WIVERN: A WInd VElocity Radar Nephoscope or a figment of the imagination?

Providing global measurements of winds, rainfall & cloud ice water, with 50km horizontal and 1km vertical resolution and daily visits poleward of 50°

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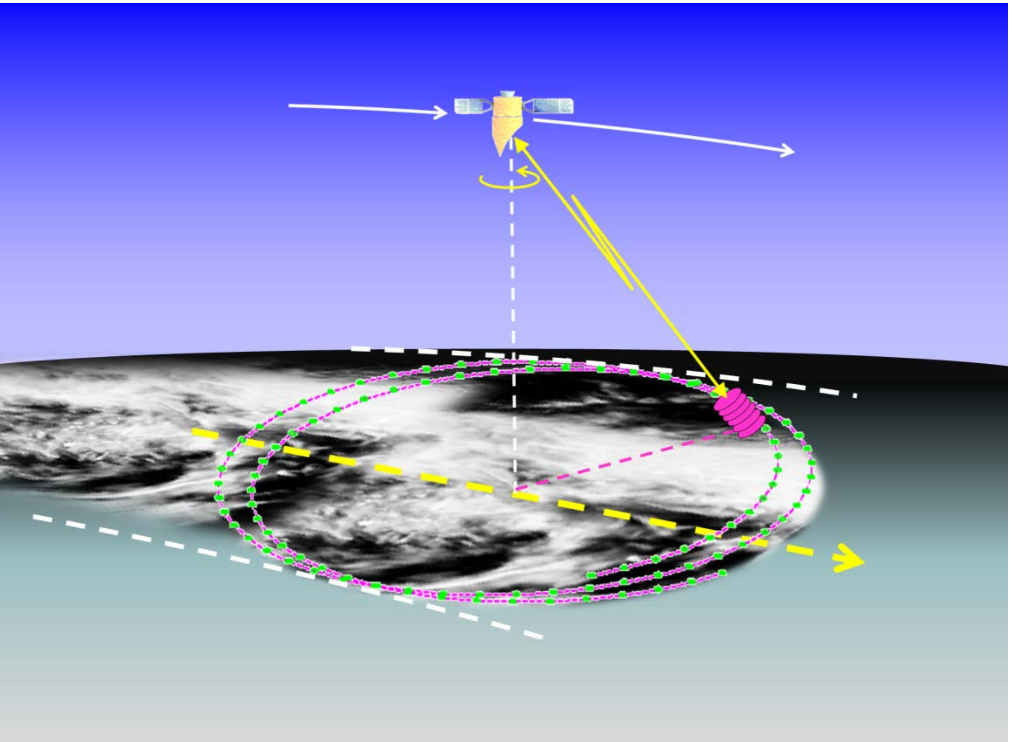
NCEO/CEOI Joint Sci Conf , Sheffield, 26 June 2014.

Results of a study for ESA by Astrium (Airbus DS) and U of Reading;
2014-2015:   NCEO/CEOI funding Univ Reading and Leicester for ground based evaluation of the radar concept.

1. WIVERN – RADAR CONCEPT



BASELINE: 800km swath:
Slant range 651km
Conical scan 37.9° off-nadir
(41.4° off zenith at surface)

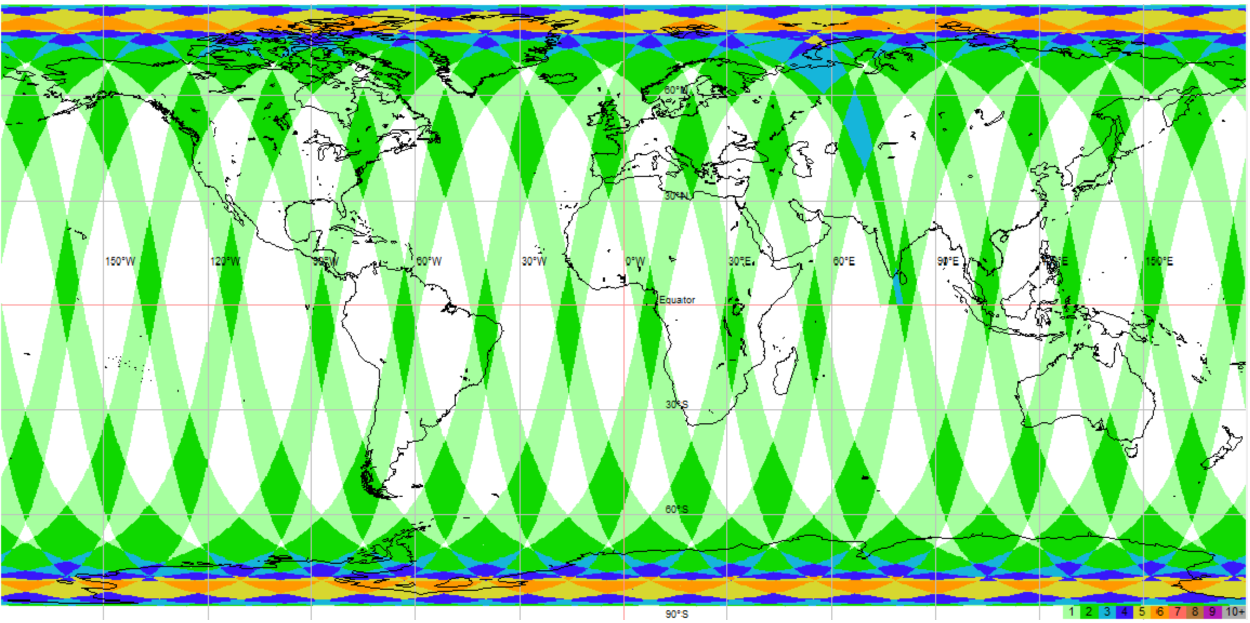
Scan every 7 seconds
- move 50km along track
- sample every 50km along arc

NARROW BEAM - must use 94GHz – 2.9m elliptical antenna
- 3dB two-way beamwidth 0.001rad - pulse length 500m,

Detect line of sight winds - Doppler shift of cloud return also precipitation rate and cloud ice water content.

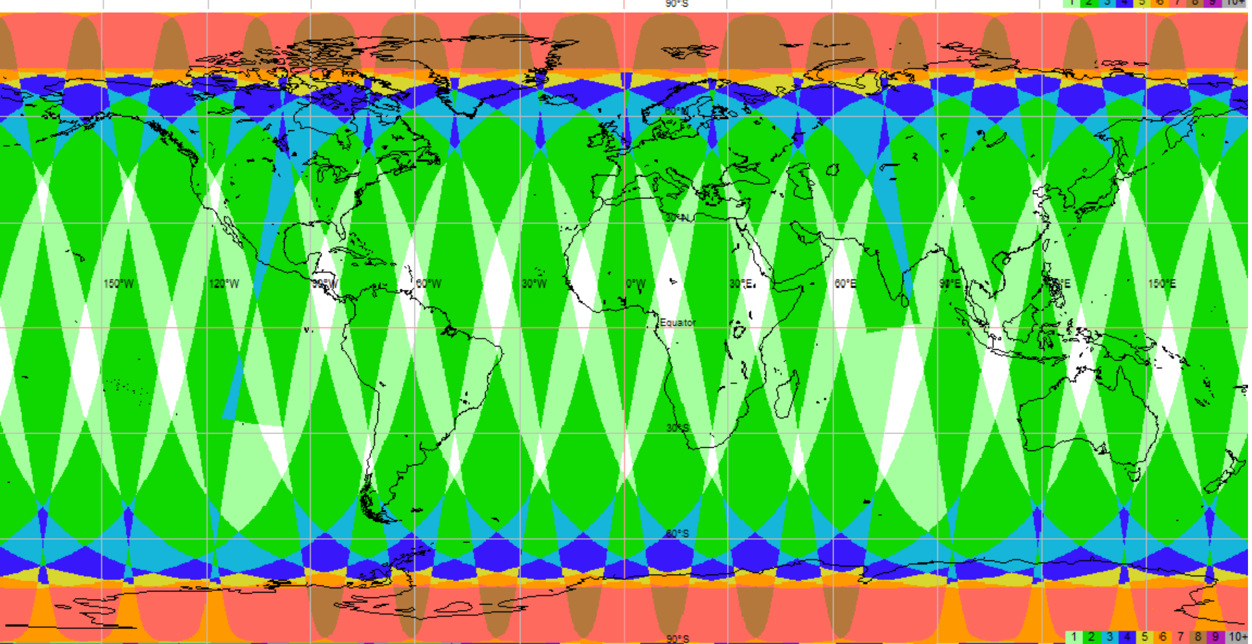
Two configurations 1: 500km orbit /800km full swath, and
2: For shorter revisit time, 700km orbit/1800km swath

Trade off – halve revisit time, lose 6.5dB sensitivity?



