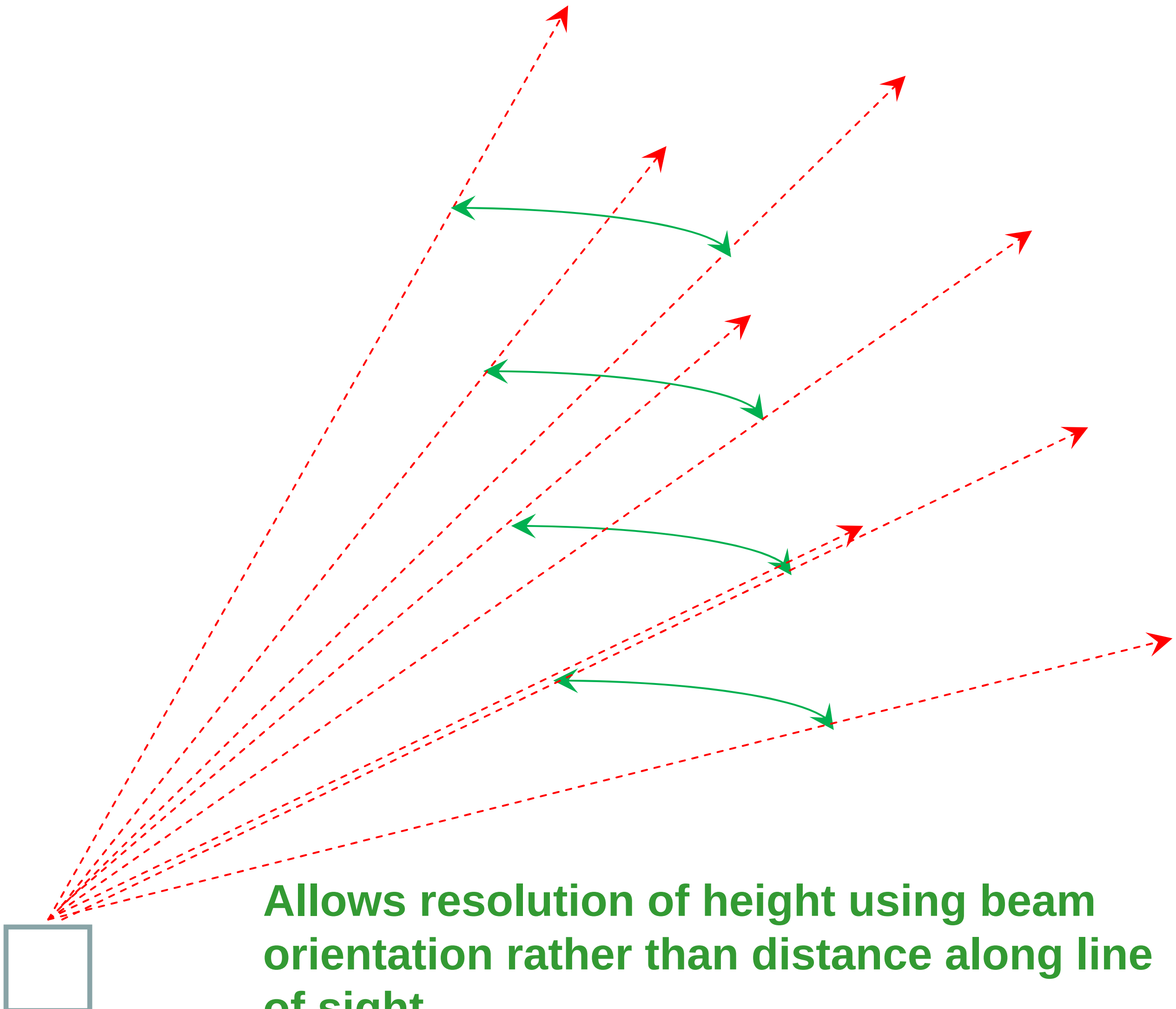
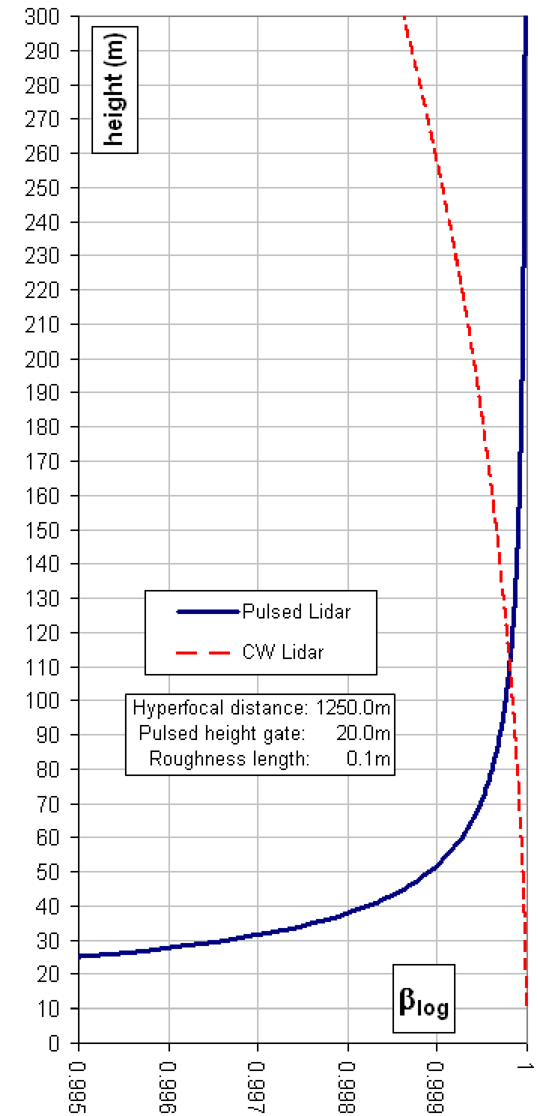
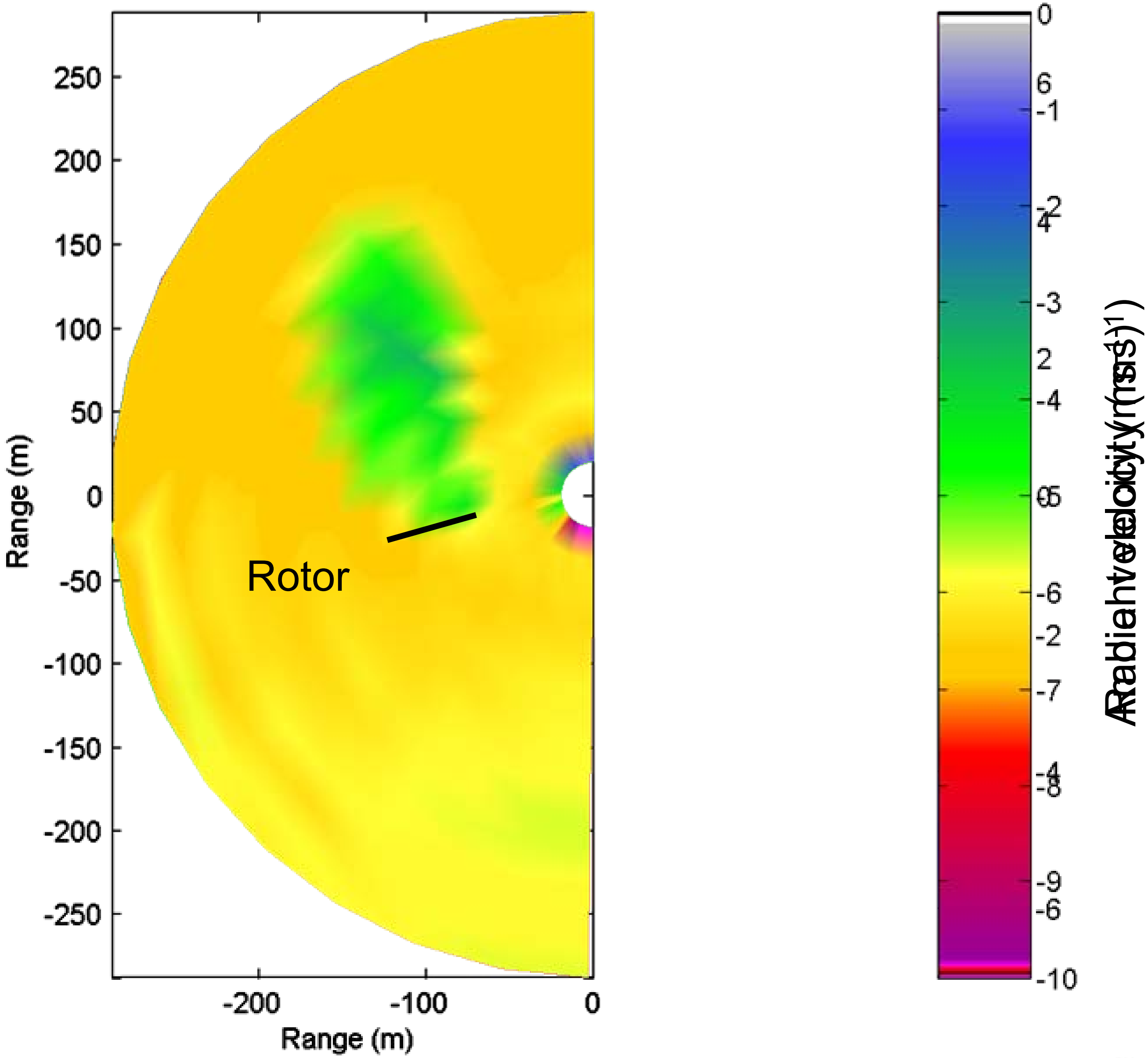


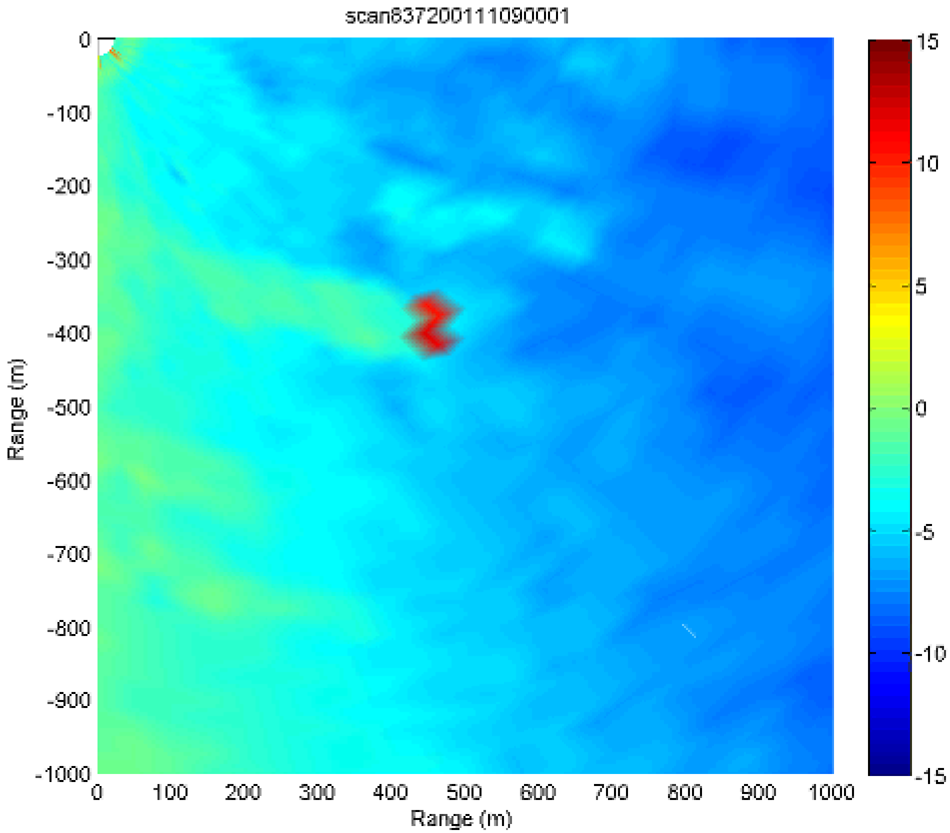


Allows resolution of height using beam orientation rather than distance along line of sight

