WIVERN: A CONICALLY SCANNING DOPPLERISED 94GHZ CLOUD RADAR MISSION TO MEASURE GLOBAL IN-CLOUD WINDS

Alessandro Battaglia, University of Leicester
Anthony Illingworth, University of Reading

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University of Reading

NRC·CNRC Canada

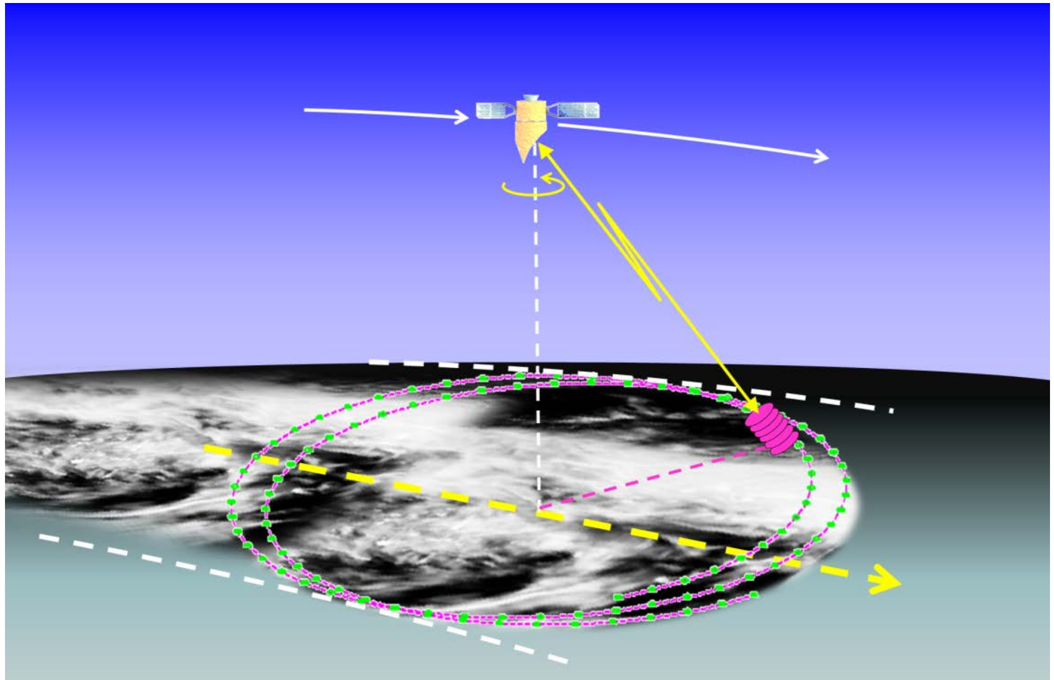
Science & Technology Facilities Council

VT·VITAM HAB·EANT

2014-2015: CEOI funding Univ Reading and Leicester for ground based evaluation of the radar concept.
2015-2017: ESA funding Univ Reading, Leicester and EC for airborne evaluation of the radar concept.
Several previous ESA/CEOI activities involving UoR, UoL, RAL, Astrium

Wivern: rationale of the mission

A **WInd VElocity Radar Nephoscope (**instrument for measuring the altitude, direction, and velocity of clouds**)**



a fire-breathing dragon used in medieval heraldry

Primary goal: to provide global measurements of vertical structure of winds in cloudy regions with 50km horizontal and 1km vertical resolution and daily visits poleward of 50° for improving NWP via data assimilation ➔ produce better warnings of damaging European wind storms, tropical cyclones, flash floods

Secondary goal: rainfall & cloud ice water products

Instrument: 94 GHz conically rapidly scanning Doppler radar with polarization diversity, pulse compression and frequency hopping.

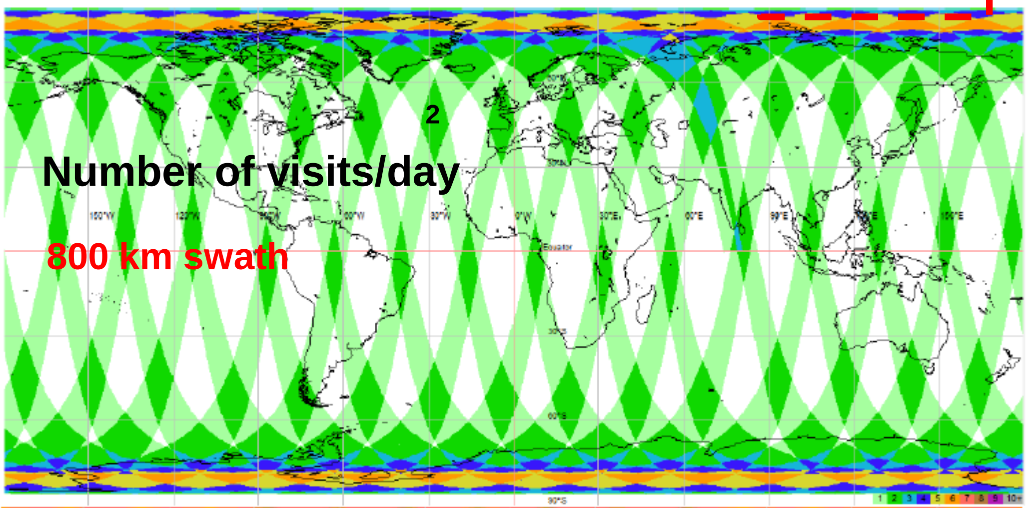
Target: candidate for EE9

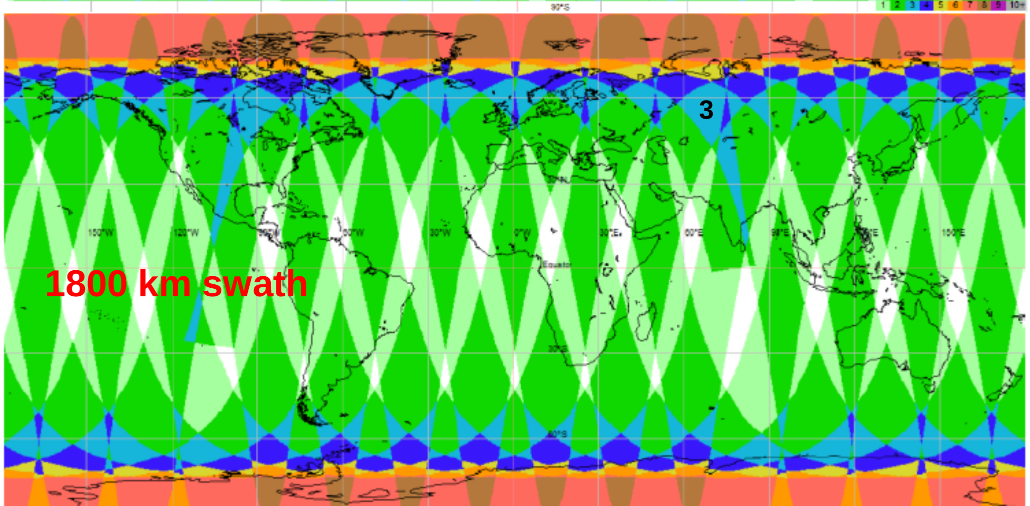
Coverage: trade-off study for the two configurations

WMO Rolling Requirement Review (RRR)

Very demanding

Horizontal wind	Uncertainty	Horiz	Vert res	Observing Cycle
Goal	1 m/s	15 km	0 .5 km	60 min
Breakthrough	3 m/s	100 km	1 km	6 hrs
Threshold	5 m/s	500 km	3 km	12 hrs





Frequency	94 GHz
Peak/Mean power	1.8 kW/176 W
Satellite height	500/700 km $(v_{sat} = 7.6/7.5\ \mathrm{kms}^{-1})$
Speed at surface	7.05/6.75 kms^{-1}
Incidence angle	$41.4°/57.7°$(scanning angle $= 37.8/49.6°$)
Swath width	$796.4 - 1801.9$ km
Scan circumference	$2502 - 5661$ km
Distance from ground	$(648.8 - 1178.6)$ km
Antenna rotation velocity	8.6 RPM Scan speed 357.4/806.7 km/s
Antenna diameter	2.9 m × 1.8 m $\theta_{3dB} = 0.077° \times 0.124°$
Pulse-length	3 μsec $(\Delta r = 500\mathrm{m})$
Pair separation	TBD(V_{Nyq} accordingly)
PRF_{pairs}	11.1-11.20kHz [frequency diversity]
Integration time	TBD
MDT	$-25/-19.8$ dBZ

Scan every 7 seconds (FAST!)