500Km ORBIT
800Km
SWATH

Dark green twice a day
Light blue three times



700Km ORBIT
1800Km
SWATH

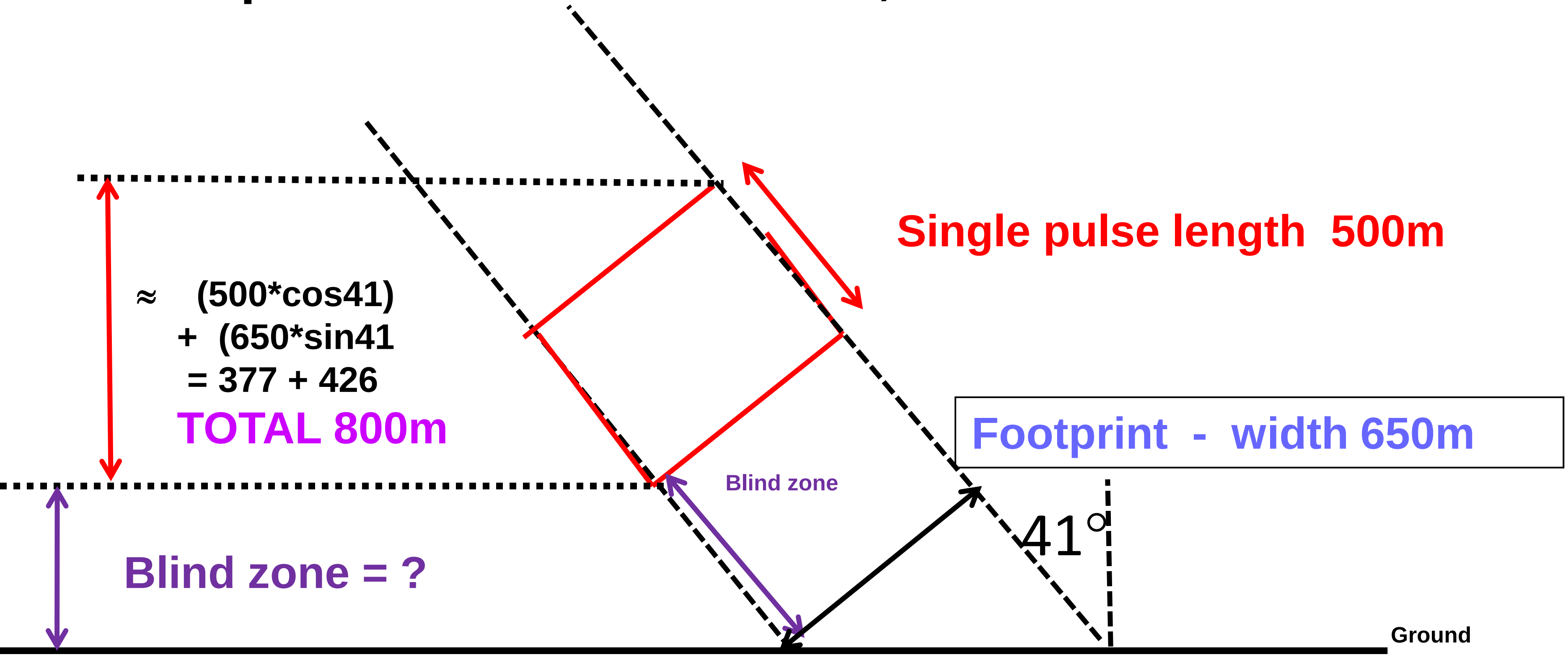
Slant path 1178 not 651km, lose 5dB sensitivity,
Plus 1.5dB loss = longer circumf

Total loss 6.5dB

2. MAJOR DRIVER: VERTICAL RESOLUTION <1km

800Km SWATH – 500km orbit – range 650km,

elliptical antenna – 0.001rad, beam width 650m M



VERTICAL RESOLUTION OF PULSE IS ≈ 800m (3dB point)

{BROAD 1800km SWATH – VERTICAL RESOLUTION 1200m}

3. WIVERN – REQUIREMENTS AND PRODUCTS

WMO Rolling Requirement Review (RRR)

Horizontal wind	Uncertainty	Horiz Res'n	Vert Res'n	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

WIVERN PERFORMANCE:

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

Surface ppn	Uncertainty	Horiz Res'n	Observing Cycle
Goal	0.1mm/hr	0 .5 km	6 min
Breakthrough	0.5mm/hr	15 km	30 mins
Threshold	1 mm/hr	50km	6 hrs

WIVERN PERFORMANCE:

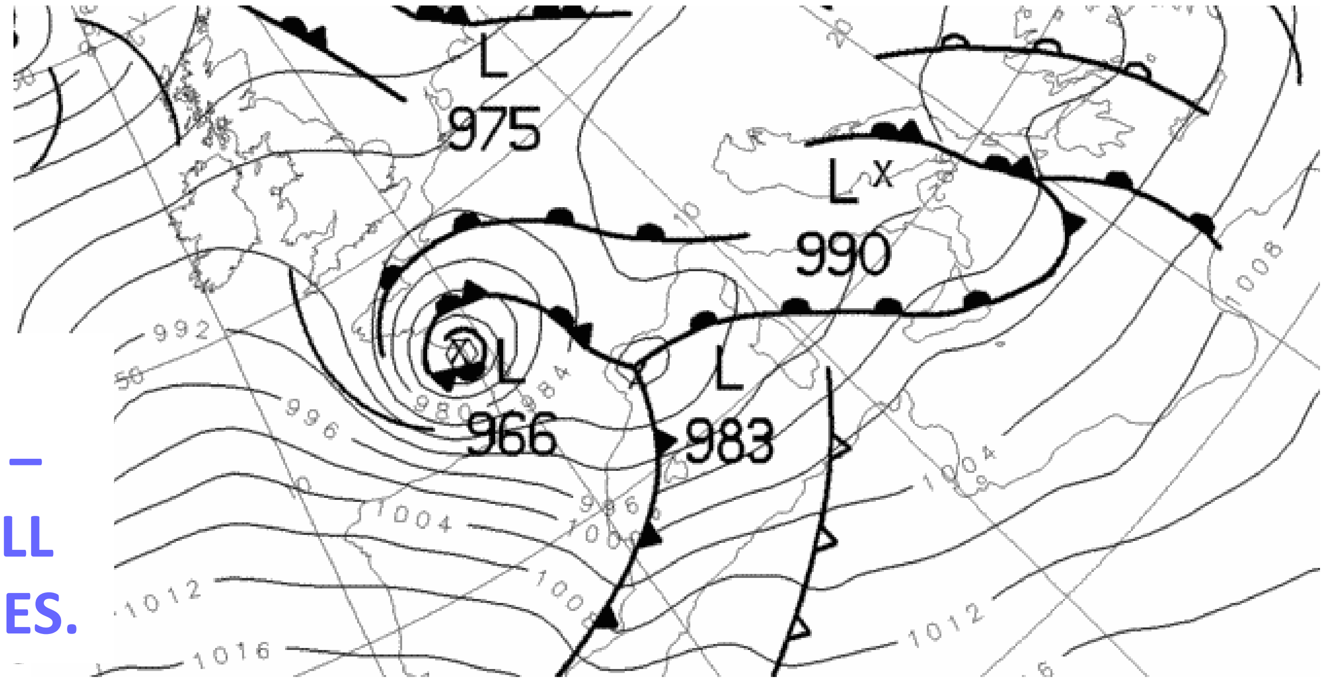
Precipitation	1mm/hr	50km/1km along arc	(12)/24 hours
Ice water content	50%	50km/1km along arc	(12)/24 hours

APPLICATION OF WINDS FROM WIVERN?