PPI

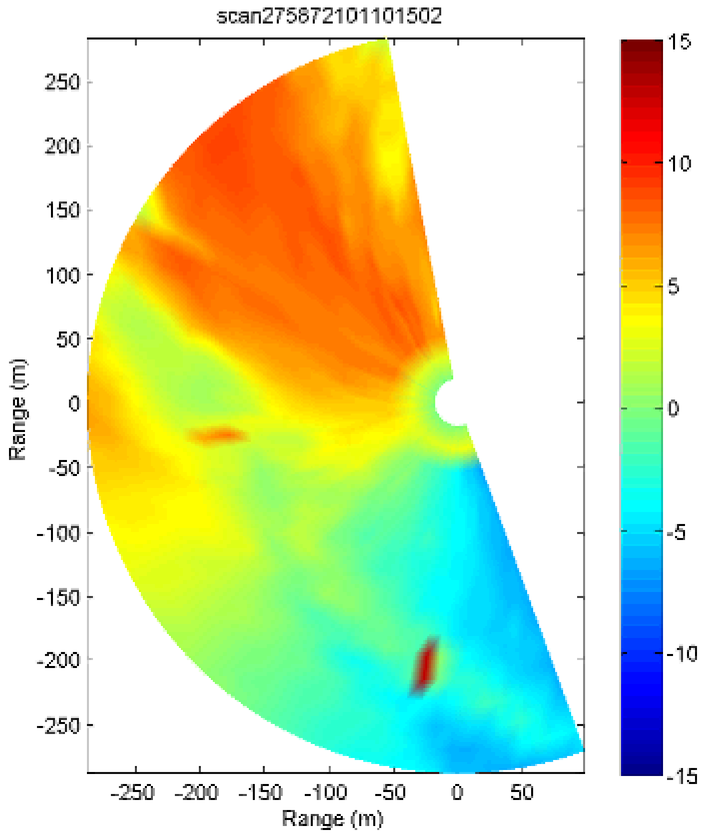

250
200
150
100
50
0
-50
-100
-150
-200
-250
Range (m)
-200
-100
0
Range (m)
Rotor
0
-10

PPI



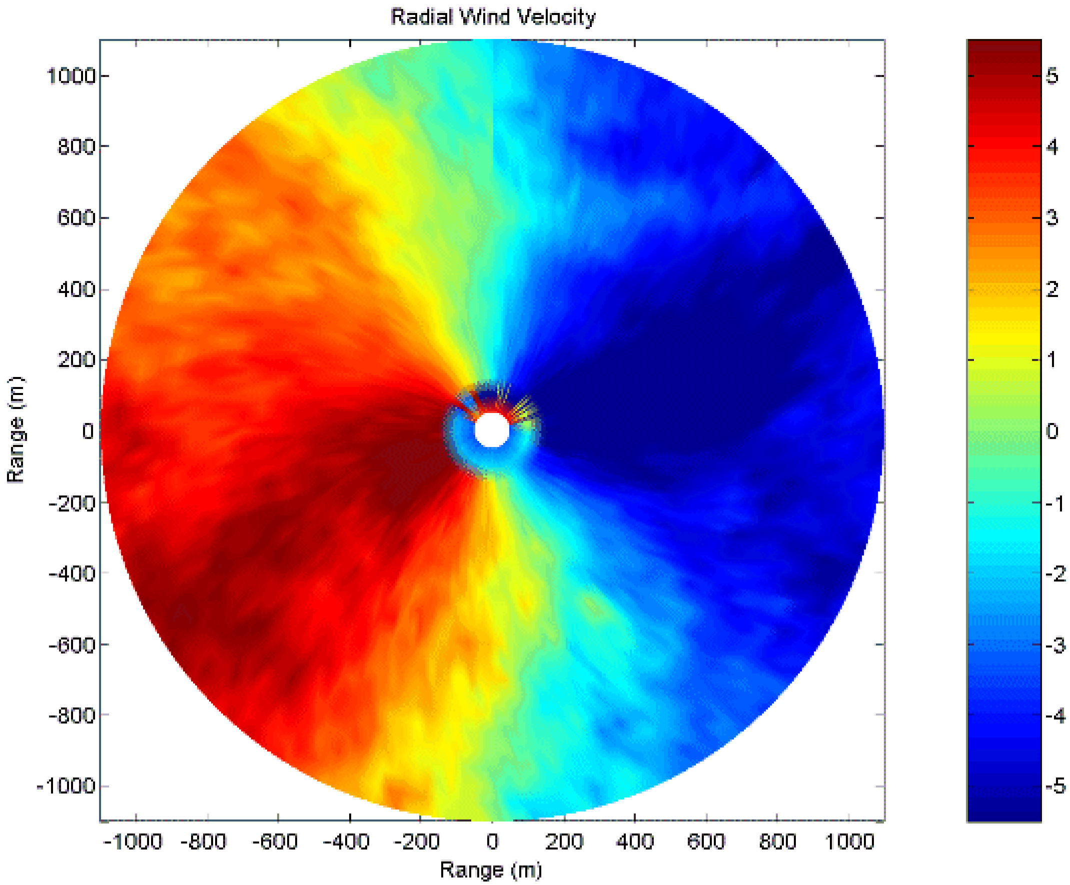
Galion installed at (0,0)
Radial velocities/line-of-sight data
Velocity deficits seen where turbine wakes intersect PPI

PPI



Galion installed at (0,0)
Radial velocities/line-of-sight data
Velocity deficits seen where turbine wakes intersect PPI

PPI


Radial Wind Velocity
1000
800
600
400
200
0
-200
-400
-600
-800
-1000
Range (m)
-1000 -800 -600 -400 -200 0 200 400 600 800 1000
Range (m)
5
4
3
2
1
0
-1
-2
-3
-4
-5

RHI

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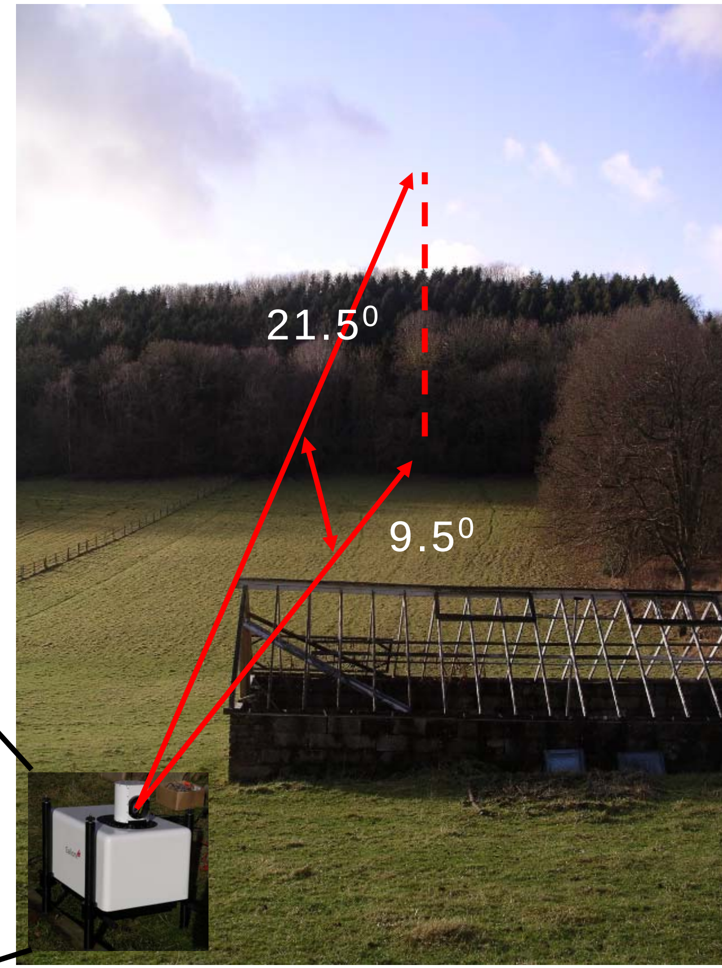
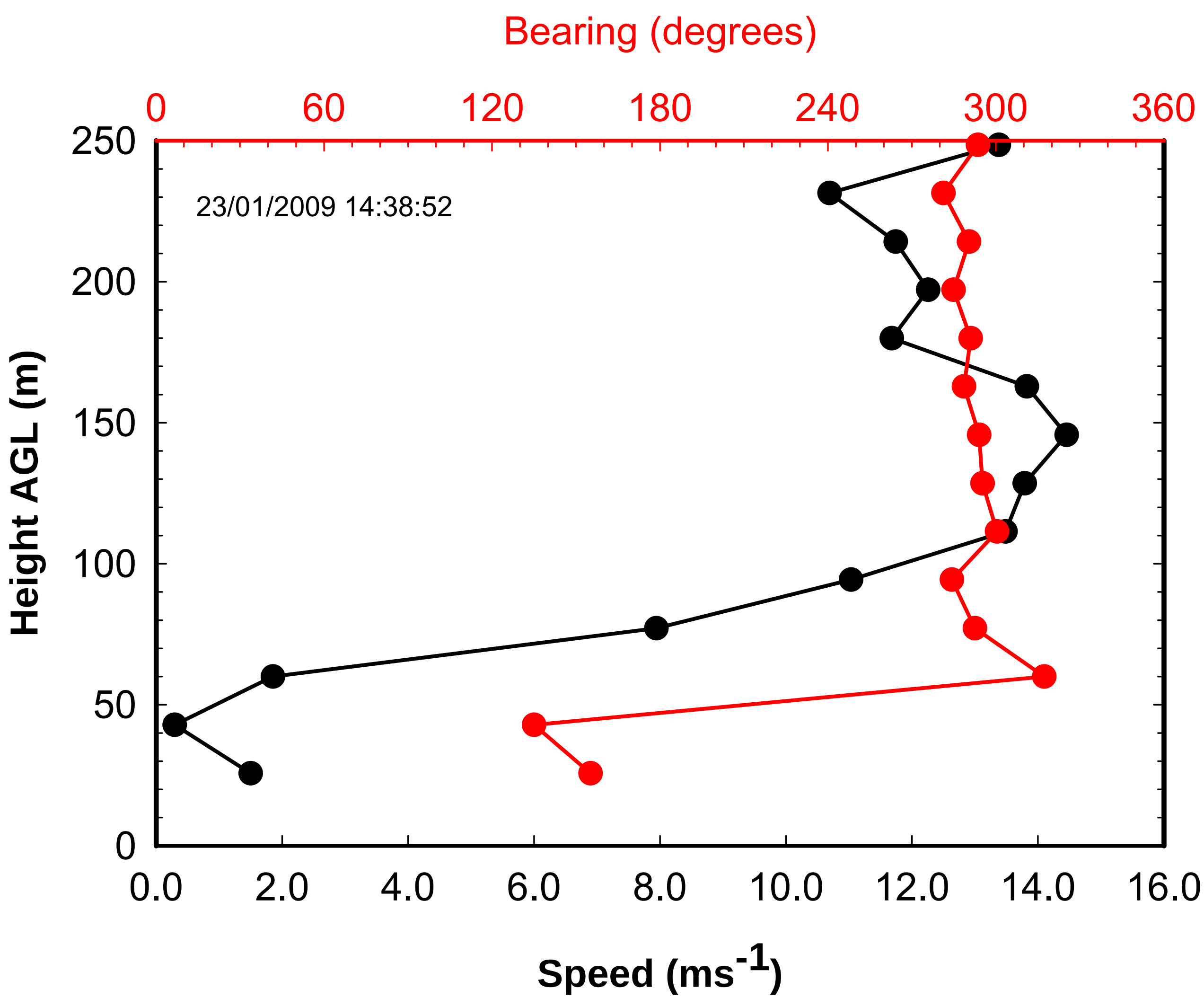
- Fixed azimuth (260^0), elevation scanned
- Each frame: 13 rays, 1 degree step, 30 sec per scan
- 16 frames
- Wind coming towards lidar over trees
- Clouds were scudding along but
  it was relatively calm down at the lidar