- **move 50km along track**
- **sample every 50km along arc**

Vertical resolution: trade-off for the two configurations

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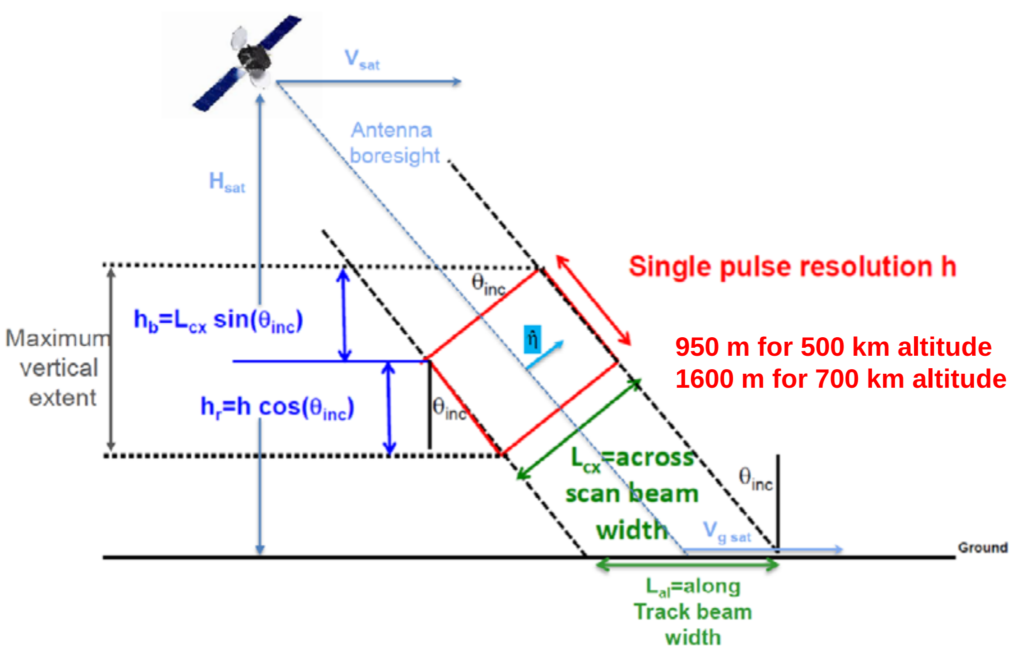

FIG. 3. Geometry of the pulse volume for off-nadir incidence.

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Vertical resolution is significantly worsen for the large-swath configuration with increased ground clutter and size of the beam close to the ground (➔ NUBF), which is not desirable especially for mid-latitude systems (shallow)

Wind Uncertainty

WMO Rolling Requirement Review (RRR)

Horizontal wind	Uncertainty	Horiz	Vert res	Observing Cycle
Goal	1 m/s	15 km	0 .5 km	60 min
Breakthrough	3 m/s	100 km	1 km	6 hrs
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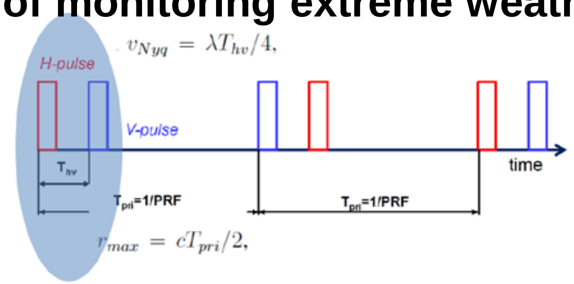
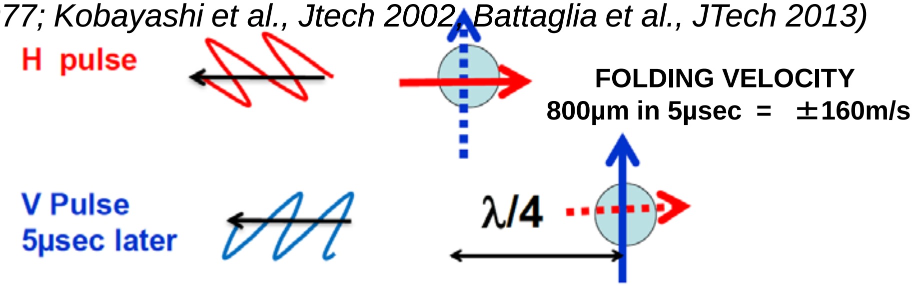
This is the most difficult to assess. But to have a chance to meet the WMO requirements with LEO-orbiting Doppler radar

1) Large antenna (for accuracy)

$$\sigma_D^{sat} = \frac{\theta_{3dB} V_{sat}^{\perp}}{4\sqrt{\log(2)}}. \qquad T_{dec} = \frac{\lambda}{2\sqrt{2}\pi\sigma_D}$$

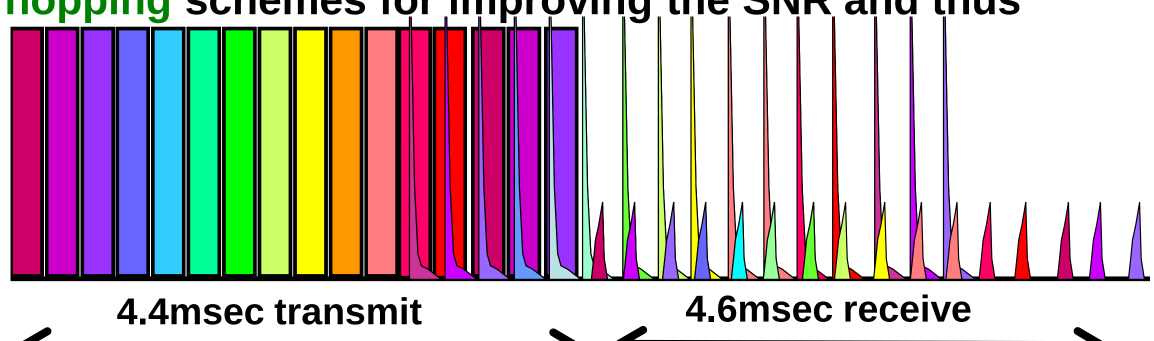
2) Polarization diversity for increasing significantly the Nyquist interval and then being able of monitoring extreme weather events *(Zrnic, 1977; Kobayashi et al., Jtech 2002, Battaglia et al., JTech 2013)*





3) Pulse compression/frequency hopping schemes for improving the SNR and thus coverage ➔ high duty cycle