Winds in cloudy regions, accuracy 1 to 2 m/s or better, with 50km horiz and 1km vertical resolution: revisit every 12 hours.

NOT FOR INDIVIDUAL SHORTLIVED THUNDERSTORMS

'KLAUS' 24 Jan 2009
26 deaths
1.7 million without Electricity.



ST JUDE STORM 0500H 28 OCT 2013 – RAILWAYS CLOSED TILL 0900H TO CLEAR TREES.

ALL THOSE VERY DEEP DEPRESSIONS UK DEC 2013 – FEB 2014

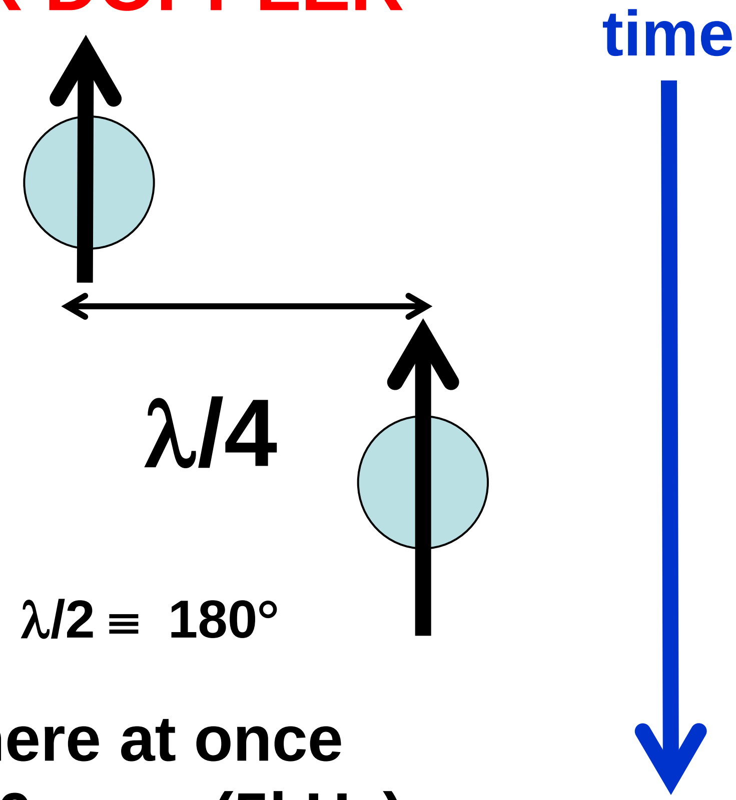
1999 - £18.5B windstorm damage in Europe
2008 - 138,000 deaths 'Nargis' in Myanmar
2013 – better warnings only 43 deaths – super-cyclone 'Phailin' India Oct 2013

4. CAN WE GET DOPPLER TO WORK IN SPACE?

PULSE-PAIR DOPPLER

Pulse one

Pulse two
Δt later



Move $\lambda/4$=800µm: Extra path length $\lambda/2 \equiv$ 180°

Only one pulse in the atmosphere at once
– 30km separation, Δt = 200µsec (5kHz)

FOLDING VELOCITY = 800µm in 200µsec = ±4m/s
BUT WE NEED TO MEASURE UP TO 150m/s!!

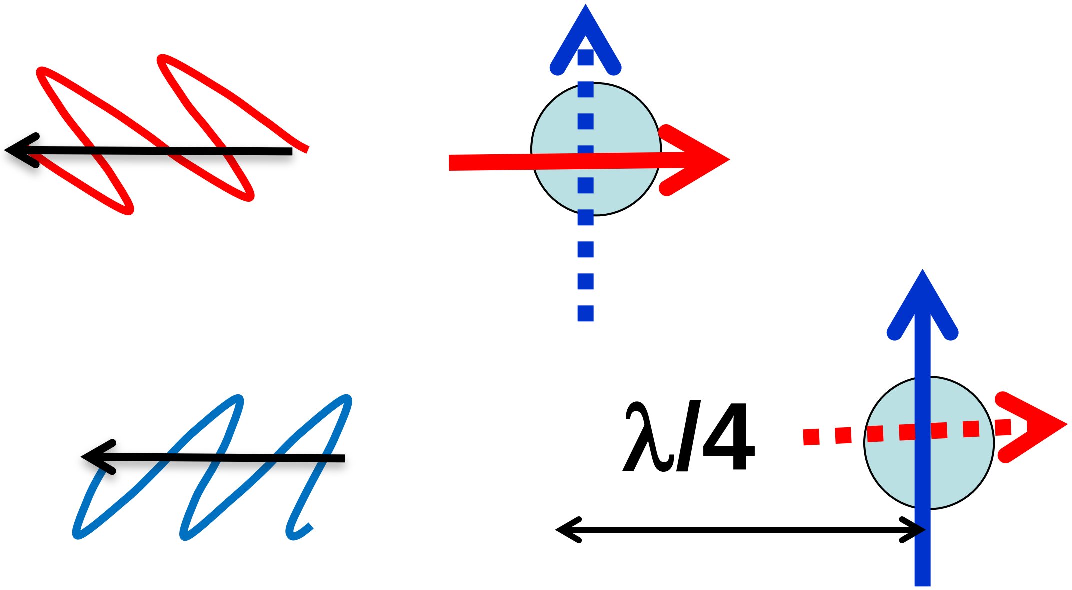
SOLUTION: CLOSELY SPACED PAIR OF H AND V PULSES

SMALL SPHERES: RAYLEIGH SCATTERING

ASSUME H AND V PULSES ARRIVE IN PHASE (no propagation difference)

H pulse

V Pulse
5µsec later



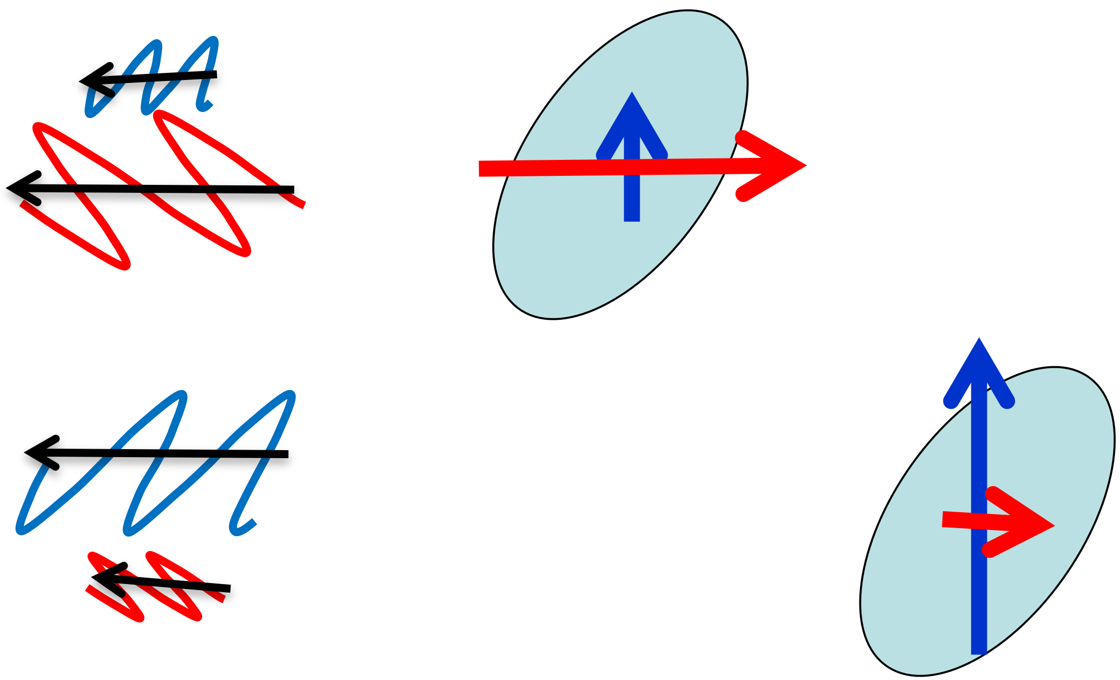
The H and V dipoles are coincident in space.
(Zrnic, 1977, Kobayashi, 2002 – suggested but never implemented)
FOLDING VELOCITY = 800µm in 5µsec = ±160m/s
and 1m/s IS ABOUT 1°

WHEN FIRST (H) PULSE HITS GROUND, RETURN DEPOLARISES AND OBLITERATES V PULSE RETURN. WITH 5µsec (750m) SEPARATION CAN MEASURE DOWN TO 1KM ABOVE GROUND ('BLIND ZONE')

PROBLEM: OBLATE WET ORIENTED HYDROMETEORS **DEPOLARISE** EVEN FOR RAYLEIGH SCATTERING

H pulse
Also excites
Small V
dipole

V pulse
excites
Small H
dipole



SOLUTION: 1 in 10 TWIN PULSES IS A SINGLE H/SINGLE V.
IF RETURNS IN BOTH H &V – CROSS TALK - FLAG DATA
PROBABLY DIFFICULT TO MAKE MEASUREMENTS IN THE CORE OF CONVECTIVE STORMS AND V HEAVY RAINFALL

5. EXISTING SATELLITE WINDS FROM SPACE

Scatterometer winds surface winds over the sea.