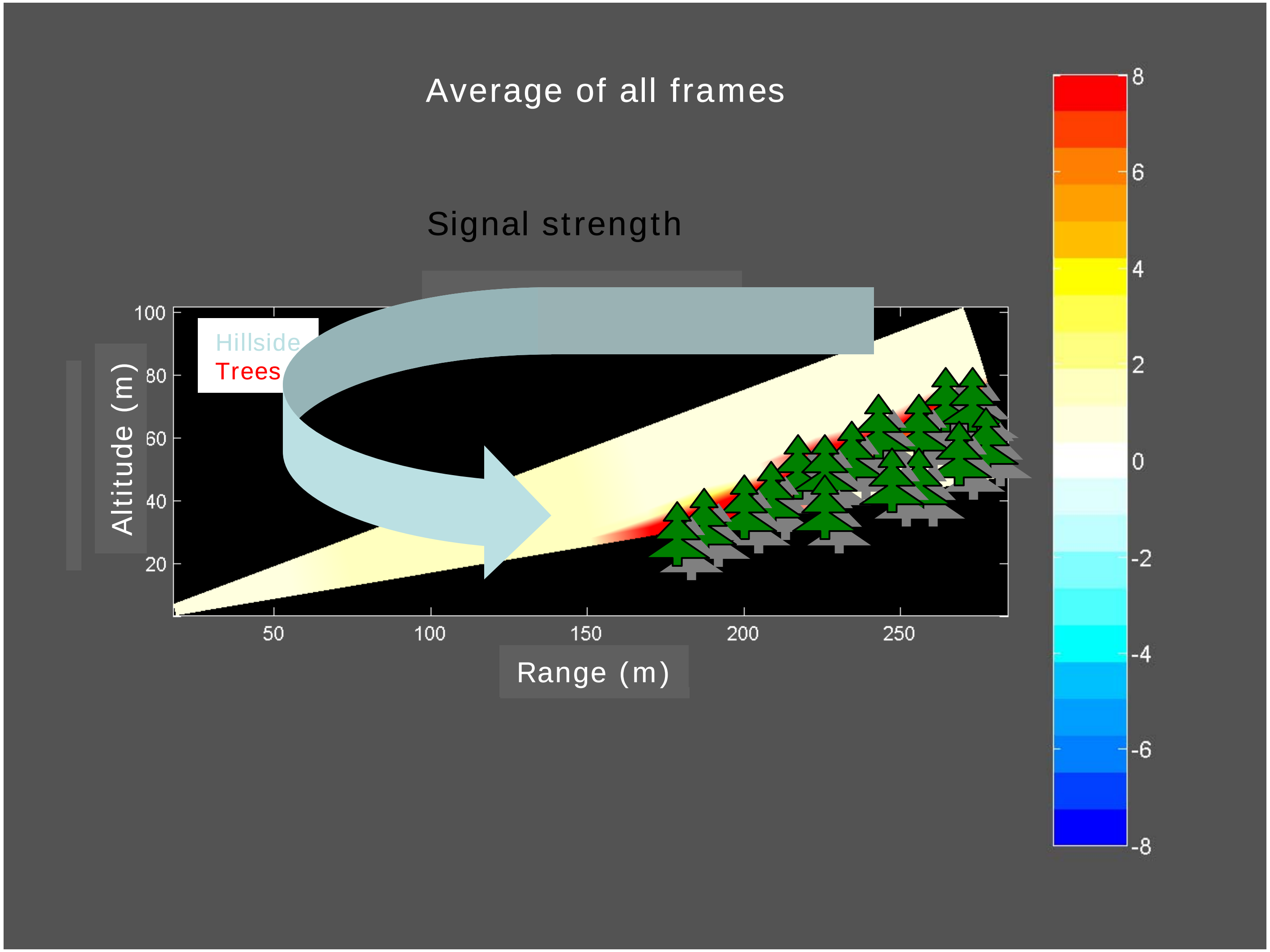


RHI

Wind profile taken at the end of the scan sequence



RHI


Average of all frames
Signal strength
Hillside
Trees
Altitude (m)
Range (m)
100
80
60
40
20
50
100
150
200
250
8
6
4
2
0
-2
-4
-6
-8

Is remote sensing bankable?

Bankability depends on being able to quantify uncertainty, not on the specific instruments used.

- Compliance with the articles of the Boulder Protocol* should ensure that the contribution of remote sensing to project uncertainty is understood and can be represented in the project P90.

- Every instrument :
  - Introduces uncertainty as a result of measurement errors;
  - Removes uncertainty by virtue of the data acquired.

  This includes conventional cup anemometry.

*Proposed at the IEA Wind Energy Task 11 Topical Expert Meeting on Remote Sensing of the Wind held in Boulder, Colorado in October 2009

Overview

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Understand how your wind turbine will operate
- Mechanical fatigue loading
- Performance assessment

Wind turbine performance

Input
- Wind shear
- Wind veer
- Flow inclination
- Turbulence
- Etc

System condition
- Gearbox
- Controller
- LRUs
- Sub-LRUs
- Etc.

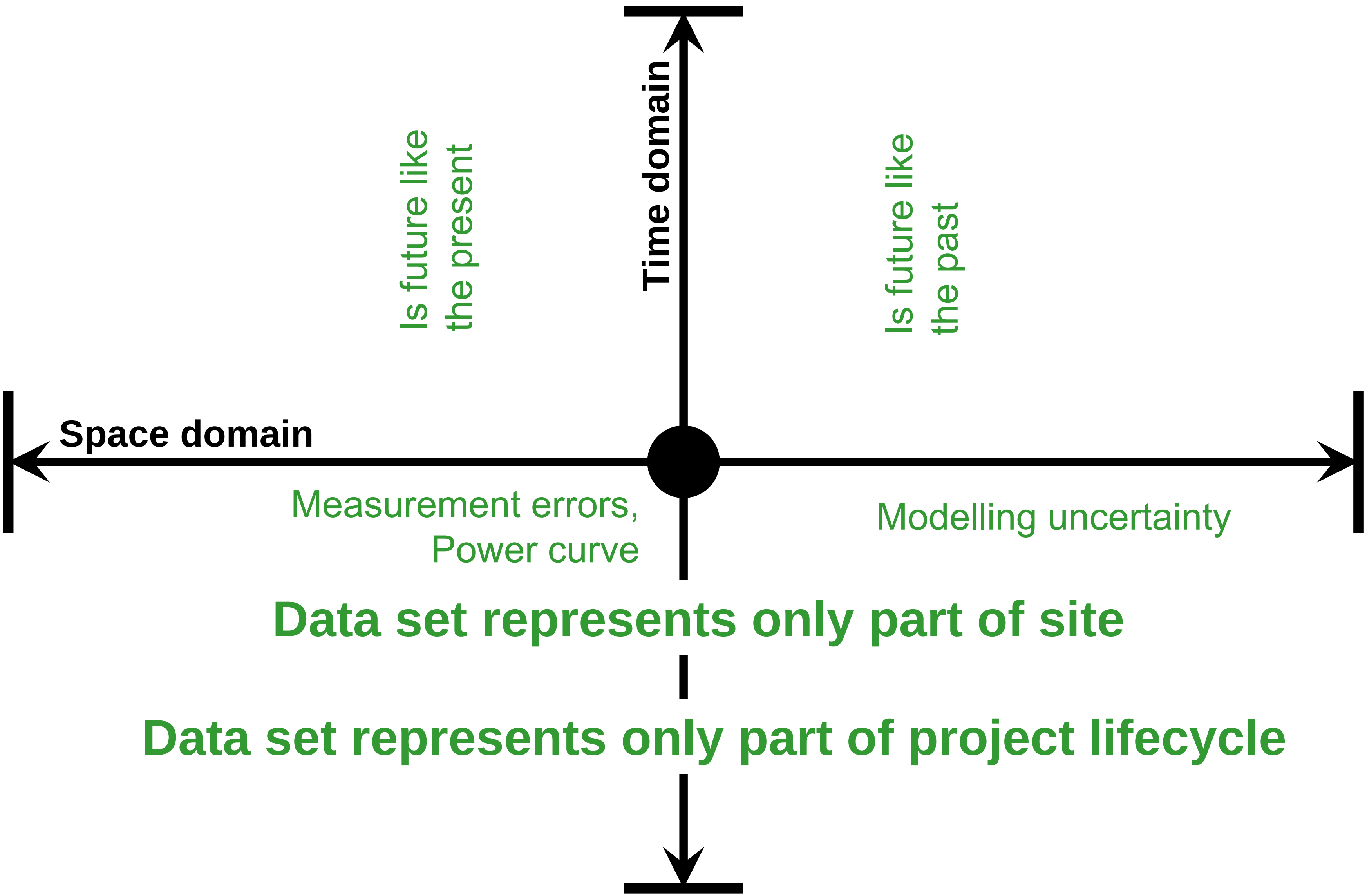
Output
- Energy yield
- Alarms
- Pitch/yaw
- Reactive power
- Etc.

Lidar improves understanding here (c.f. current nacelle anemometry)

Condition monitoring

Response deficit analysis improves understanding Here (e.g. sgurr***trend***)