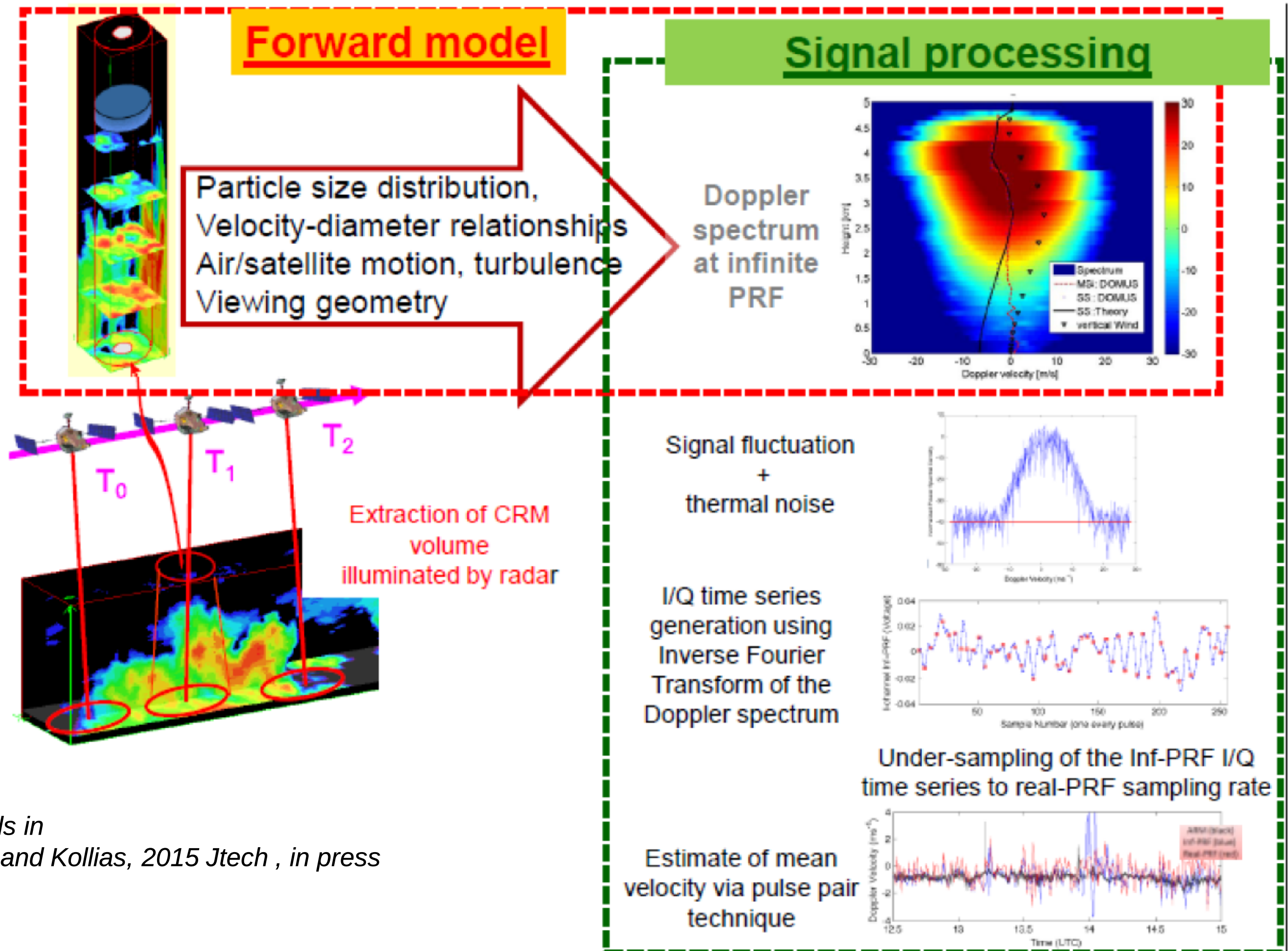
110 chirped pulses
both in H and V



How to assess wind uncertainties?

$$\epsilon_{TOT}^2 = \epsilon_N^2 + \epsilon_{NUBF}^2 + \epsilon_{aliasing}^2 + \epsilon_{MS}^2 + \epsilon_{pointing}^2$$

There are different sources of errors. They can be assessed by an end-to-end simulator built upon the EarthCARE simulator

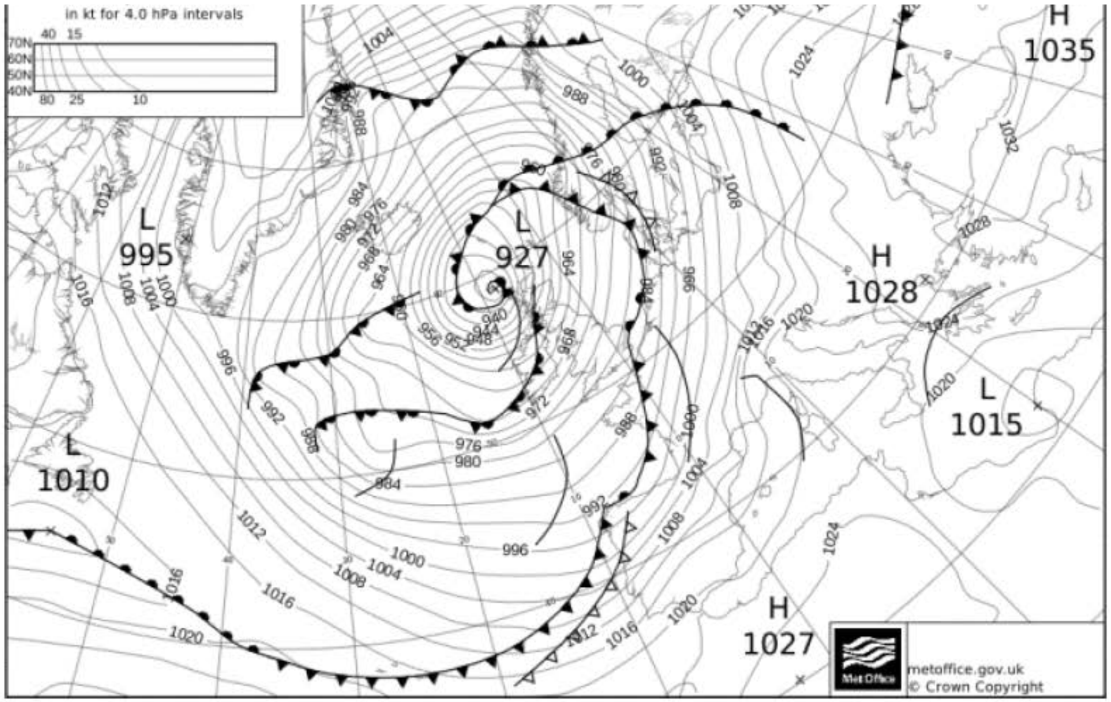


Full details in
Battaglia and Kollias, 2015 Jtech , in press

The simulator accounts for 3D structure of clouds (important for space-borne Doppler systems), surface clutter, cross talk between H and V polarization

A case study: the 2013 Christmas storm

Several deep depression systems occurred over UK in Dec2013–Feb2014. These extra-tropical cyclones can be quite destructive (e.g. in 1999 - **£18.5B windstorm damage** in Europe)