Two scatterometers in orbit – ASCAT & OSCAT. 6 hour revisit

700km orbit, 1800km swath. 1m antenna spinning: 3 second period.

50km resolution surface winds – positive impact on forecast.

Cloud motion winds sequential geostationary images

- **Up to 2km error in height assignment**
- **Orographic clouds appear stationary**
- **Mostly during the day. Use water vapour at night.**
- **Can't see into the clouds and hazardous weather systems.**

ADM – Aeolus – launch 2015

Measure Doppler shift from molecules in cloud free atmosphere.

Look 35° across track – narrow strips 1500km apart at the equator.

Wind profile (±2m/s) every 100km (14secs) along track;

1km vert resolution. In the clear air - up to 6171 profiles per day

JET STREAMS: STEERING SYSTEMS: GOOD FOR 4 -5 DAY FORECASTS

6. HERITAGE

CloudSat first 94GHz radar in space: 1.2km swath.

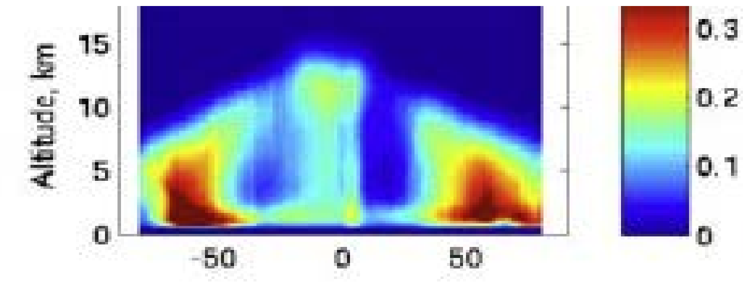
Tube lifetime was a worry, but since launch 2006, power loss <0.5dB.
Sensitivity and ability to detect clouds now known from CloudSat.
Transmits high power pulses – duty cycle 1.2% - mean power 20W

DOPPLER SENSITIVITY FOR SCANNING INSTRUMENT

Transmit chirps rather than CloudSat's single pulse
10dB more power (technique well established)
for broader swath rather than nadir pointing.
(CPI – tube manufacturer – mean power OK)

Doppler accuracy 2m/s for 50km along arc
for clouds with reflectivity above - 25dBZ

From CloudSat these occur 25-30% of the time
in the mid-latitude storm tracks



DJF N S

Cloudsat – Zonal average of fraction of the time with clouds with Z >-25dBZ

7. FSO – Forecast sensitivity to observations.

New technique can now quantify impact of individual observations in reducing forecast error

METEO-FRANCE ASSIMILATE LINE OF SIGHT WINDS FROM GROUND BASED PRECIPITATION RADAR

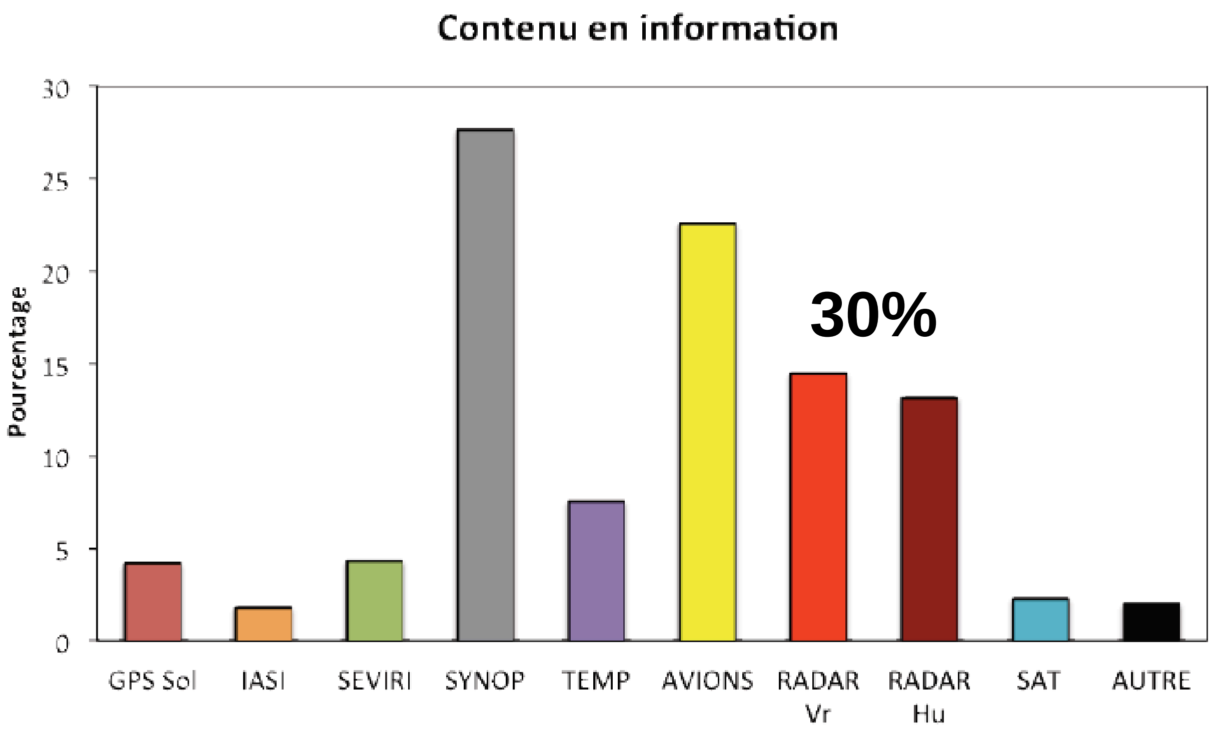


Figure 7 : Contenu en information des observations assimilées (exprimé en pourcentage) dans le modèle AROME pour la journée du 11 Octobre 2012 (avec des pluies importantes)

11 Oct 2012
30% of forecast improvement due to:
POSITIVE IMPACT OF WINDS (Vt)
ALSO OF KNOWING ICE WATER CONTENT FROM Z ‘Humidity’

CAN CARRY OUT EXPERIMENTS OF WIVERN IMPACT, EFFECT OF:
REVISIT TIME
VERT RESOLUTION
BLIND ZONE.

NERC IS FUNDING EVALUATION STUDIES

NERC FUNDED STUDIES (UoR) 2014
Upgrade existing 94GHz radar at Chilbolton so it can transmit twin pairs of H-V and V-H pulses, and occasional H or V single pulses.

CEOI funding 2014-5 (Univ of Reading and Leicester - Battaglia)
1.Make 3 months continuous measurements

2.Frequency of depolarising targets – identification – and effect on Doppler retrievals.

3. Frequency of ghost echoes when big vertical gradients of Z

4. H-V, V-H to identify differential phase shift on backscatter of targets.

5. Any occasions of multiple scattering?

6. Rainfall measurement at 94GHz?

5 FUTURE STUDIES NEEDED for TRL5

1.CONFIRM EXTRA 8dB POWER THROUGH PULSE CODING to get broad swath? Quantify range sidelobes – effect on blind zone.