Uncertainty model



Sources of uncertainty affecting energy

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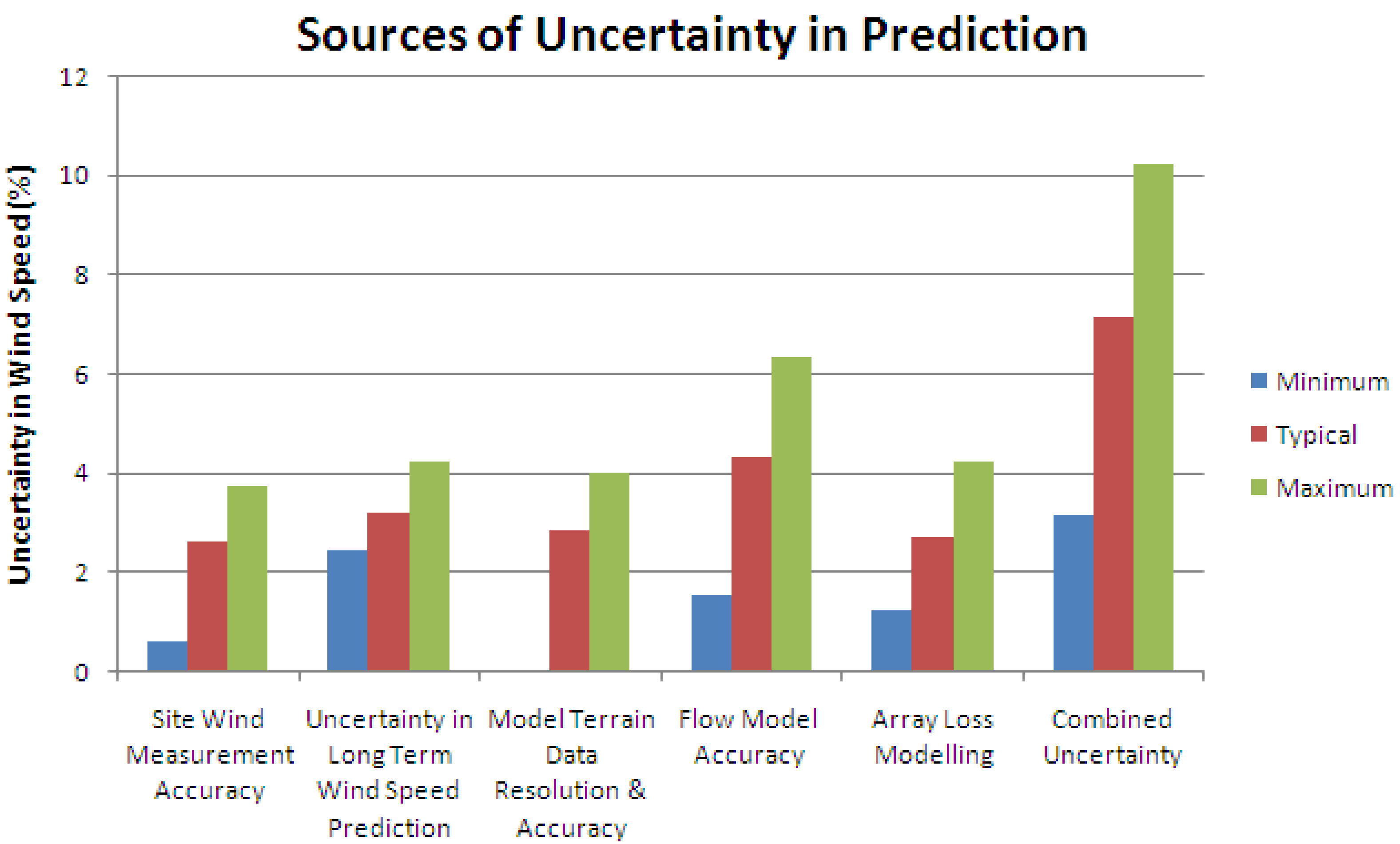
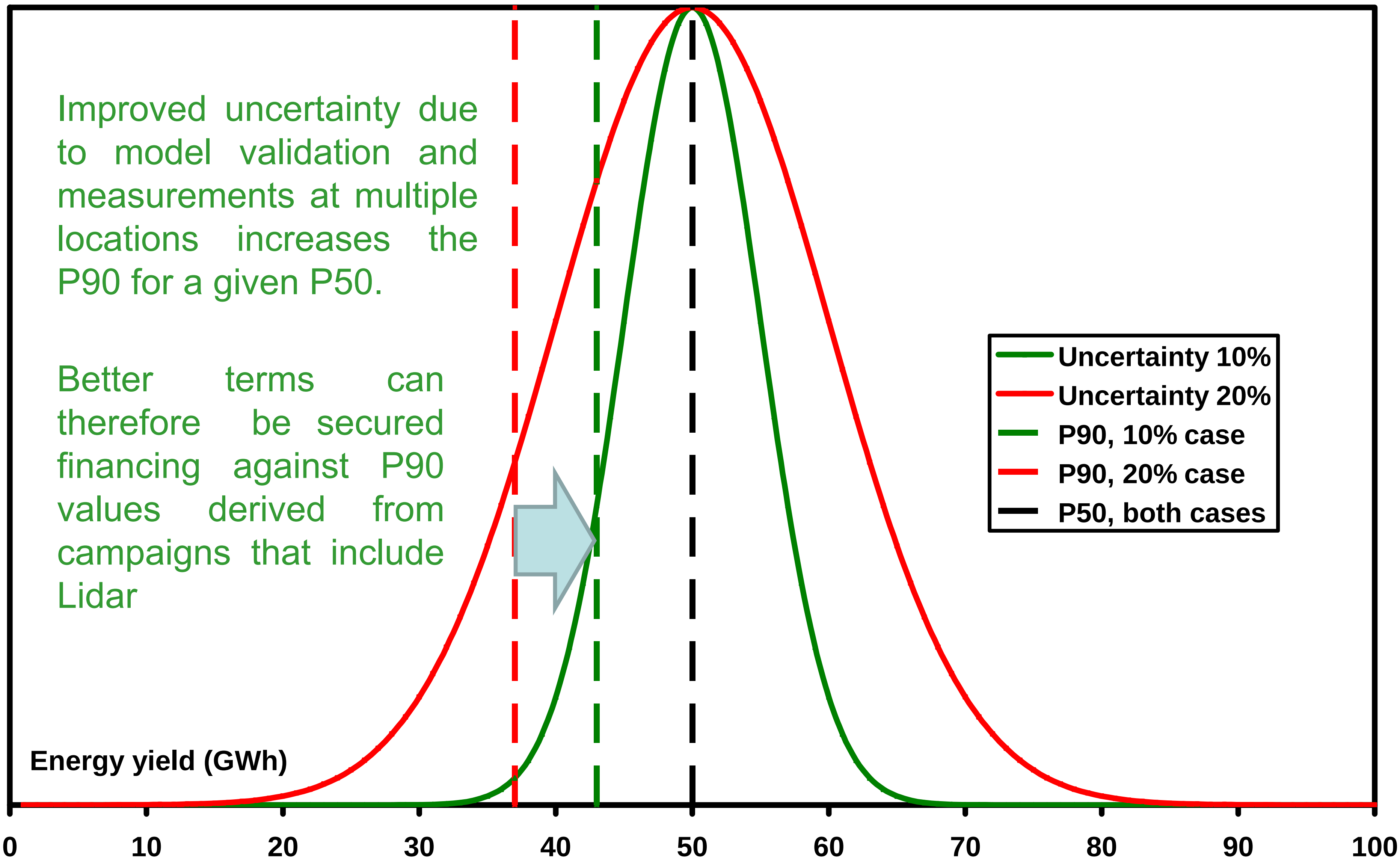


Benefit of reducing uncertainty

Improved uncertainty due to model validation and measurements at multiple locations increases the P90 for a given P50.

Better terms can therefore be secured financing against P90 values derived from campaigns that include Lidar



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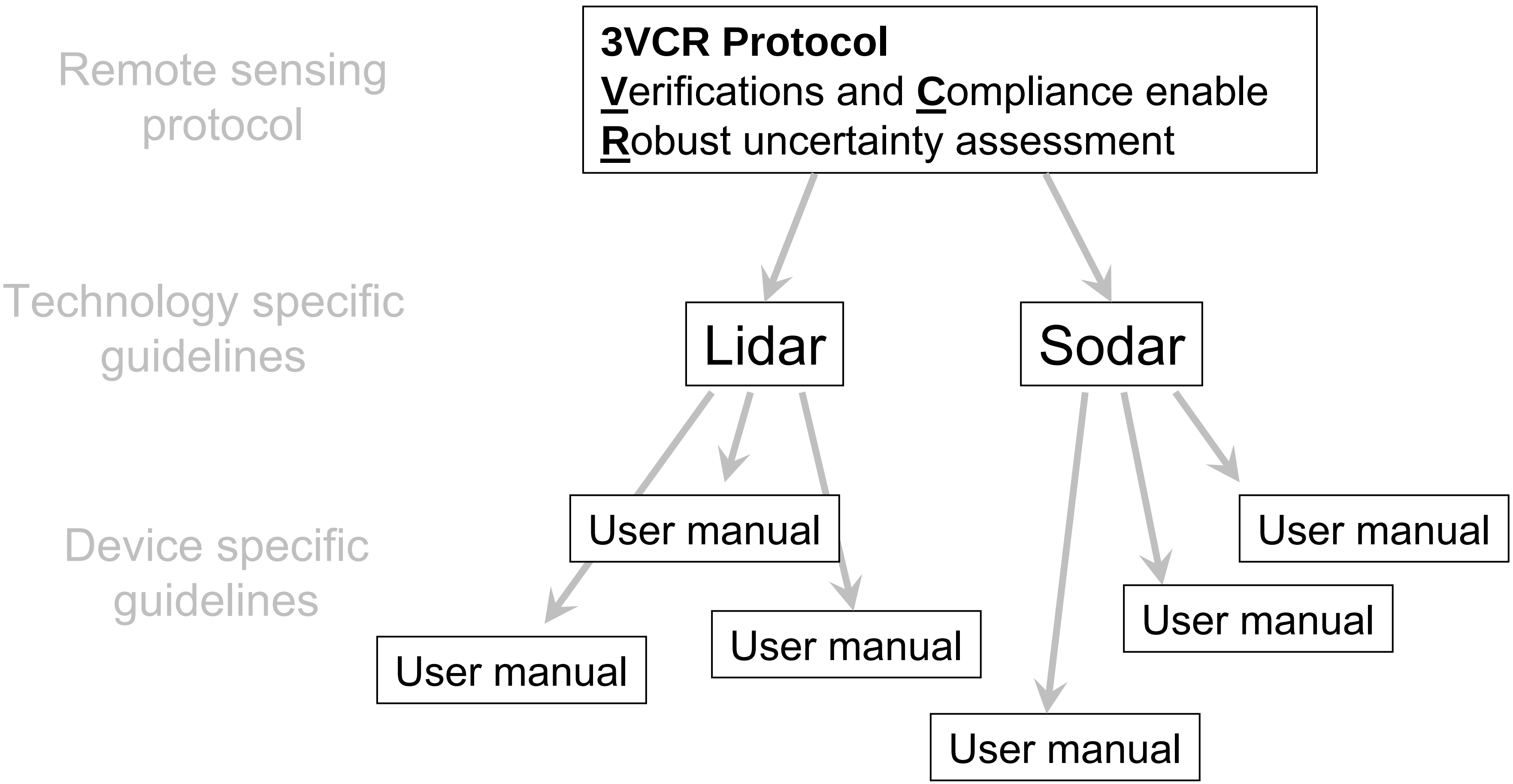
IEA Hierarchical Recommendations



Boulder Protocol

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Memorandum: Remote Sensing Data Acceptability Criteria
Remote sensing devices, including commercially available Sodars and Lidars developed for wind power applications, are considered to be an acceptable source of data for use in a wind power investigation such as, but not limited to

- undertaking a quantitative assessment of wind resource to which reference may be made when setting the terms for raising finance for a project to exploit that wind resource for power generation;
- acquiring wind inflow information in relation to the assessment of the performance of operational wind power assets in response to inflow conditions;

under the following conditions. All stated examples are illustrative only.

0: General Requirements
A preliminary requirement is that the data is acquired during a measurement campaign that in all respects additional to those pertaining specifically to remote sensing is well designed and is fit for purpose. For example, compliance with relevant standards and guidelines has been

2.1: Methodology is adequately documented to ensure repeatability of the measurements. The statement of the methodology details any dependence of device performance on the prevailing conditions. For example, the impact of flow inhomogeneity in the volume penetrated by the remote sensing measurements and the influence of other parameters such as temperature is described.

3: Verification of Conditions
The conditions prevailing during the element of the measurement campaign in which the device is operated to acquire data for the wind power investigation are considered sufficiently similar to those prevailing during the performance verification period that a divergence in the performance of the device from the performance observed during performance verification would not be expected.

3.1: The influence of the deviation of conditions during the measurement campaign from the conditions during the verification period is understood sufficiently to enable remote sensing measurement uncertainties and biases arising as a result to be reported and adequately

5: Compliance with IEA Guidelines

The specific remote sensing technology, such as Sodar and Lidar, adopted for the purposes of the wind power investigation, is operated in compliance with the most current IEA Guidelines for Best Practice published in relation to the technology, as formulated by the relevant IEA Topical Expert Committees.

1.3: The degrees of concurrency and co-location are those that enable the most precise and well understood relationship between the device and reference measurements to be determined. So, for example,

- The same averaging intervals are used for the device and reference datasets being compared;
- Regression methodologies accommodate errors in all instruments;
- The device is sited and analysis of the measurements conducted in a manner that minimises extraneous influences such as
  - flow perturbations;
  - fixed echoes;
  - real variations in the flow between the device and reference instrument measurement locations;
  - divergent levels of data coverage within averaging intervals.

1.4: The verification exercise has been conducted recently enough for its results still to be valid.

2: Verification of Methodology
The element of the measurement campaign in which the device is operated to acquire data for the wind power investigation is conducted according to the methodology adopted during performance verification.

investigation;

- The uncertainty analysis on which the percentiles chosen to represent the long term productivity available to service debt - such as, for example, the P90 against which the finance is secured - is based on an uncertainty analysis that adequately represents the measurements and methods employed during the assessment of the long term productivity of the project.