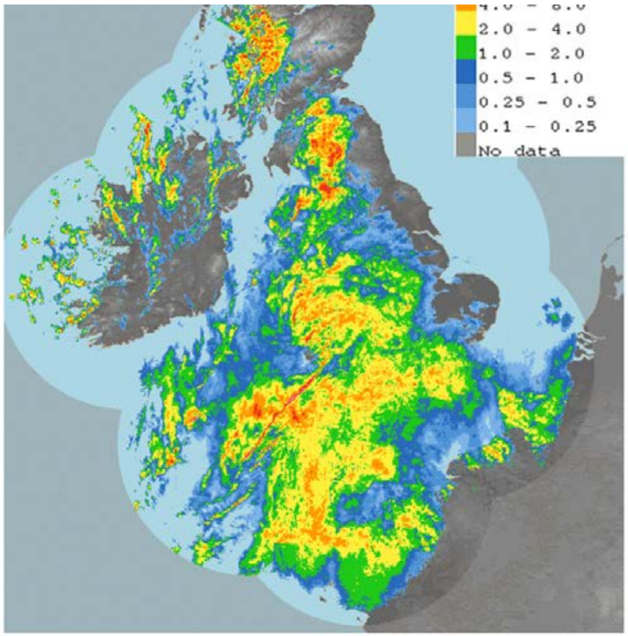


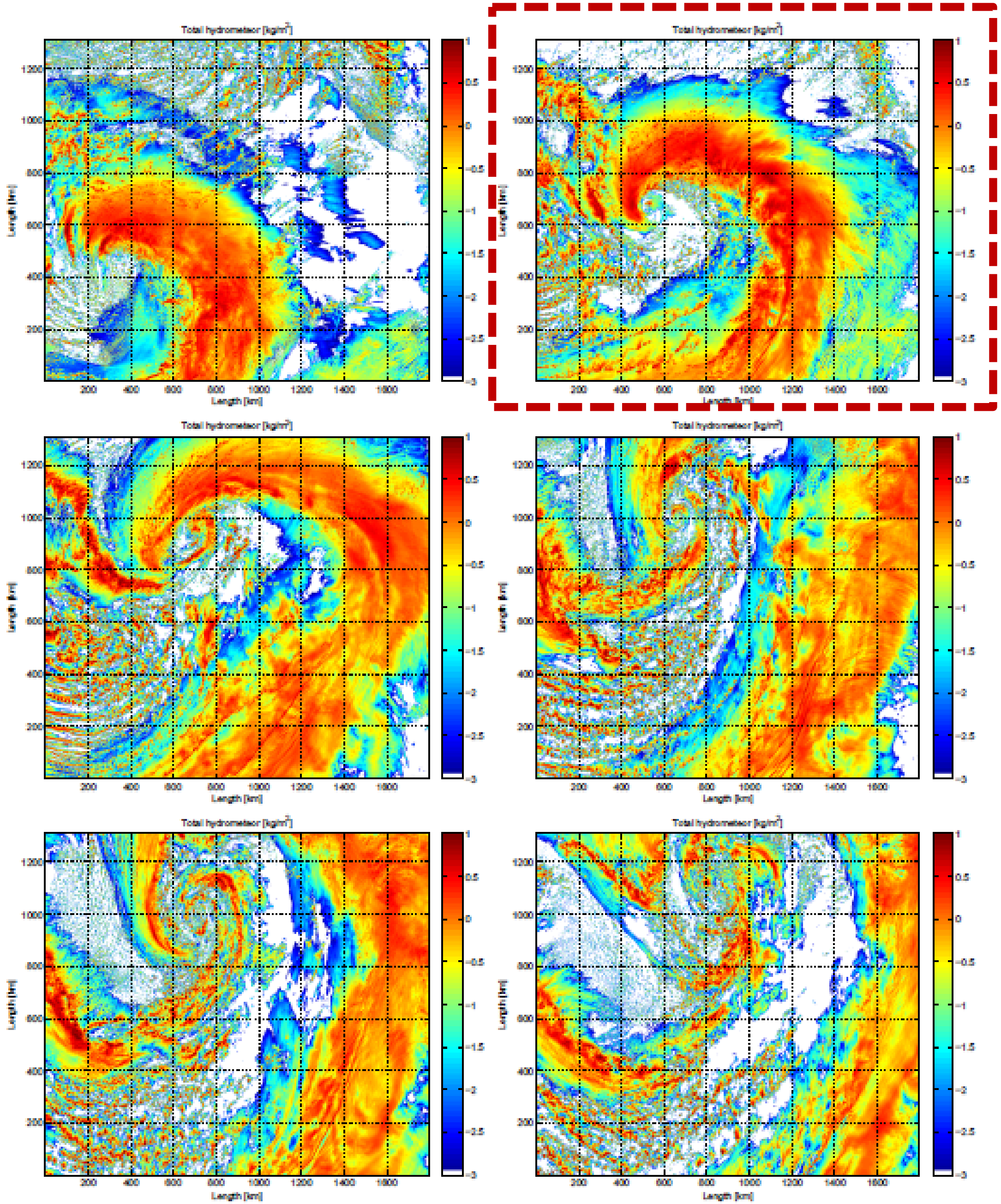
Figure 3: UK rain radar 2200 GMT 23 December 2013.

The synoptic situation at 1200 UTC 24 December 2013 shows an exceptionally deep area of low pressure to the north-west of Scotland with winds gusting at again at 60 to 70 kt across much of Scotland, the coast of Wales and South Coast of England. The storm brought particularly heavy rain to southern England and Wales, with a swathe from Dorset to Kent recording 50 to 70 mm, causing significant flooding problems.

WRF 1km simulation of the storm evolution

Snapshots of the storm evolution every 6 hours starting from the 23*rd* Dec. at 6 UTC till the 24*rd* Dec. at 12 UTC