2. Optimise antenna trade-off: minimum beamwidth for good vertical resolution without compromising cross polar isolation

3. Beam waveguide rotary joint – so the heavy transmitter not rotating.

4. Confirm we can achieve accurate pointing knowledge for elevation & azimuth of conical scan to correct for 7000m/s satellite motion. (Learn from ADM-Aeolus – it has this problem as well)

5.What is the sea and land return at 45deg at 94GHz and its effect on the blind zone?. Collaboration with French 94GHz airborne radar (Rasta

STUDIES BY WEATHER SERVICES ON IMPACT ON REDUCING FORECAST ERRORS FOR VARIOUS TRADE-OFFS:

a) Swath width/revisit time v loss of sensitivity and resolution?

b) Vertical resolution 1km or 2km c) Blind zone: is 1km or 2km OK?

H AND V PULSES – TARGETS > λ, MIE SCATTERING?

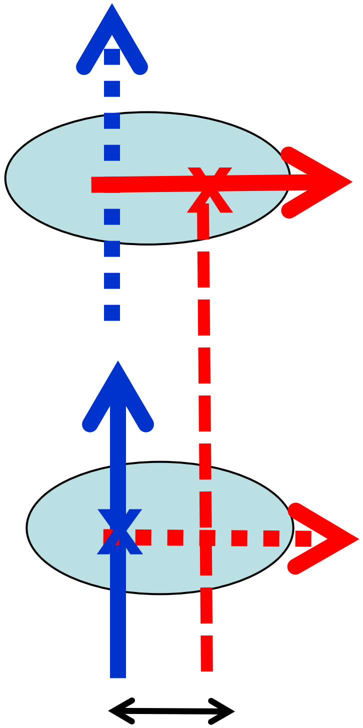
DIFFERENTIAL PHASE ON BACKSCATTER (δ)

APPARENT VELOCITY – EVEN IF STATIONARY

ASSUME H AND V PULSES IN PHASE (PROPAGATION THE SAME)

H pulse

V Pulse
5μ sec later



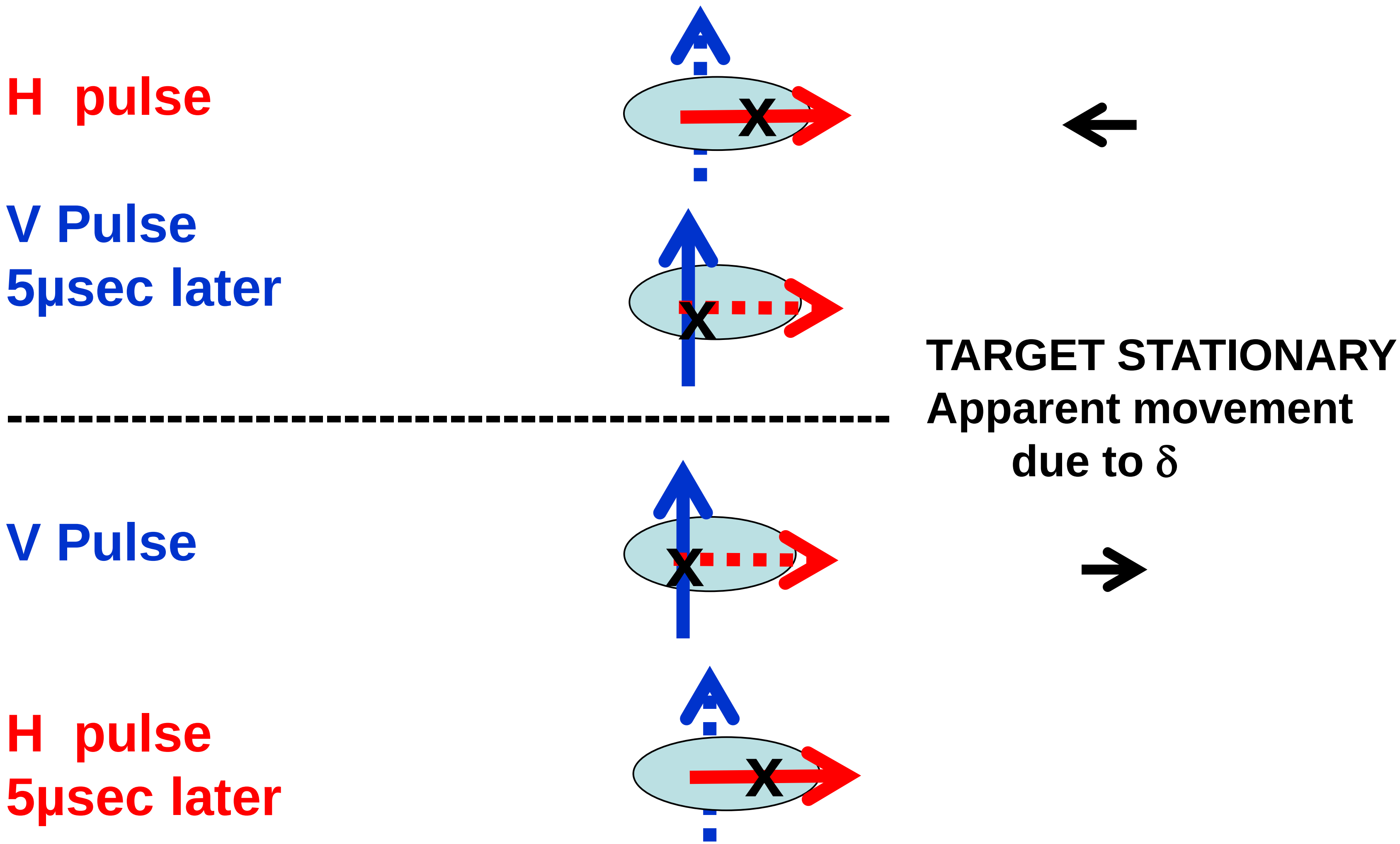
Apparent movement: δ a few degrees (i.e. velocity of a few m/s)

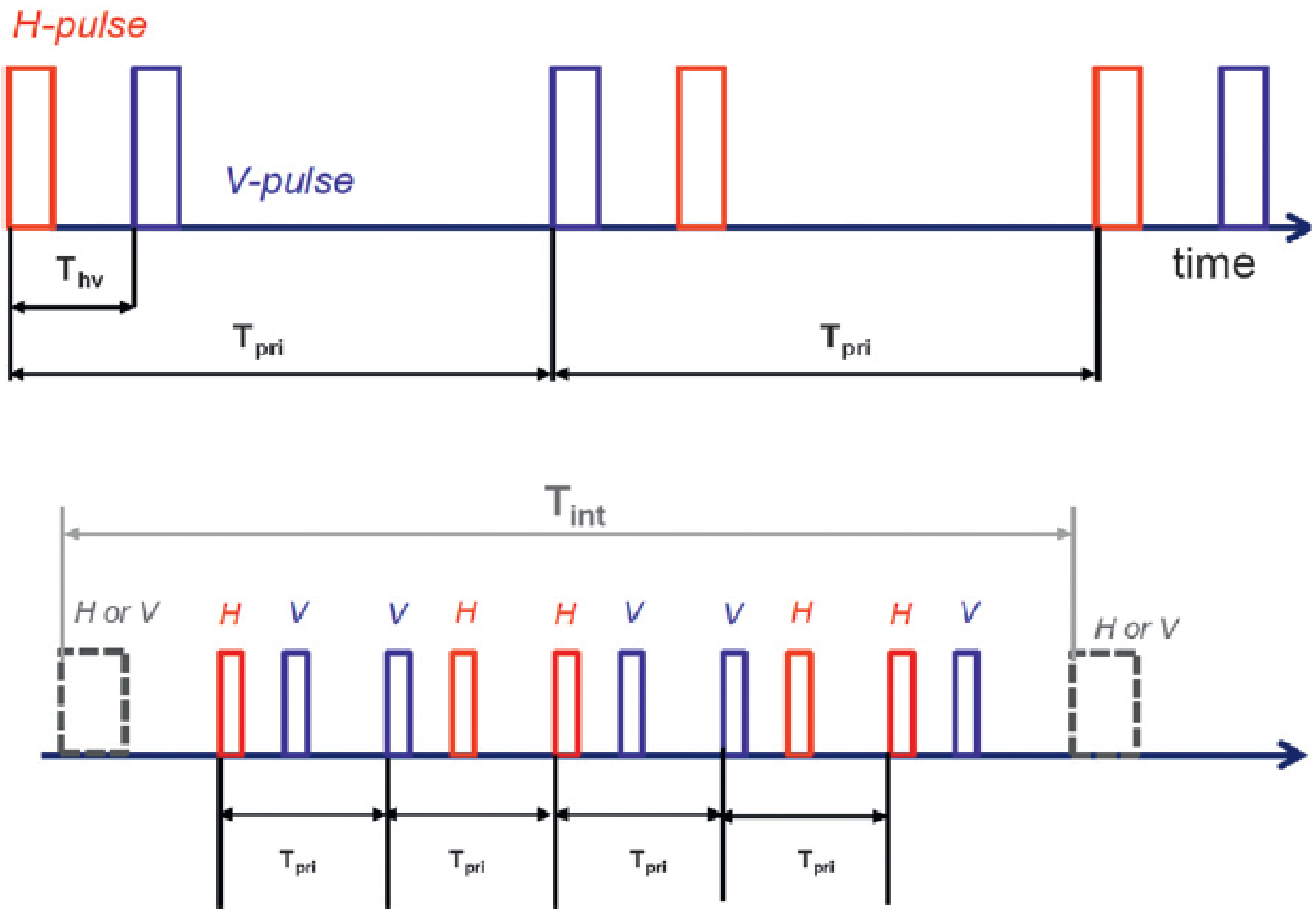
THIS PROBLEM occurs for droplets and ice particles ≈ ≥ λ (3.2mm)