5: Compliance with IEA Guidelines
The specific remote sensing technology, such as Sodar and Lidar, adopted for the purposes of the wind power investigation, is operated in compliance with the most current IEA Guidelines for Best Practice published in relation to the technology, as formulated by the relevant IEA Topical Expert Committees.

5.1: Guidelines for Best Practice with Lidar and Sodar are presented in separate documents.

Example: NorseWind acceptance criteria

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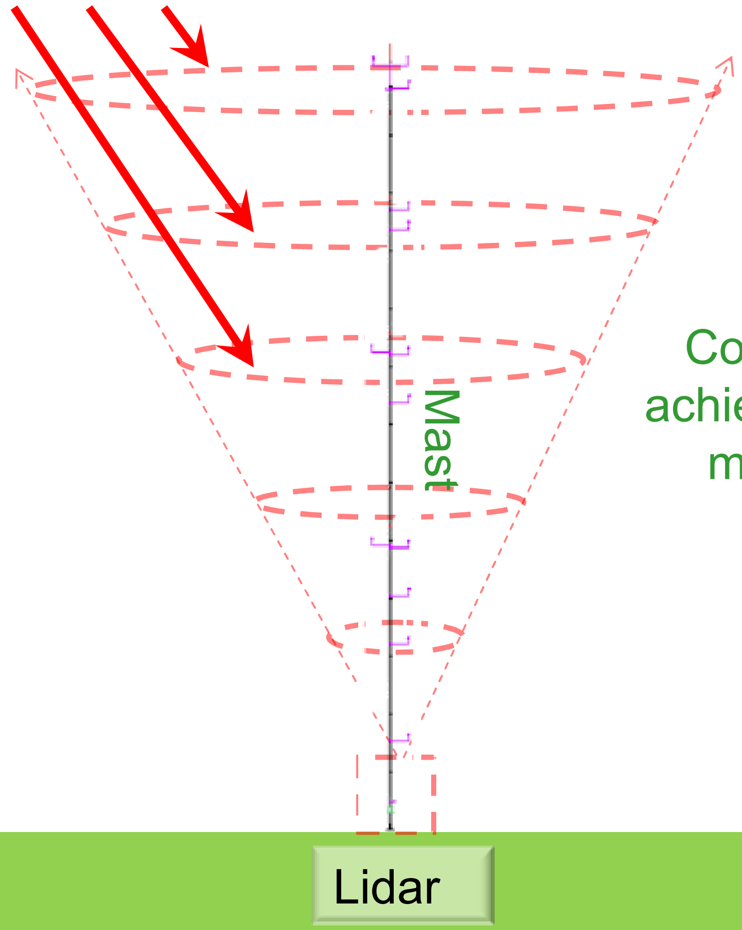
NorseWind Criteria

Parameter	Criteria	Sub-Ranges (height & speed)
Absolute error	<0.5m/s; Not more than 10% of data to exceed this value	All valid data
Data Availability	Assessed case by case – Environmental conditions dependent	All valid data
Linear Regression - Slope	Between 0.98 and 1.01 <0.015 variation in slope	All heights 4-8m/s & 8-12 m/s
Linear Regression – R^2	>0.98	All heights 4-8m/s & 8-12m/s

Source: "Testing and calibration of various Lidar remote sensing devices for a 2 year offshore wind measurement campaign"; D Kindler, M Courtney, and A Oldroyd; European Wind Energy Conference, Marseilles, France, 2009

NorseWind Criteria

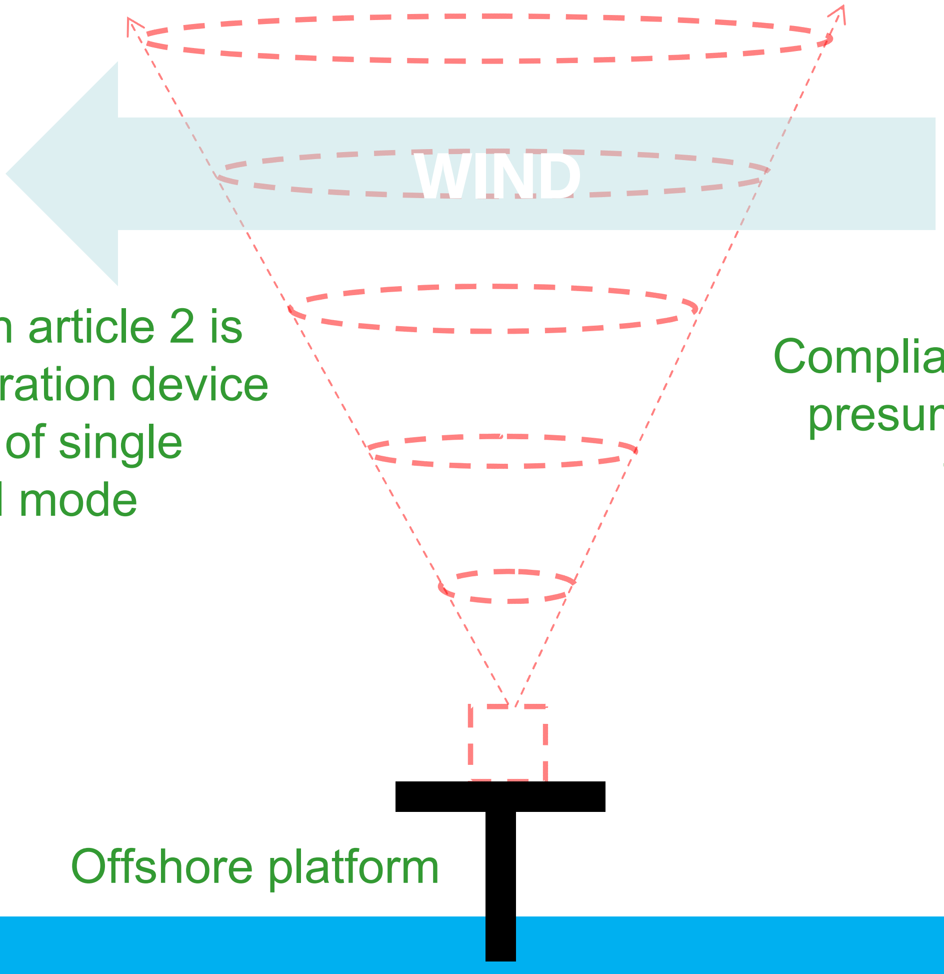
Lidar measurements acquired at heights where mast is instrumented



Compliance with article 1 achieved by comparing Lidar measurements to mast measurements

NorseWind Criteria

Compliance with article 2 is trivial as 1st generation device only capable of single operational mode



Compliance with article 3 is presumed due to lack of topography

NorseWind Criteria

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1. Criteria developed for testing devices used in the NorseWind project;

2. The criteria stipulate performance levels to be achieved when verifying performance in compliance with article 1;

3. The criteria only apply to 1st generation devices with a single mode of operation, which therefore trivially comply with article 2 as a result of their intrinsic limitations;

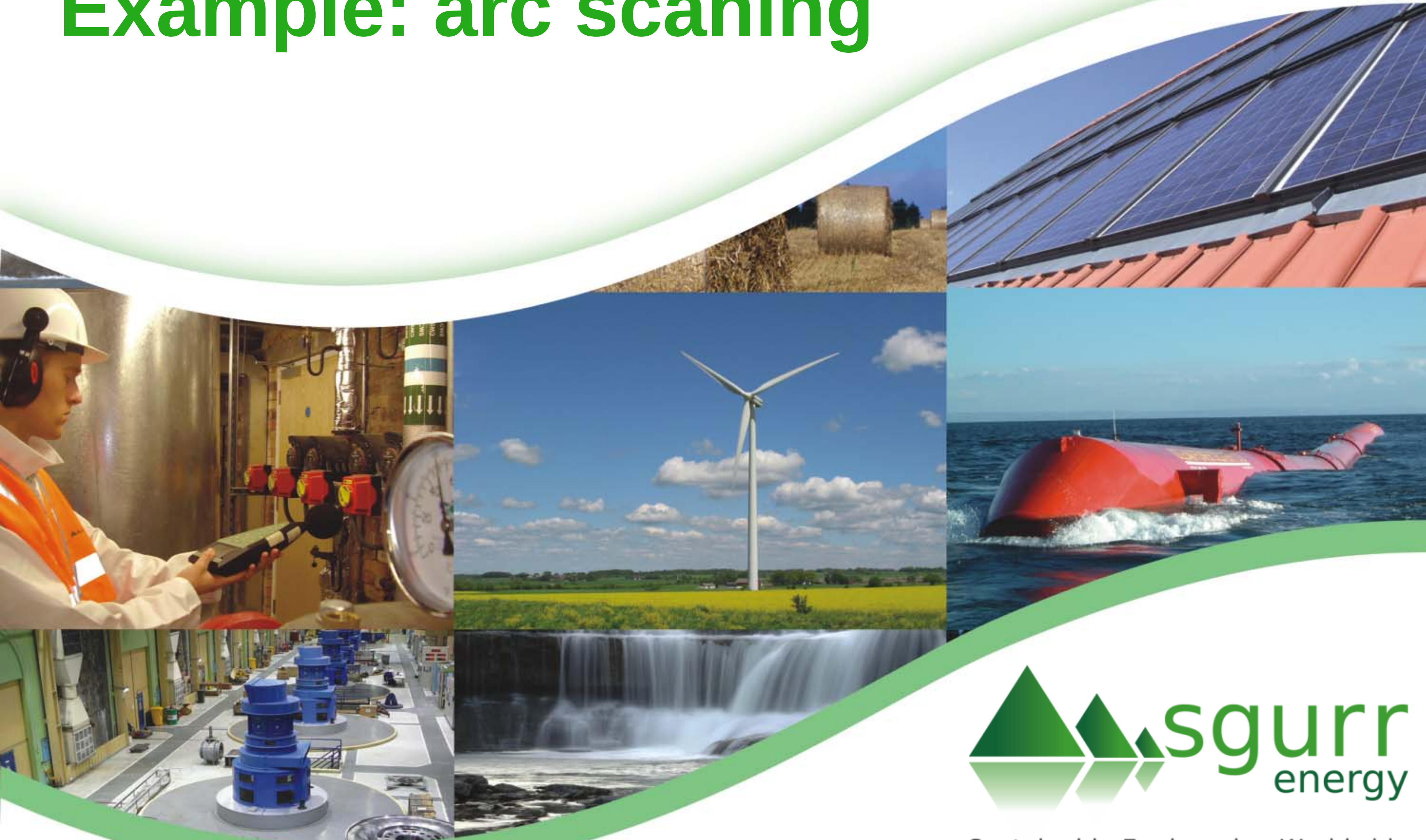
4. Performance levels which satisfy the criteria do *not* demonstrate compliance with article 3. This must be established separately, for example, by limiting the use of devices to locations in simple terrain similar to the test sites where performance was verified;

5. The criteria are weak and designed to enable the acceptance of continuous wave devices[1]: observed performance levels of pulsed Lidars such as Galions are generally well within the limits set[2].