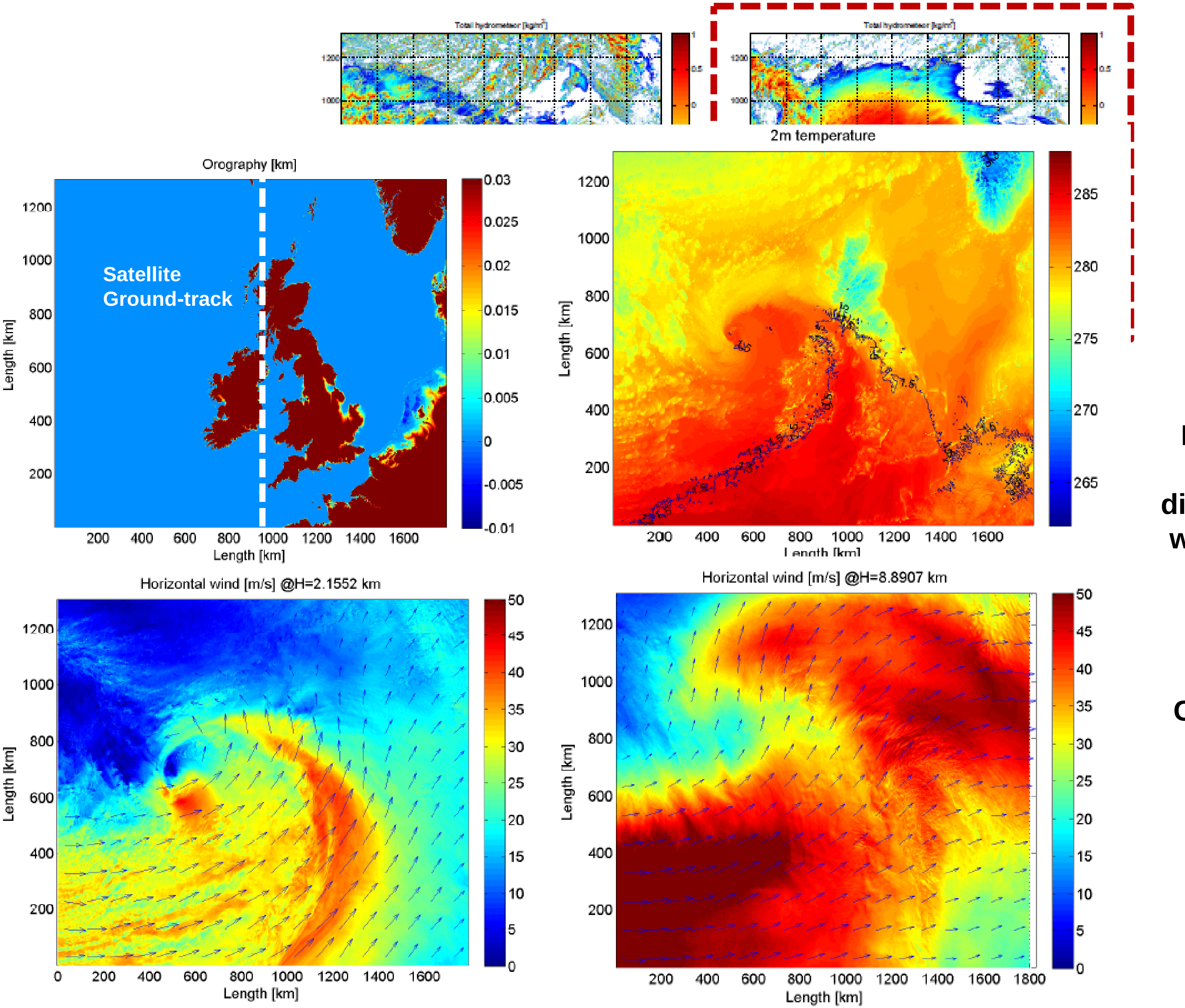
2000x1300 km^2 centered around UK



Colorbar modulated by Log_{10} of the Integrated hydrometeor content

System swirling around the north-east moving pressure minimum

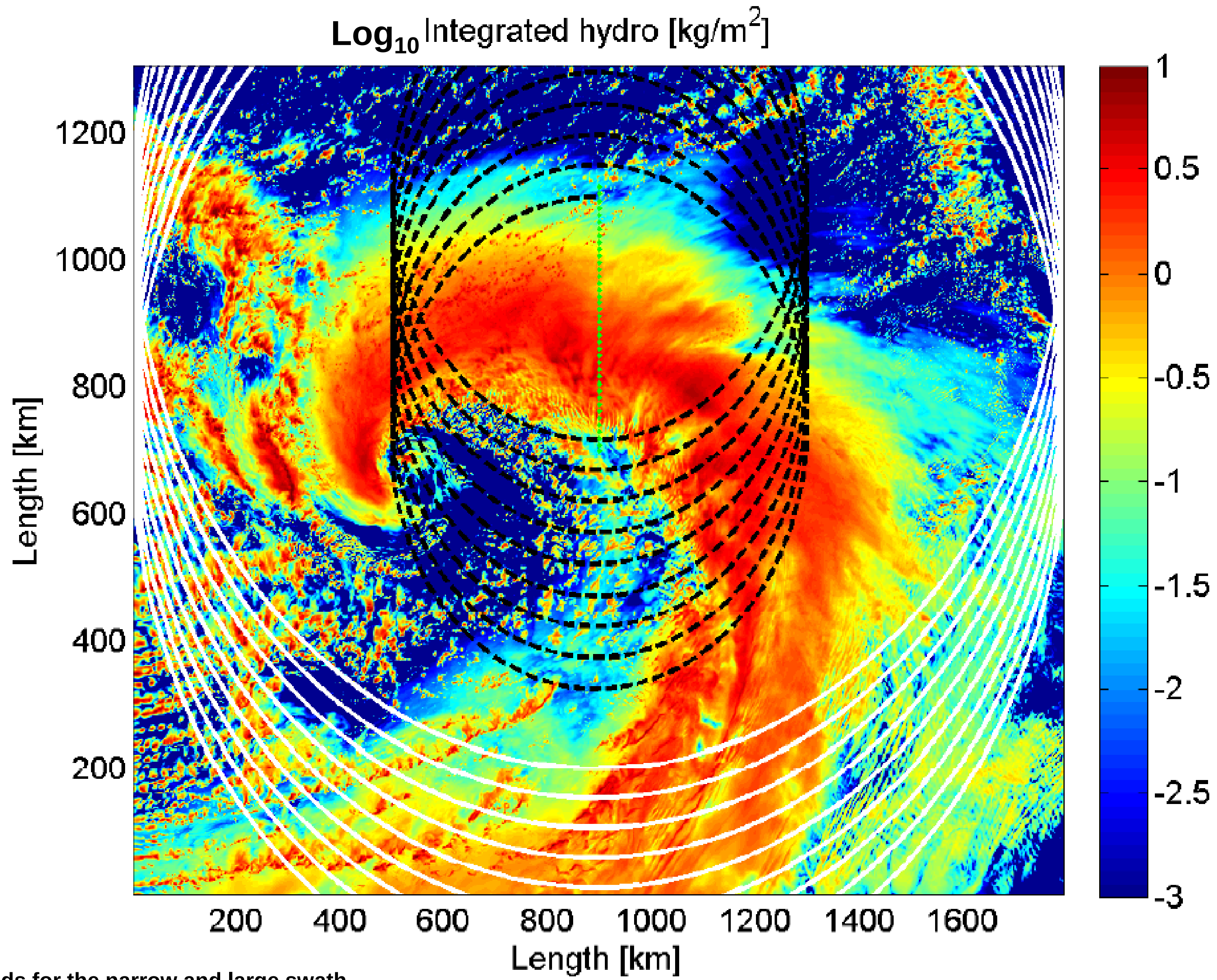
WRF 1km simulation of the storm evolution



Note the change in intensity and direction of the winds when moving from 2 to 8 km in the atmosphere.

Can we capture this variability with Wivern?

Narrow and wide swaths

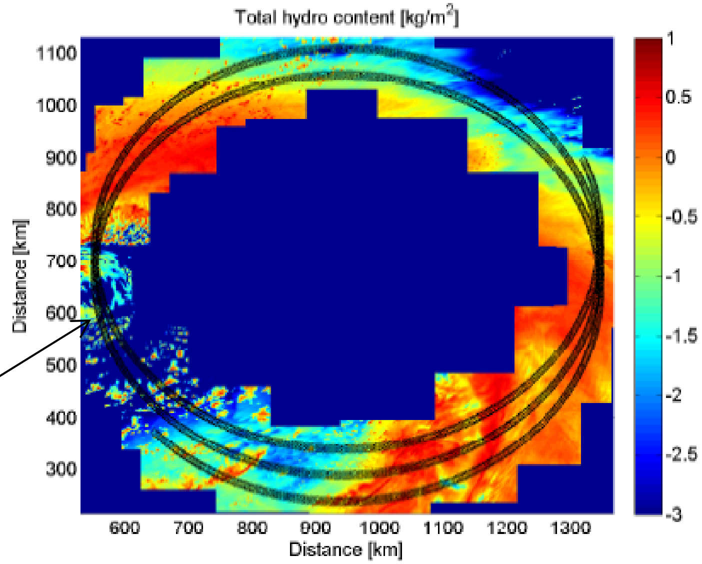


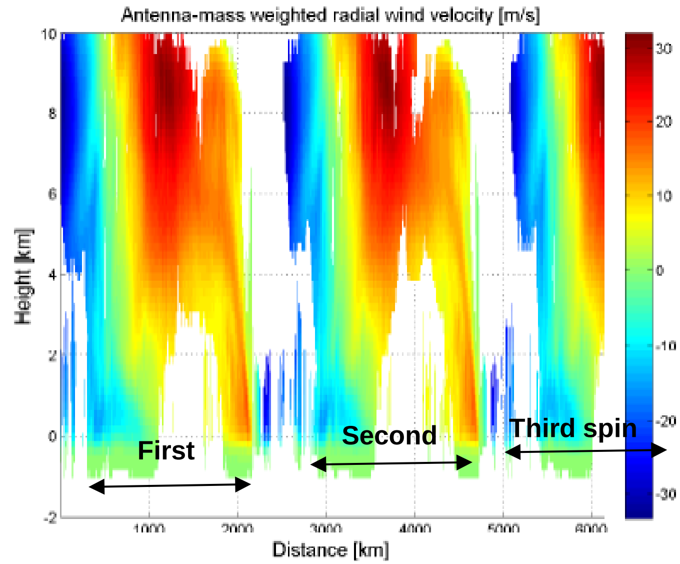
Different cycloids for the narrow and large swath

Example of 6000 km forward model profiles

Projection on a 2D-plane of the reconstructed vertical profiles along the cycloid