SOLUTION – SEND H-V PULSE PAIR, THEN V-H ‘TWIN PAIR’

Average the two : δ - CANCELS OUT – true velocity

Propagation: provided H and V pulse arrive with the same phase





Top: pulse patterns for a polarization diversity mode. T_{hv} and T_{pri} represent a pulse-pair interval and a pair repetition interval, respectively. Bottom: schematic for the interlaced LDR mode. The T_{int} is the repetition interval of the LDR mode, typically $T_{int} >> T_{pri}$. Extracted from Battaglia et al., 2013b

7.DOPPLER SWATH NEED MORE POWER THAN CLOUDSAT

CloudSat: 3µsec pulses @ 4kHz: 1.2% duty cycle 24W mean power.

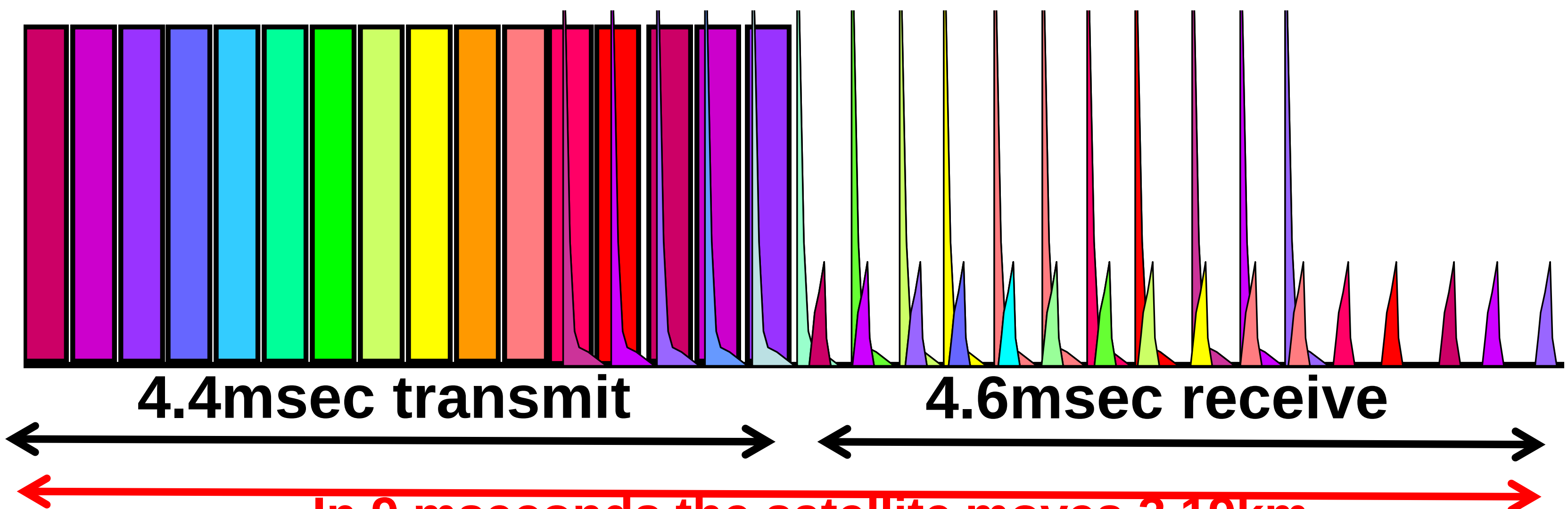
CLOUDSAT TUBE HAS OPERATED FOR 7 YEARS WITH NO PROBLEMS.

DISCUSSION WITH CPI – CAN TRANSMIT 200W MEAN POWER.

PROPOSE: A series of chirps each 40µsec (6km), each chirp compressed to a range resolution of 500m as for CloudSat. Frequency hop each chirp so that the spreading ground returns don't interfere with next chirp.

110 x 40usec = 4.4msec transmit. Then 4.6 msec SILENCE: 9msec total.

9msec is round trip time for 650km slant range. Duty cycle 48%.



110 chirps each 40µsec long with a different frequency - every tenth chirp H only.

Send 16 of these pulse trains in 144 msecs – satellite moves 50km along the arc.

With a total of 1600 chirps in H and V (from two klystrons)

3. Sampling characteristics for two orbits

	BASELINE		WIDE SWATH
ORBIT/full swath	500/800	km	700/1800
Incident angle off zenith	41.4	deg	57.7
SPEED at surface	7.063	km/s	6.766
50km along track (s)	7.08	s	7.39
SCAN CIRCUMFERENCE	2513.2	km	5654
SCAN SPEED	354.9	km/s	765.2
SLANT RANGE	650	km	1178
ROUND TRIP/Dead time	4.34/4.64	msec	7.85/8.15
Pulse train repeat	9.00	msec	16
in distance	3.19	km	12.24
data and dead zone	1.54/1.65	km	6.00/6.24
40usec chirp sample length	14.2	m	30.6
Number of 40usec chirps	110		195
Of which H/V chirps	100		180
Number of pulse trains	16		4
Over a distance of	51	km	48.96
with number of samples	1600		720
Sample time along ‘50km’ arc	144	msec	64

5. APPLICATION OF WINDS FROM WIVERN?

Winds in cloudy regions, accuracy 1 to 2 m/s or better, with 50km horiz and 1km vertical resolution. No need for two looks to get full vector wind.
Two line of sight winds equivalent to one full wind vector (Eyre, ESA, 2002)

a)Complement ADM Aeolus clear air winds.
ECMWF expects these winds to have a positive impact on the medium range forecasts – steering winds for synoptic systems.

b) Scatterometer winds 50km resolution surface winds.
ECMWF , Met Office – positive impact on forecast.
Wivern will provide vertical profile.

c) MeteoFrance – Line of sight winds from dense ground based rain radar network. Winds from precipitation. Good vertical resolution. Every 15 mins. Can capture rapidly evolving systems for high resolution models.

WIVERN revisit time 12 hours – not frequent enough for tracking individual convective storms. Application is for more long lasting features .
Would winds over the ocean help 24-48hr forecast for developing systems?
e.g. the deep depressions developing over Atlantic during winter of 2013-2014

Why do we want high resolution global profiles of winds, clouds and precipitation twice a day?

Data assimilation to better initialise weather forecast models – must revisit in a time shorter than the lifetime of the feature.

Better understanding of physical processes, for improving and evaluating parameterisations in climate and forecast models.

379kg (instrument) + 558 (platform) 938kg + 30% = 1218kg

Radar: peak transmit 1800W, mean 176W

Total mean power 2.2kW: 19.6m^2 solar array.

2.9m by 1.8m elliptical antenna??

2.9m to minimise the vertical extent of the radar pulse.