[1] c.f. the acceptance criteria listed in "Practical experience with remote sensing: a consultancy perspective"; N Douglas, IEA 51st Topical Expert Meeting, Roskilde, Denmark, 2007

[2] See "Verification of the SgurrEnergy Galion Lidar using mast mounted instruments"; J Gottschall, P Lindelöw-Marsden, M Courtney; Risø report no. ex. Risø-I-2898 (EN), August 2009

Example: arc scaning



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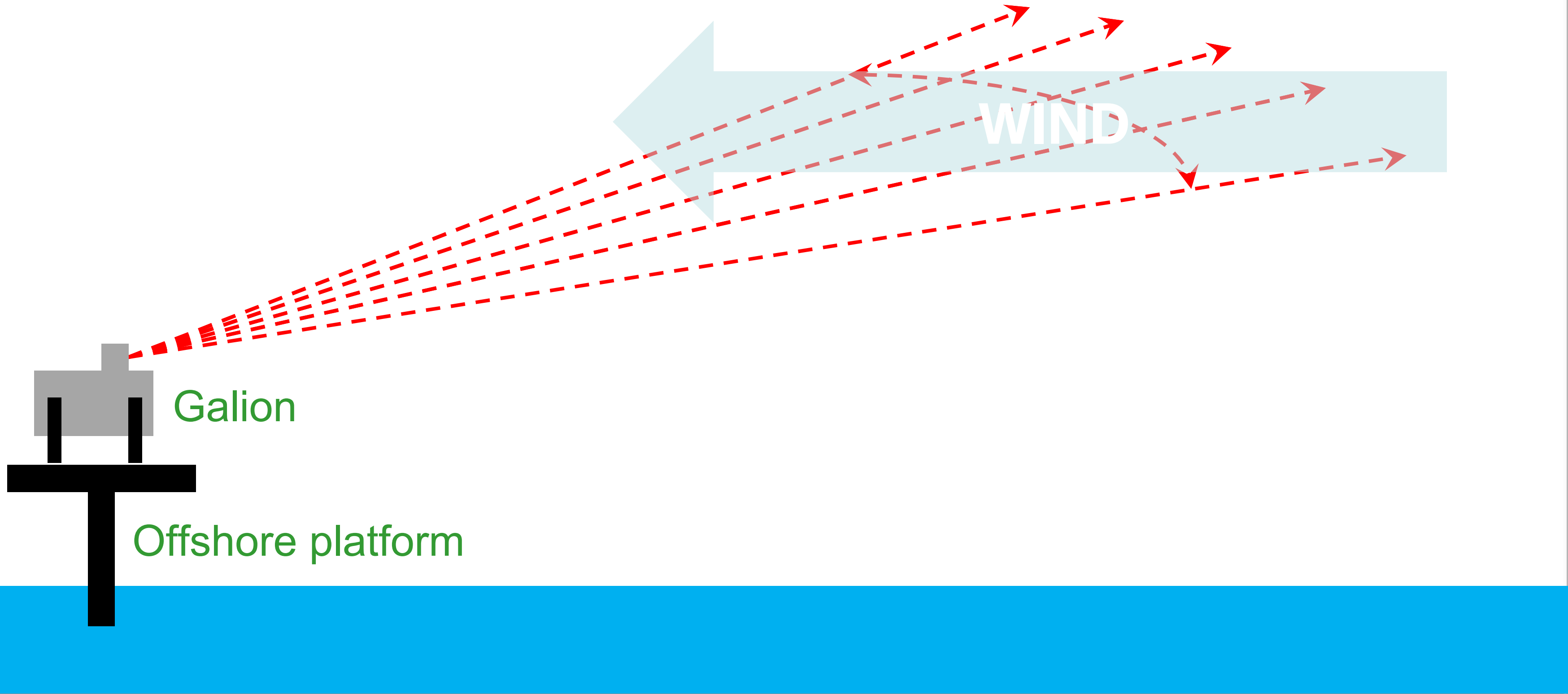
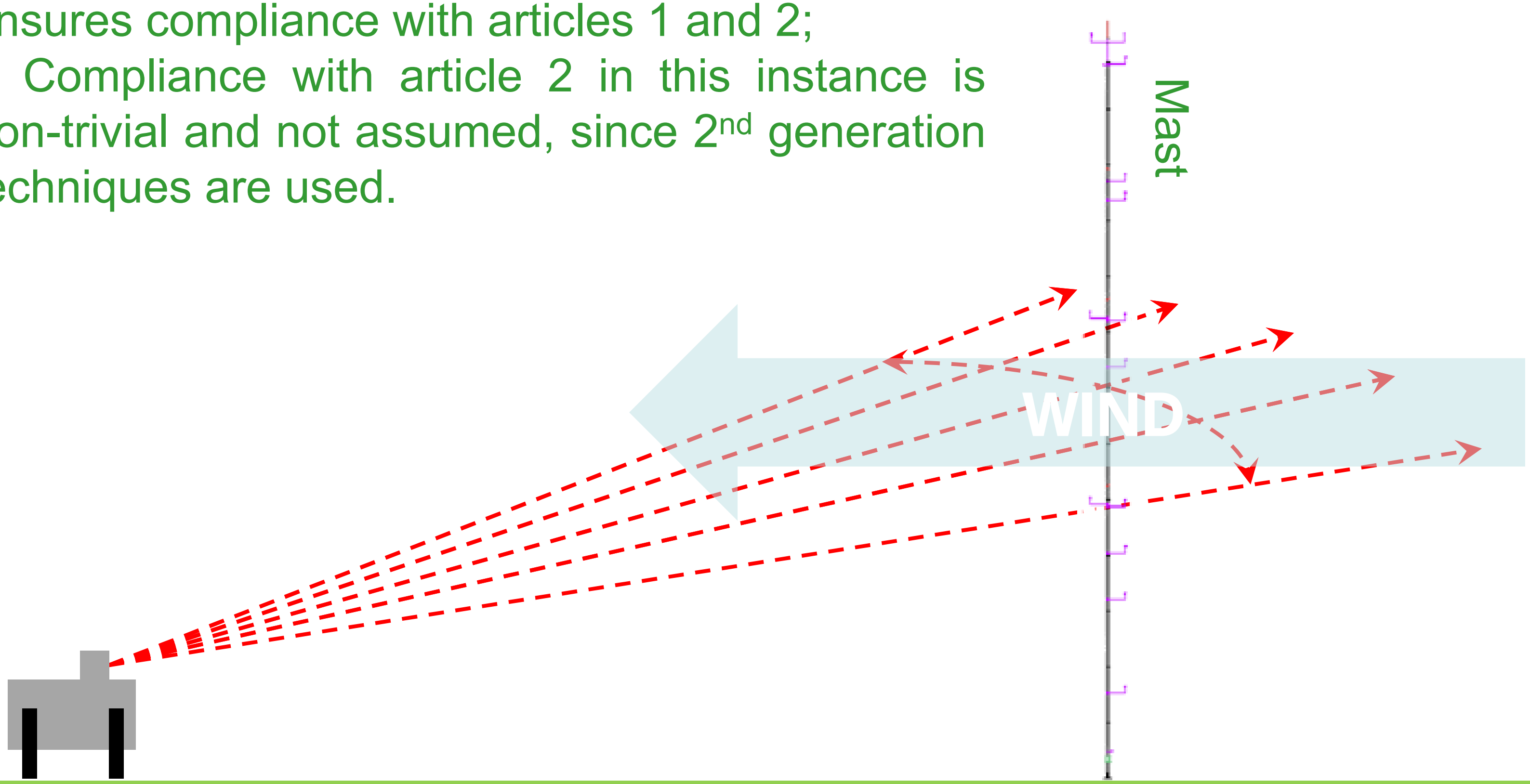
Arc scan

2nd generation scan geometry employed to survey wind directly at proposed wind turbine locations and in regions where the wind flow is unaffected by the influence of the platform to ensure compliance with article 3

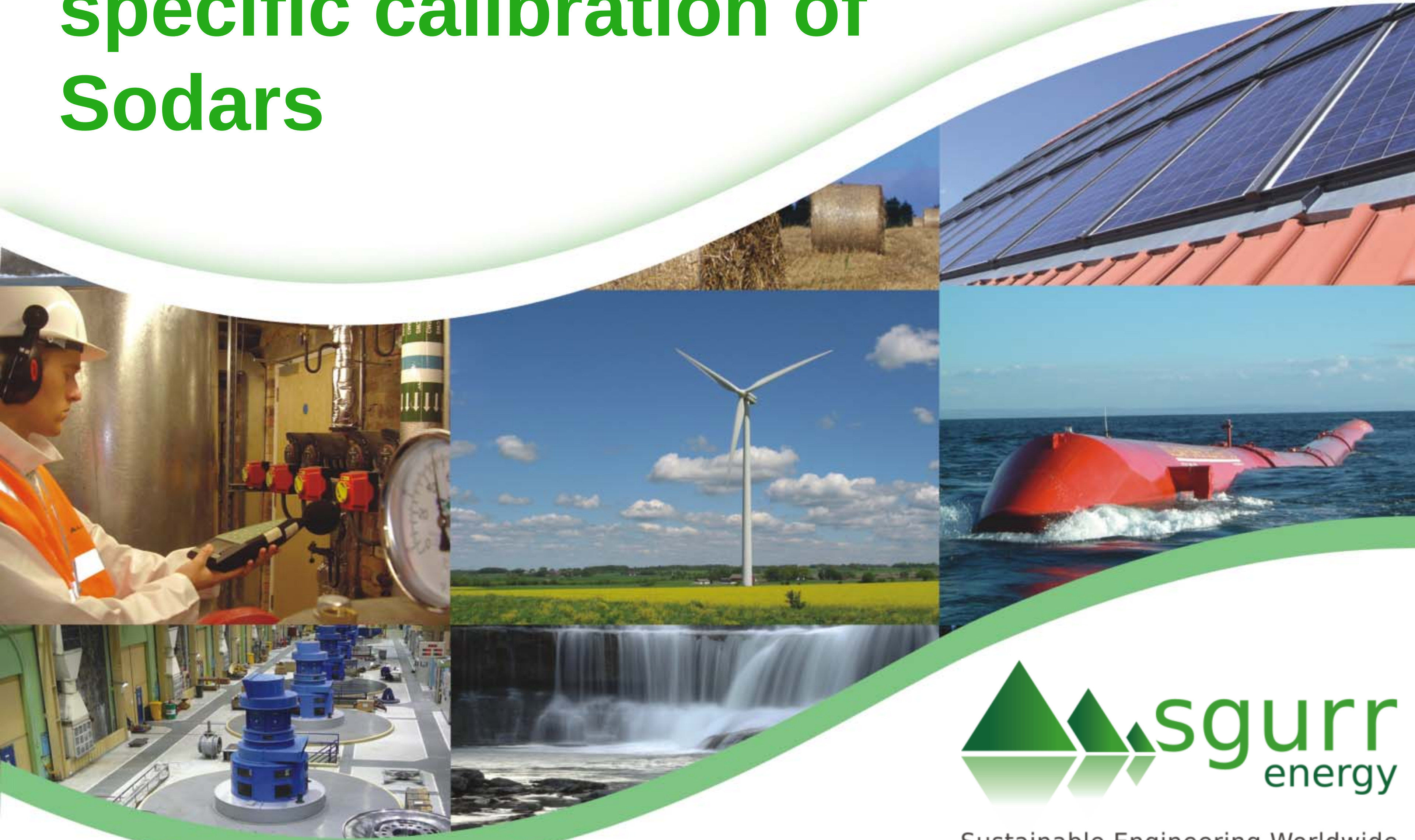


Arc scan

- Comparison with reference instrumentation before and/or after the measurement campaign ensures compliance with articles 1 and 2;
- Compliance with article 2 in this instance is non-trivial and not assumed, since 2nd generation techniques are used.