Starting point: spinning anticlockwise

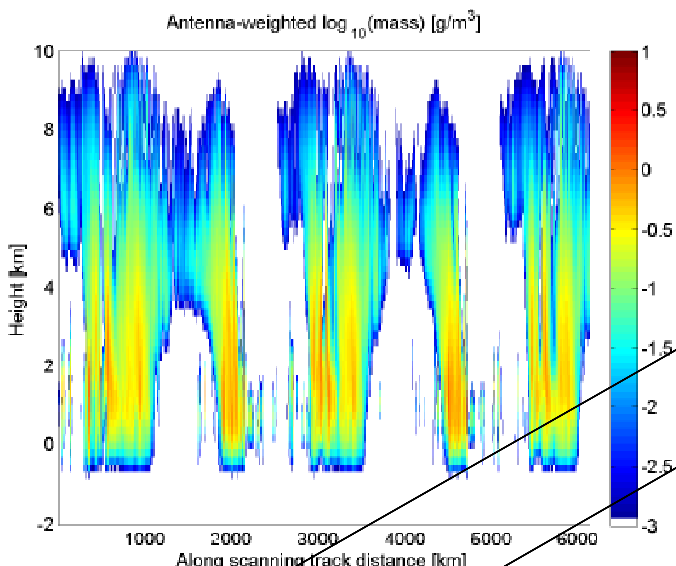


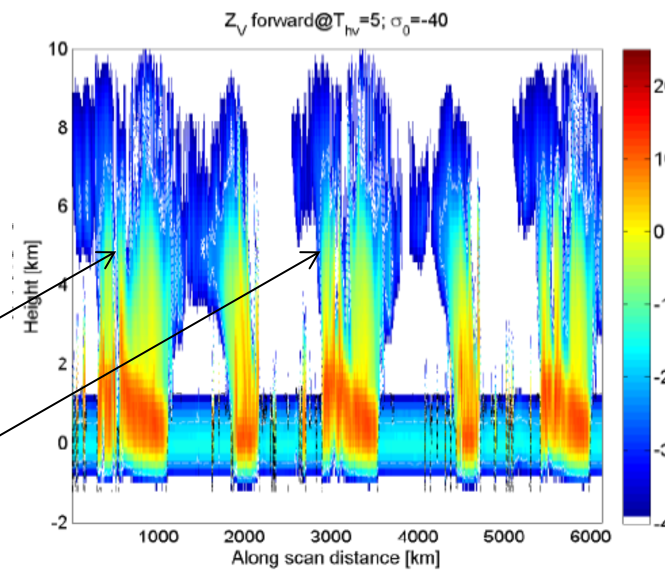


Towards radar

Wivern only measures LineOfSight winds! Here between -30 and +30 m/s depending on observing direction

Receding from radar

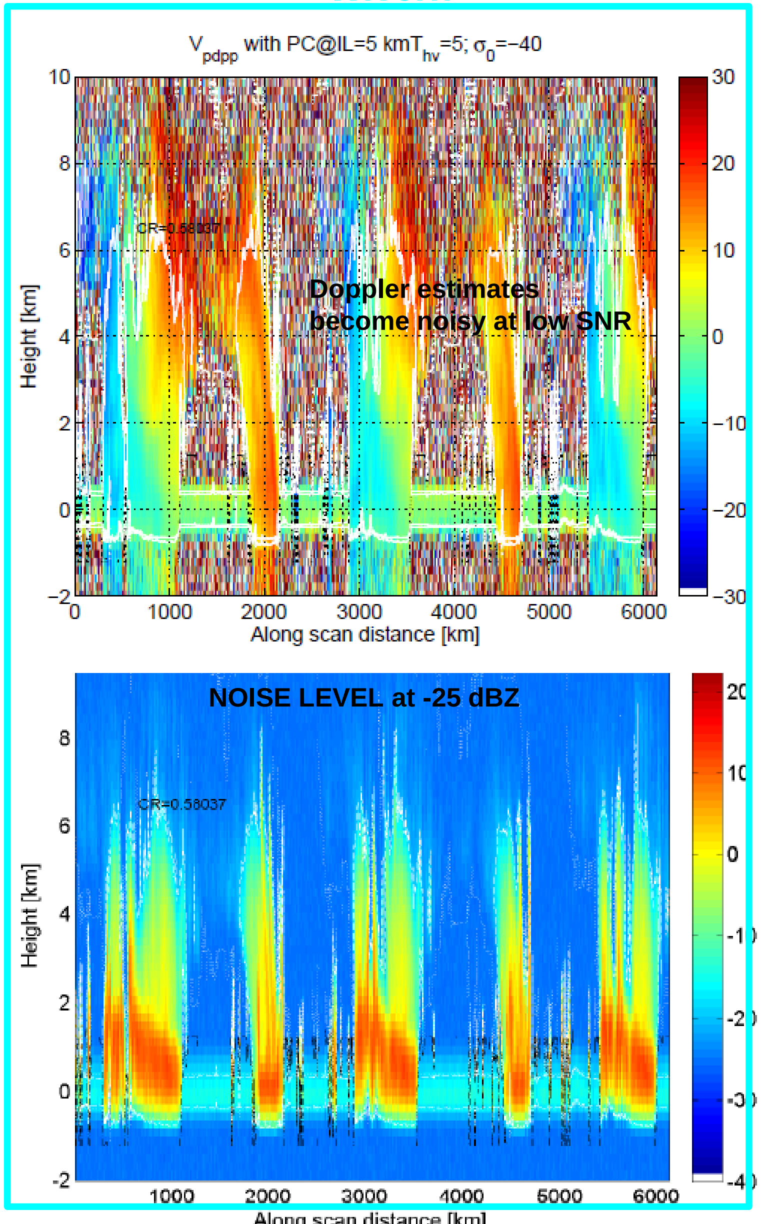




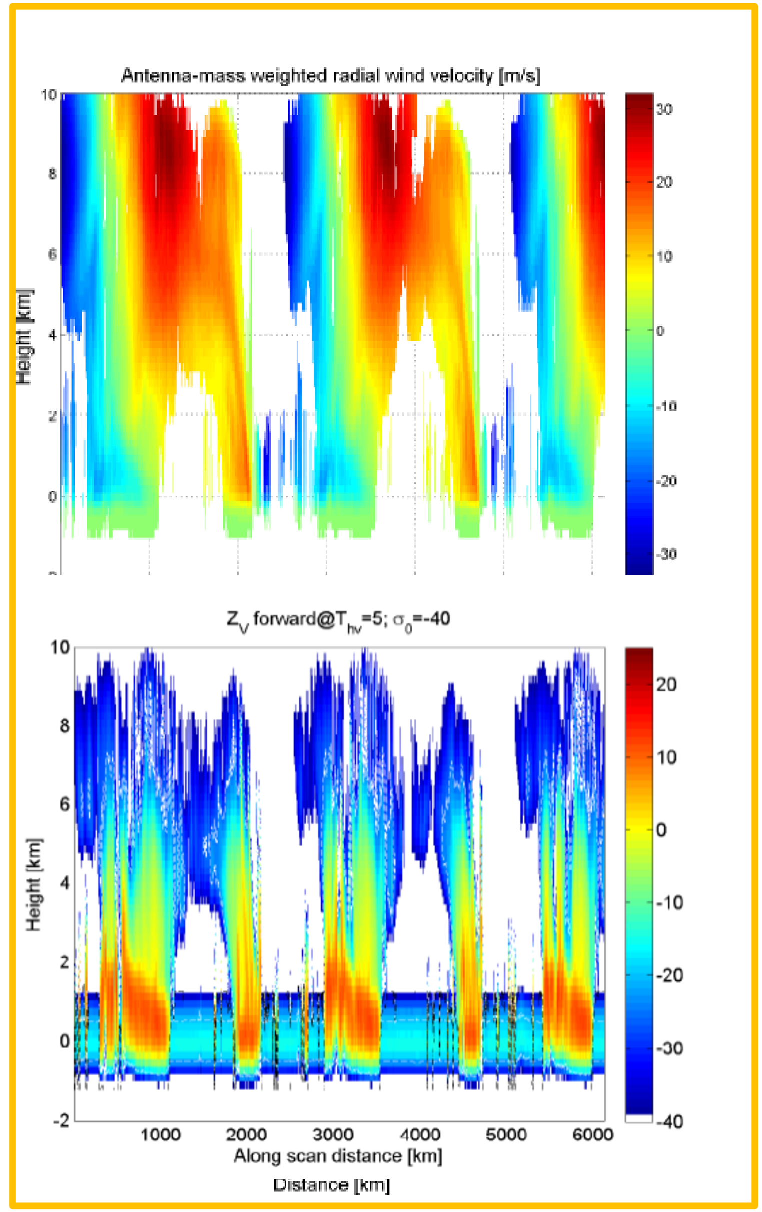
Cyan colour delineating regions where we have enough tracers in the atmosphere to get winds