Will (just) fit in the rocket

Spinning antenna mass not critical: 3m antenna ≈ 25kg

DOPPLER SENSITIVITY FROM SPACE

CLOUDSAT nadir pointing – In 160msec moves 1km along track.

Transmits 3usec pulses at 4kHz: 1.2% duty cycle.

Detects echoes down to -30dBZ

See nearly all ice cloud sand some stratocumulus

Rainfall of 3mm/hr is +30dBZ - one million times higher

WIVERN In 144msec moves 50km around the cycloid arc.

Transmits FM chirps - 10 times more mean power.

Transmit 1600 pulses

Detects echoes down to -40dBZ for 50km arc.

MUST HAVE SNR for single pulse of 0dB for Doppler

i.e. signal root(1600) = 40 = 16dB higher,

but gain 1.5dB for two gates per vertical km

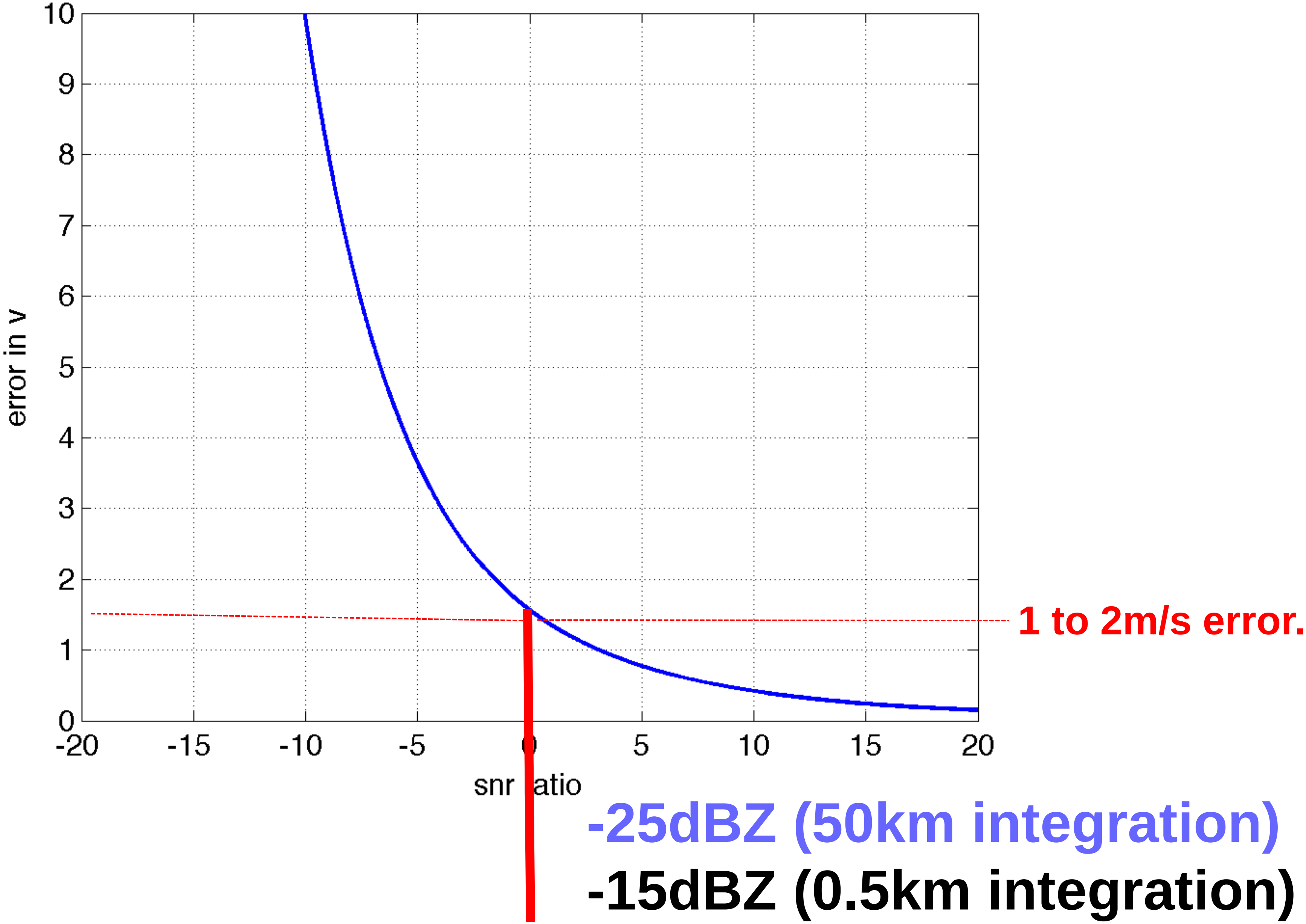
For Doppler accuracy of 1 to 2m/s

must have Z > -25dBZ (-19dBZ for broad swath)

(for an integration of 50km along the scan)

DOPPLER PERFORMANCE: 50km integration

1600 PULSES PAIRS - 5µsec H/V separation



-25dBZ (50km integration)

-15dBZ (0.5km integration)

nephoscope
[n] - a grid-like measuring instrument for measuring the altitude, direction and velocity of movement of clouds

Михаил Михайлович Поморцев

As a result of observing the movement of clouds Pomortsev constructs a device for determining The direction and angular velocity of their movement. The device consisted of a theodolite with the magnetic needle and a sundial.

9. RAINFALL MEASUREMENT (R)

At 94GHz attenuation (2-way) 1dB/km per mm/hr

So poor Doppler winds in heavy rain >10mm/hr;

1. Use Z-R Up to 0.1mm/hr and snow, little attenuation (as for CloudSat) (best method for measuring global snowfall!)

2. Attenuation of sea surface return. CloudSat estimates up to 10mm/h e.g. 4km depth of rain -40dB attenuation. NO GOOD OVER LAND. WIVERN: sea surface return down by 30dB; limited dynamic range, OK up to 3-4 mm/hr?

3. Gradient of Z. Z every 500m along slant path. 10mm/hr, ΔZ 5dB/gate. Assume rain constant across 700m footprint, and with height.

4. 'KDP' the H wave lags behind the 'V' wave in heavy rain because of large oblate raindrops, KDP; the increase in H-V phase diff with range is proportional to rain rate . Used at C band when Z attenuated. Never attempted at 94GHz – should work in theory – need to test.

WOULD HAVE RAINFALL ESTIMATE EVERY KM AROUND THE CYCLOID

ACHIEVED USING FOLLOWING NOVEL RADAR IDEAS

1. Elliptical antenna - better vertical resolution.
2. H/V pulse pairs – to get high folding velocity
3. H/V – V/H: to remove δ (diff phase shift Mie scattering)
4. 10% of twin pairs replace by single H and single V
   – to flag potential crosstalk due to depolarisiation.
5. 4.3msec Transmit, then 4.6 msec silence.
   – can send long coded pulse with monostatic reception.
6. 4.3msec FM/CHIRP – higher mean power: +8.6dB gain.
7. Frequency hop each H-V chirp pair
   – suppress previous pulse ground return.
8. Sweep COHO as scan – to reject co-time ground clutter.
9. Off-nadir ground return down by 30dB cf nadir.
10. Rain rates from attenuation - vertical gradient of Z,
    or differential phase shift (‘KDP’)

10. WINDS BIAS MUST BE < 0.5m/s

The spacecraft is moving at 7000m/s, for bias <0.5m/s,
Need pointing to 1 in 14,000, or 70urad (1 deg is 20,000urad)

ELEVATION ANGLE BIAS – conical axis must be symmetrical around zenith. Angle constant to 50urad, i.e. Range of sea surface constant to within 28m. Can measure this using the radar in altimeter mode (pulse length 500m).