Example: *in situ* site specific calibration of Sodars



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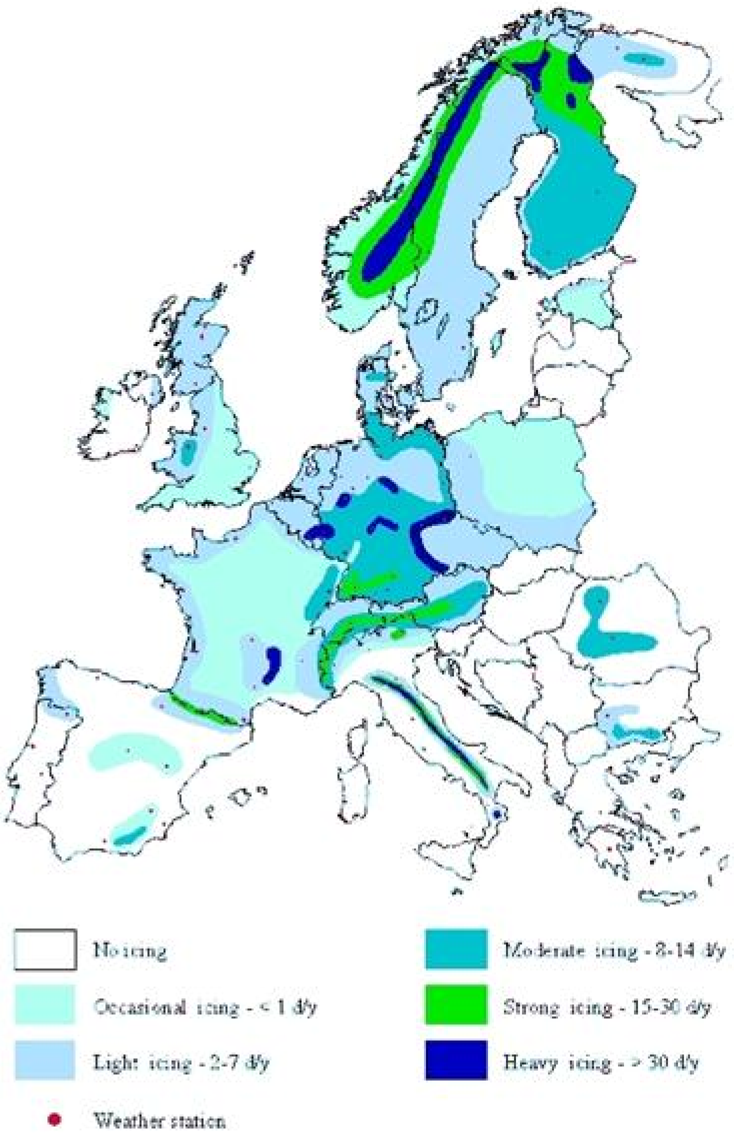
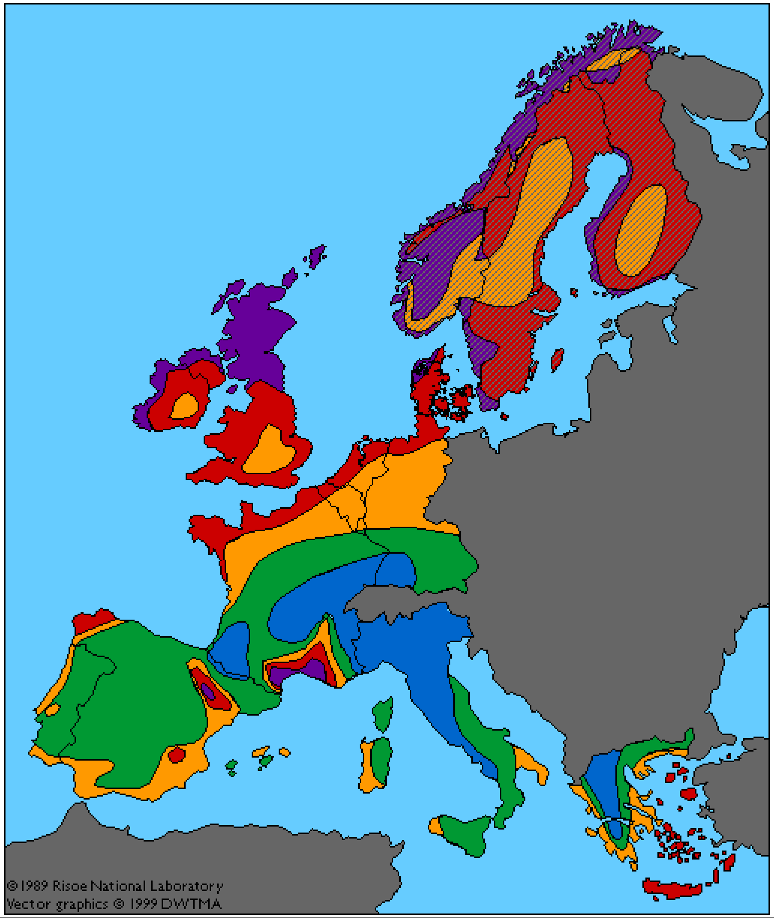
Why?





	m/s	W/m2	m/s	W/m2	m/s	W/m2	m/s	W/m2	m/s	W/m2
	>6.0	>250	>7.5	>500	>8.5	>700	>9.0	>800	>11.5	>1800
	5.0-6.0	150-250	6.5-7.5	300-500	7.0-8.5	400-700	8.0-9.0	600-800	10.0-11.5	1200-1800
	4.5-5.0	100-150	5.5-6.5	200-300	6.0-7.0	250-400	7.0-8.0	400-600	8.5-10.0	700-1200
	3.5-4.5	50-100	4.5-5.5	100-200	5.0-6.0	150-250	5.5-7.0	200-400	7.0-8.5	400-700
	<3.5	<50	<4.5	<100	<5.0	<150	<5.5	<200	<7.0	<400
			>7.5							
			5.5-7.5							
			<5.5							

Why?

- **Good resource are available in cold climate regions;**

- **Conventional mast mounted instrumentation subject to icing;**

- **Complex terrain typical of cold climate areas renders monostatic remote sensing results unreliable;**

- ***In situ* site specific calibrations of monostatic devices could provide sector-wise relationships between what a mast would measure and what the devices record;**

- **Uncertainty could be assessed in relation to the scatter evident in these relationships.**

What we would like

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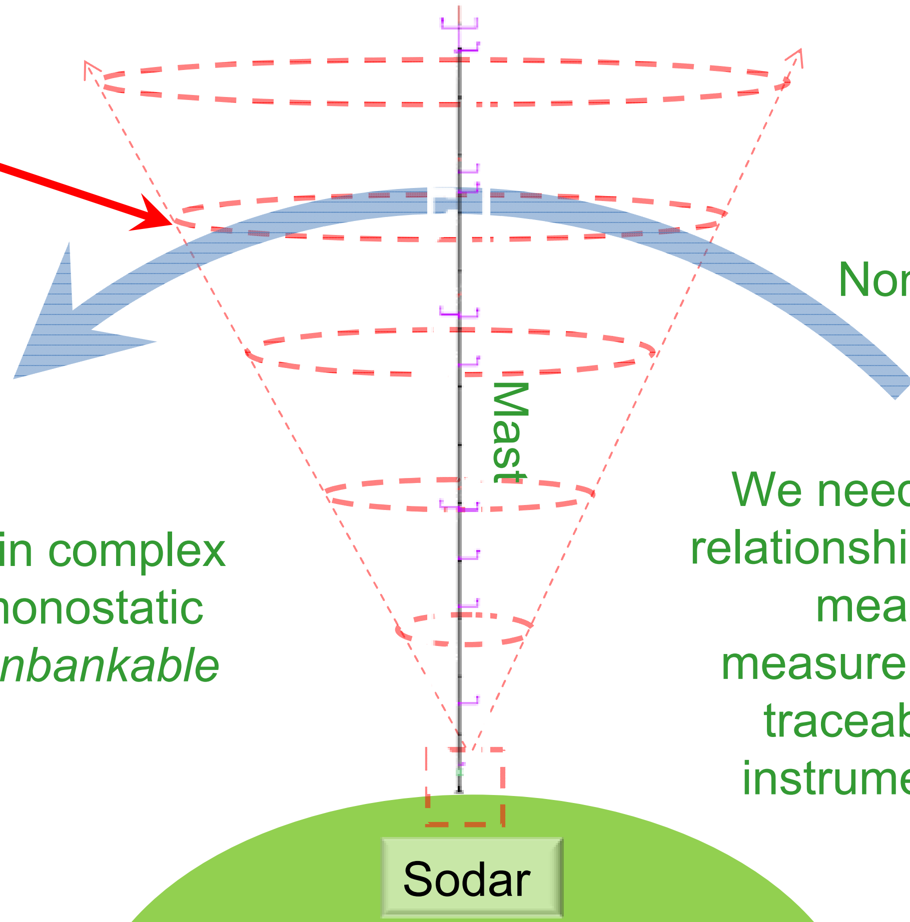
Measurement volume



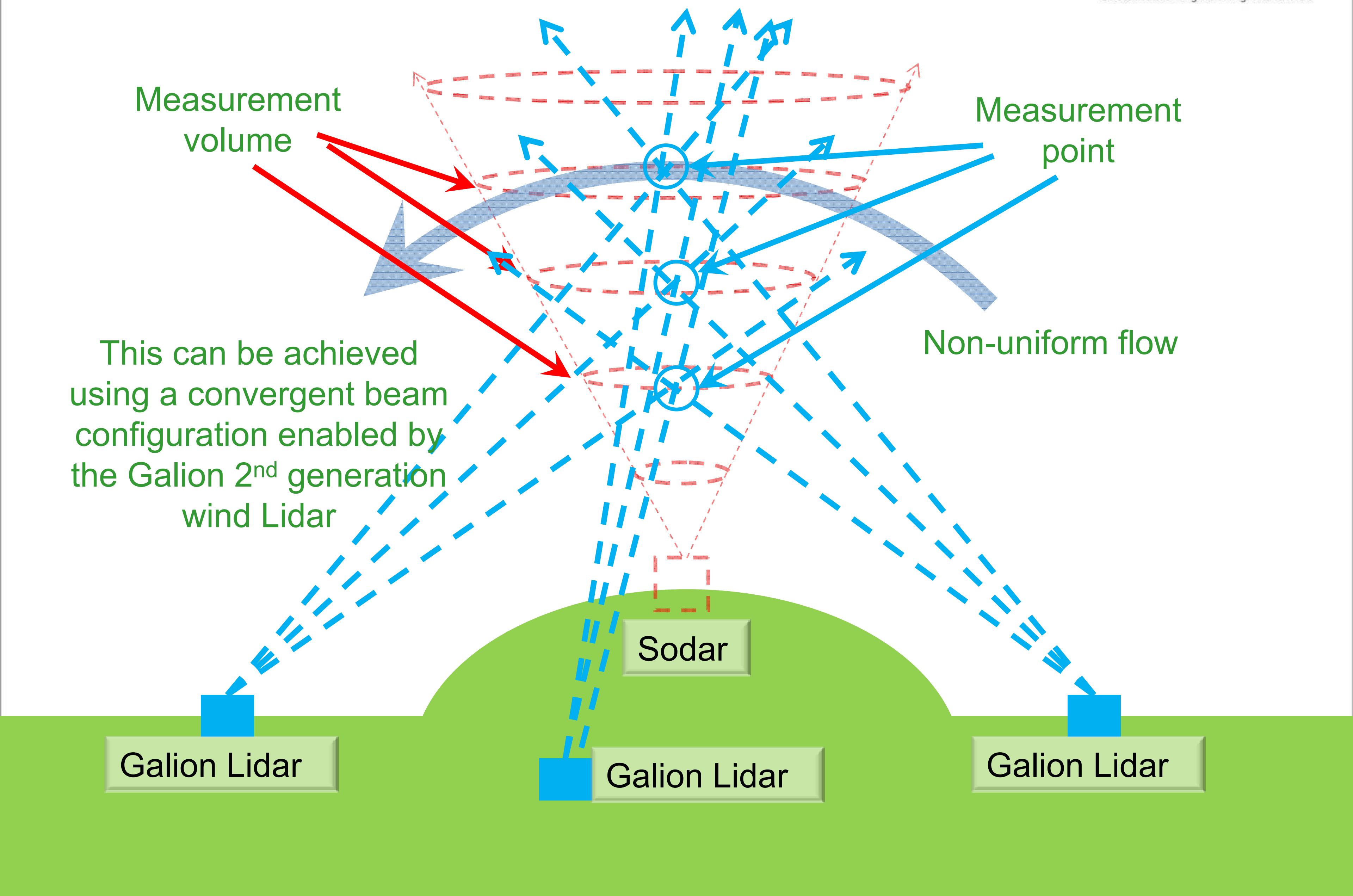
Non-uniform flow

Non uniform flow in complex terrain renders monostatic remote sensing *unbankable*