Example of 6000 km Wivern profiles

Wivern



Ideal

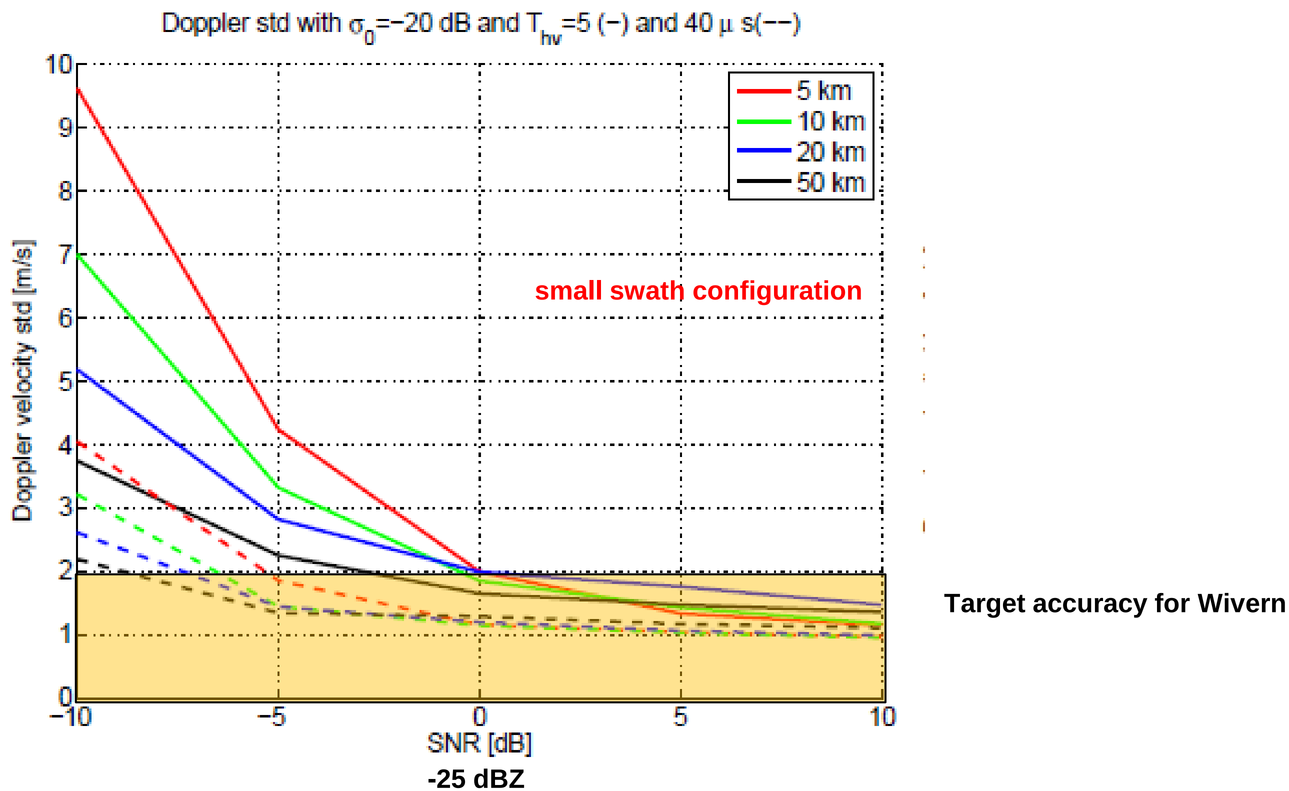


Towards radar

Receding from radar

In region of good SNR>-20dBZ Wivern is properly capturing the LOS winds ➔ simulation framework allows a full assessment of errors

Overall error budget for the Christmas storm



Errors are obviously reducing when increasing the SNR and when increasing the integration length (though integrating for too long is not always beneficial)
A 2 m/s accuracy can be achieved with an integration of 20 km at SNR of -7 dB and of 0 dB for T_{hv}=40μs and 5μs, respectively.

The large swath configuration typically requires longer integration lengths and/or larger SNR to achieve the same accuracy.
➔ Currently looking at cloud resolving model simulations of tropical cyclones.

Challenges ahead

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WIVERN EXPECTED PERFORMANCES WITH PROVIDED SPECS:

Winds	2m/s	50km	1km	(12)/ 24hrs

➔ **breakthrough**

But can we achieve the specs with a reasonable budget (<300 Meuros)?

The system is highly innovative. Several technological /scientific challenges:

1. POLARIZATION DIVERSITY (new)
2. HIGH OUTPUT POWER (new)
3. LARGE ANTENNA RAPIDLY SCANNING (pointing accuracy requirement of 200μrads for errors<1 m/s)
4. Data assimilation benefit ? ➔Observing System Simulation Experiment

Frequency	94 GHz
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Proof of concept of polarization diversity

H pulse
Also excites
Small V
dipole

V pulse
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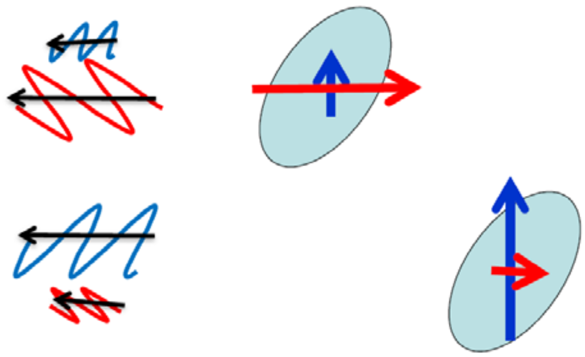
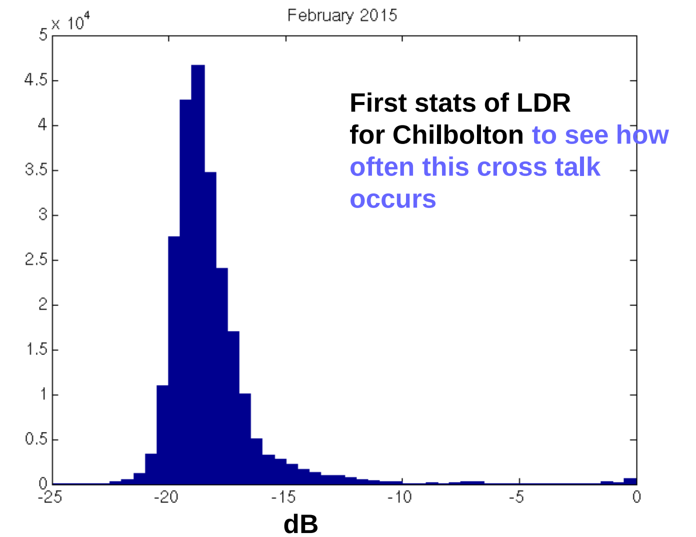


Non spherical hydrometeor and surfaces induce cross-talk which is detrimental for PD-based Doppler estimates ➔ 2 on-going activities

A. **2014-2015 CEOI-funded UoL, UoR, Chilbolton:** ground-based evaluation of the radar concept. 94 GHz Chilbolton radar now upgraded to PD



(a) (b) (c)

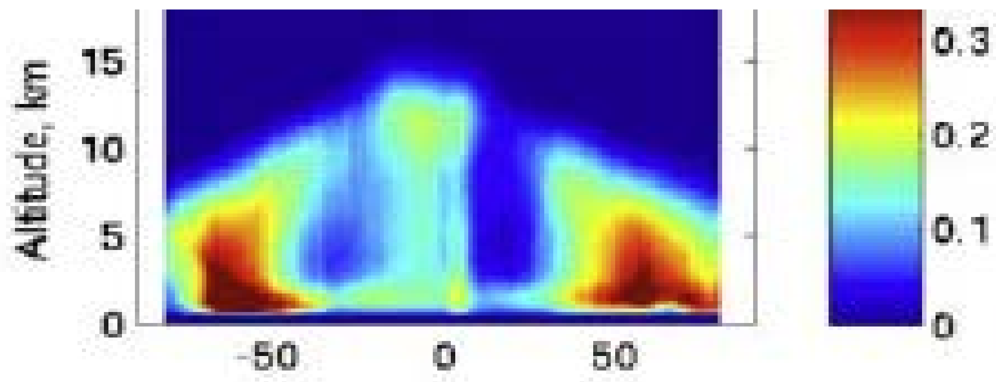
B. 2015-2016 ESA funded UoR, UoL, EC: NRC Airborne W and X band radar to be equipped with polarization diversity ➔ field campaign to assess Doppler performances and fully characterise the surface backscattering at slant angles

High output power

Heritage of CloudSat: first 94GHz radar in space, transmits high power pulses – duty cycle 1.2% - mean power 20W. Tube lifetime was a worry, but since launch 2006, power loss <0.5dB.
Wivern: coverage requires to increase mean power from 20W to 200W by sending a series of chirps hopped in frequency (CPI – tube manufacturer – mean power OK) but issues with high voltage power supplier unclear (unknown territory).

2014 -15 NSTP: Chilbolton demonstration of Chirp technique (+ Airbus)
This is critical to demonstrate coverage

Sensitivity and ability to detect clouds now known from CloudSat ➔ for instance DJF zonal average of fraction of the time with clouds



Small and large swath MDT

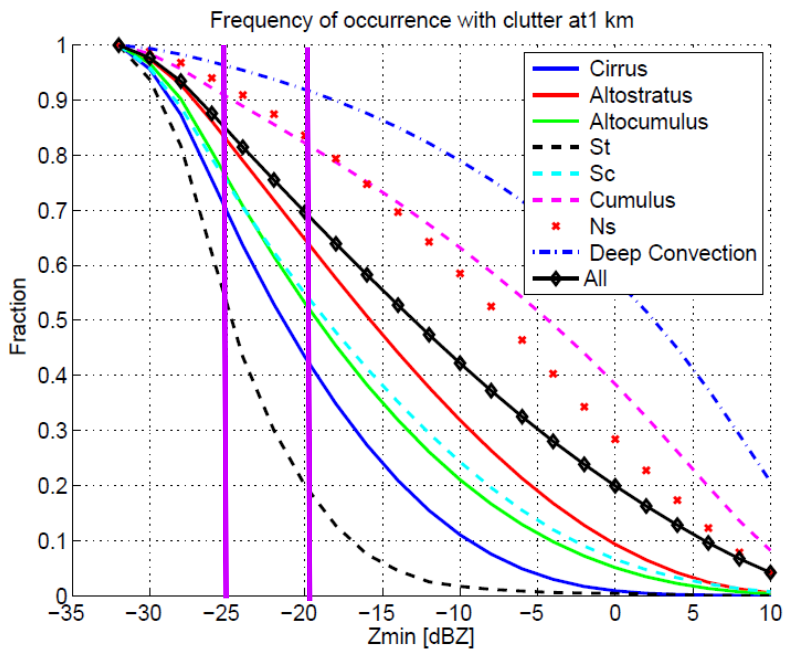


FIG. 15. Cloud detection as a function of a W-band minimum reflectivity for different cloud types as classified in the 2B-CLDCLASS (Mace et al. 2007). CloudSat is assumed as a reference, i.e. detection level of 100% corresponds to detecting all clouds seen by CloudSat.

ObservingSystemSimulationExperiments

New technique can now quantify impact of individual observations in reducing forecast error➔ Meteo France is currently assimilating line of sight winds from ground-based precipitation radars

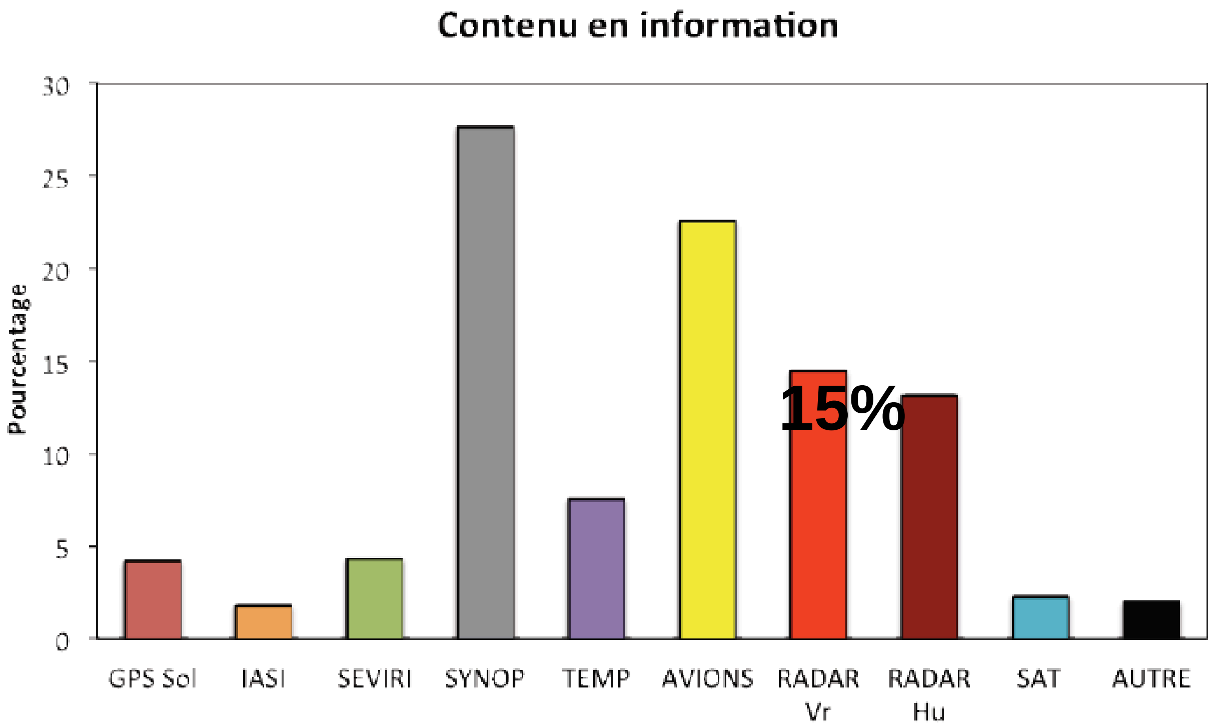


Figure 7 : Contenu en information des observations assimilées (exprimé en pourcentage) dans le modèle AROME pour la journée du 11 Octobre 2012 (avec des pluies importantes) Courtesy J-F Mahfouf, MeteoFrance

Case study: 11 Oct 2012 15% of forecast improvement due to radar winds (V_r)

MeteoFrance will simulate Wivern impact and quantify trade-offs of changes in: revisit time, vertical resolution, surface blind zone.

Currently no direct UK involvement

Conclusions

The Wivern system has the ambition and potential of providing global measurements of winds, rainfall & ice water, with 50km horizontal and 1km vertical resolution and daily visits poleward of 50°.

Wivern can represent an essential component of the Global Observing System for the monitoring of the vertical structure of winds, a key aspect for capturing early stages of cyclogenesis and thus improving NWP of European wind storms, tropical cyclones (e.g. 2008 - 138,000 deaths 'Nargis' in Myanmar), flash floods with obvious societal benefits ➔ impact on operational services.

Wivern complements in cloudy areas observations from scatterometers, ADM-AEOLUS and cloud motion winds from sequential geostationary images.

An ***end-to-end simulator*** of the instrument has been developed based on the heritage of the EarthCARE simulator ➔ tool for assessing instrument-related uncertainties.

Ground-and airborne demonstrators are currently operated for providing a full proof of concept for the polarization diversity.

In preparation of EE9 bid future activities should focus at:

1) Full evaluation of ***costs and technological challenges*** with current specs.
2) In-depth assessment of benefit of line-of sight observations in a data assimilation system ***(OSSE)***.