We need to understand the relationship between the Sodar measurements and measurements conventional traceable mast mounted instruments *would* acquire

Complex terrain (hill) induces non-uniform flow in the measurement volume

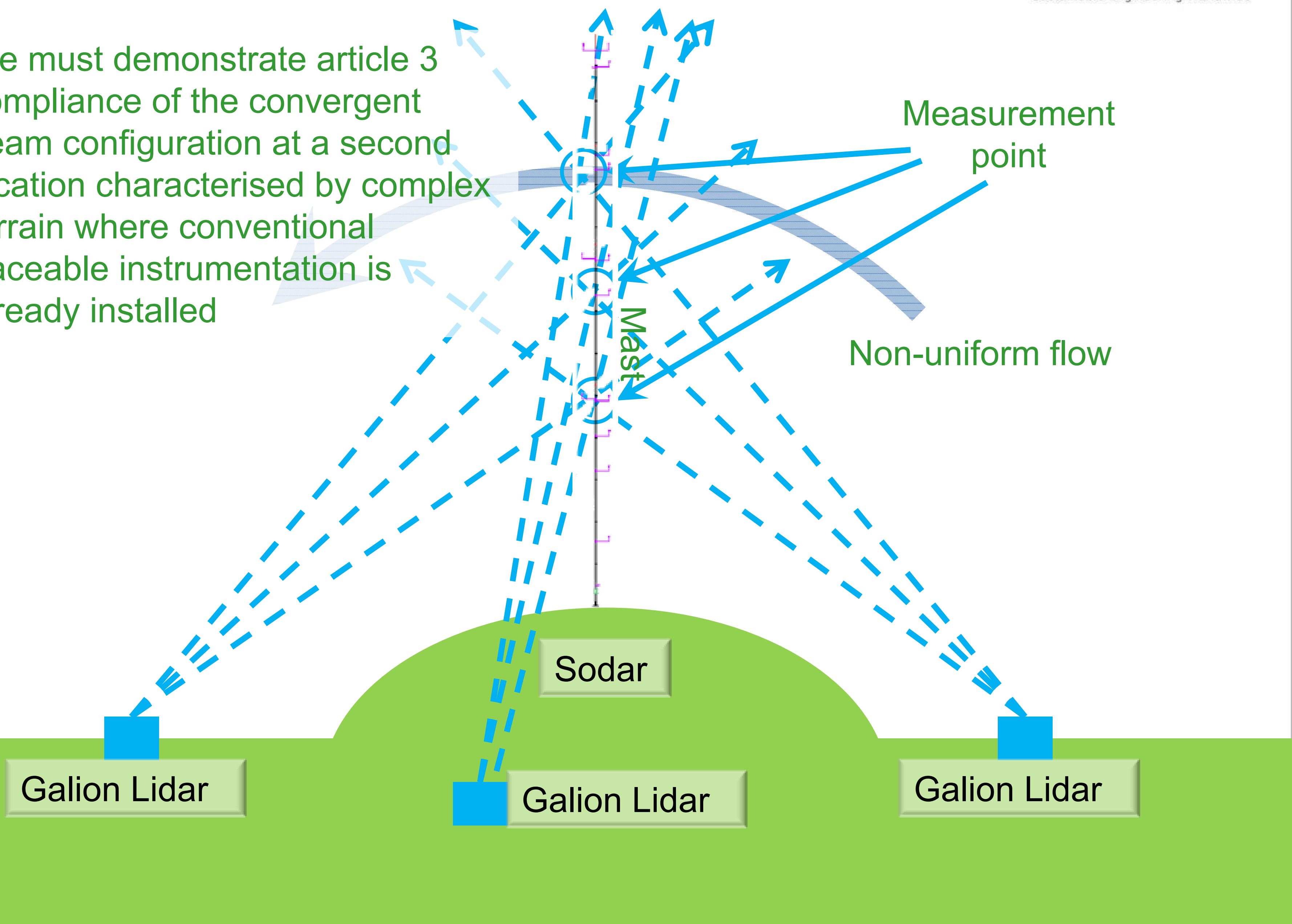
What we can have



This can be achieved using a convergent beam configuration enabled by the Galion 2nd generation wind Lidar

Demonstrating article 3 compliance

We must demonstrate article 3 compliance of the convergent beam configuration at a second location characterised by complex terrain where conventional traceable instrumentation is already installed



Convergent beams

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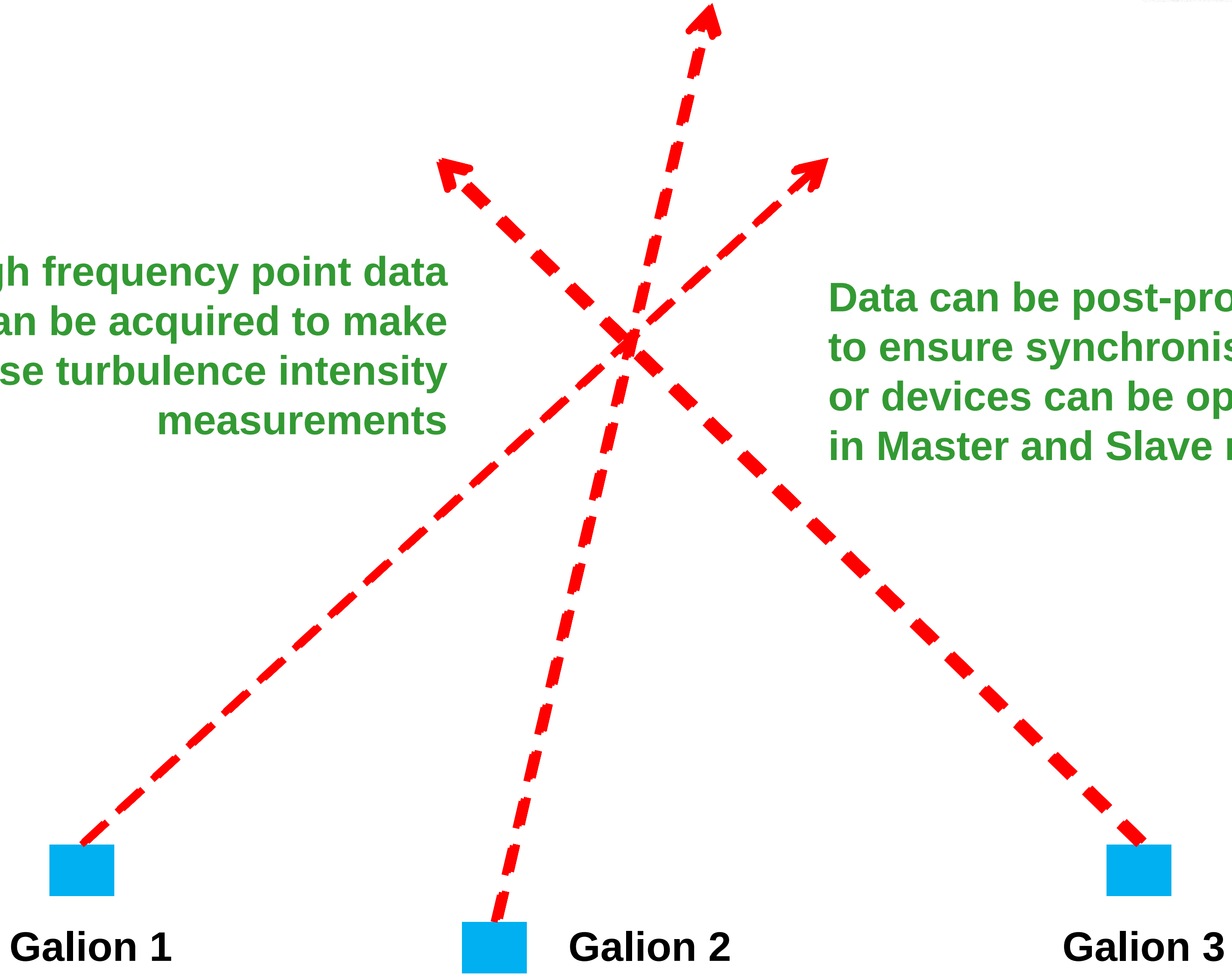
High frequency point data can be acquired to make precise turbulence intensity measurements

Data can be post-processed to ensure synchronisation, or devices can be operated in Master and Slave mode



Conclusions

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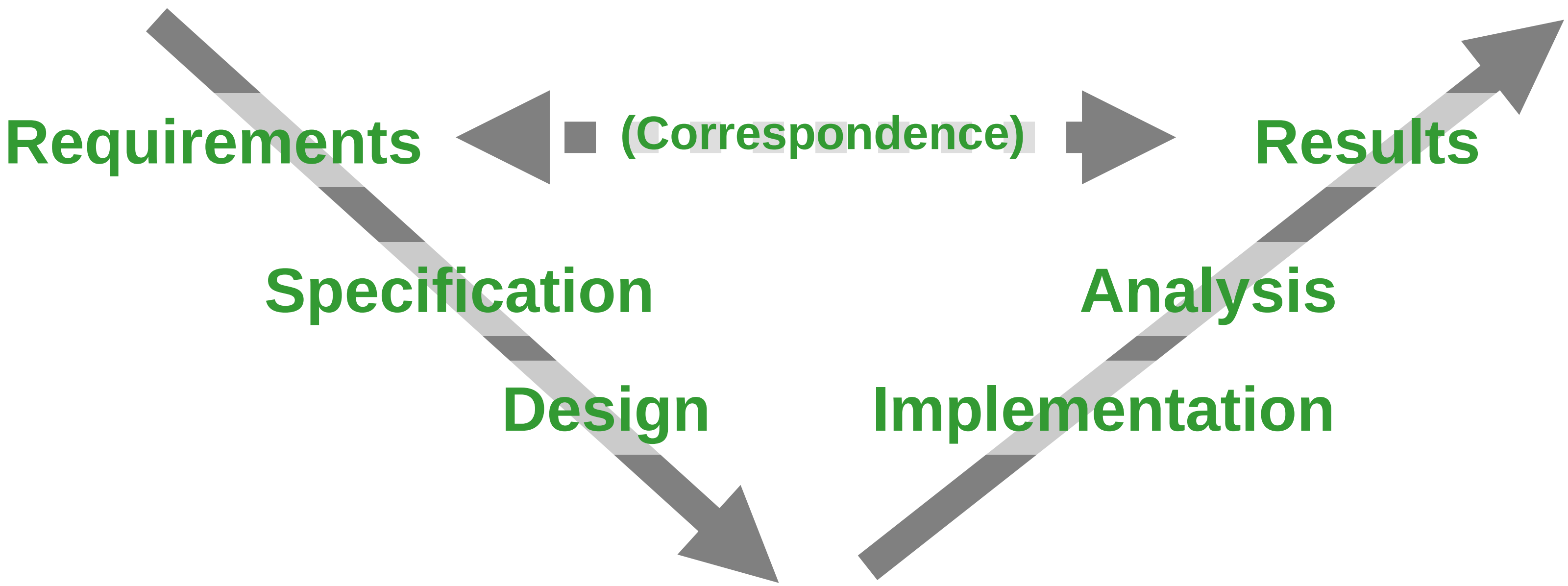
Campaigns were previously designed around what measurements were possible

The capabilities of the Galion mean campaigns are designed around what is required



Conclusions

- **Wind Power applications demand high precision, low cost, robust, and compact remote sensing solutions for projects with narrow margins in challenging locations;**

- **1st generation remote sensing solutions encounter difficulties in complex terrain;**

- **These challenges have driven developments that have produced devices that are now suitable for airport applications, and wind Lidars are now entering the airport space.**