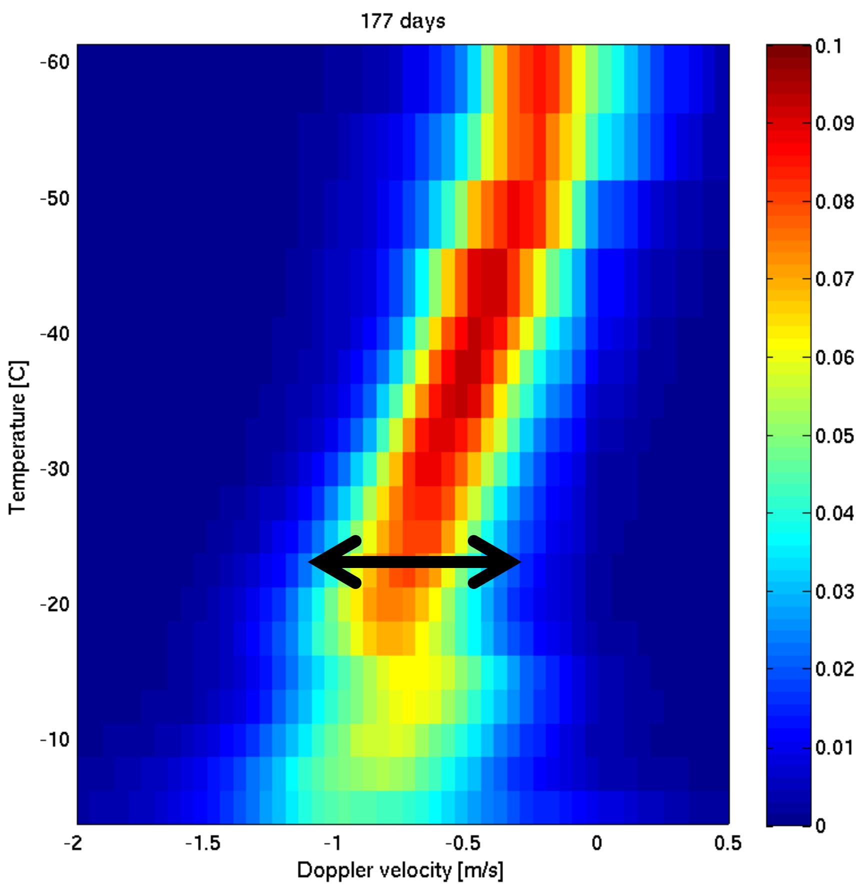
AZIUTHAL POINTING KNOWLEDGE – must be within 70urad (slant range 650km so: 46m along the ground).!
Zero velocity when pointing exactly across track.
For solid ground - not ocean (moving waves)
but ground depolarises – so use two successive pulses of the same polarisation (no folding problem – velocity low)

CORRECT FOR TERMINAL VELOCITY OF HYDROMETEORS.

Can we CORRECT TERMINAL VELOCITY TO 0.6m/s?

ICE CLOUDS

Analysis of 177 days of ground based 35GHz vertically pointing radar at Chilbolton. Use of T looks pretty good! Use Z as well – even better.



RAIN:

C-BAND RAIN FALLS AT 6-7M/S.

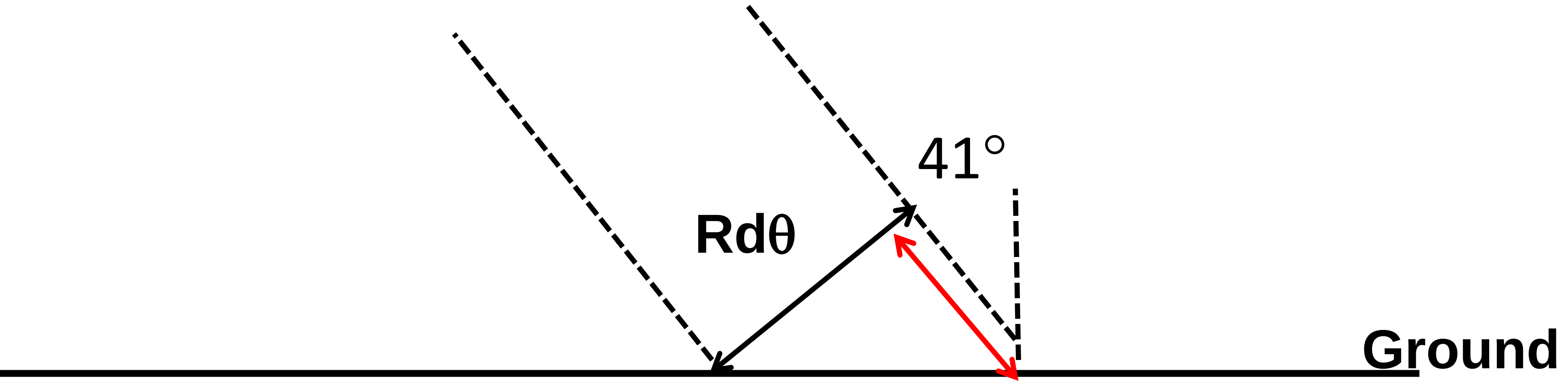
94GHz max speed about 3m/s. (Mie scattering reduces the radar return from the larger drops).

WORK IN PROGRESS ON HOW GOOD IS THIS CORRECTION.

ELEVATION POINTING KNOWLEDGE

500km orbit – range 651km

Use the radar as an altimeter.



Error of Rdθ in elevation :

extra range Rdθ tan(41) = 650,000 (1/17,500) .87 = 32m

Need to measure the rise time for the pulse from the sea surface with an accuracy of 32m (or 213nsecs), total pulse length 3.3usec (500m).

Need an A-D of (say) 10MHz. Footprint on the sea about 1km diam – surface perturbations much smaller and will be averaged out.

Monitor any changes in return time of pulse around the scan, and correct the velocity for this mis-pointing. Can also detect nutation.

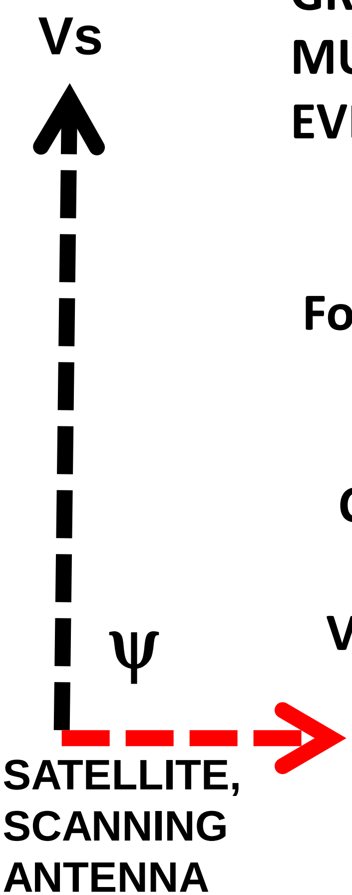
QUESTION – Do we expect any changes of the axis of rotation as the satellite goes around the orbit. Measurements over ocean only.

AZIMUTHAL POINTING KNOWLEDGE: CAN'T USE CLOUDS THEY MOVE GROUND TARGETS ACROSS TRACK STATIONARY :

NEED dψ to 1 in 14000.
AT RANGE OF of 651km distance along the arc is 46m.

GROUND TARGETS – MIE SCATTERING (phase shift between H and V).
MUST USE CHIRPS OF ONLY H OR ONLY V.
EVERY 40μsecs – folding velocity 800μm/40μecs = 20m/s
Ground velocity of 0.3m/s will be 3° phase shift
- at 355 m/s around the arc chirp every 14m
For velocity from a single chirp need Z > -10dBZ
- Z of ground clutter should be larger than this.

Clutter randomly positioned within the beam - average over many
to get true zero velocity average over many gates and scans .
Velocity change across beamwdith (0.0016rads) due to spinning
0.0016*4200 = 6.7m/s. < folding velocity ± 20 m/s
averaging should work



3.4 BIAS: NON-UNIFORM BEAMFILLING (NUBF)

AZIMUTHAL NUBF:

Consider a 50km length of arc with non-uniform Z, the variation in azimuthal angle is 50/400 = 0.125 or about 7°.

Remembering that the COHO is continually changing to compensate for the velocity due to the spinning motion, then as we will know the distribution of Z along the arc for each pulse train (1.6km), then the true weighted wind direction can be derived to better than 1°.

VERTICAL BEAM FILLING.

The vertical beam width is 800m, and in the presence of a vertical gradient of reflectivity the wind will be representative of the velocity at a height rather lower than the beam centre. This height can be estimated from the gradient of Z estimated from the slant path of neighbouring azimuthal paths (for the 50km arc, the slant paths will be available every 1.6km)

INHOMOGENEITIES IN INDIVIDUAL PIXELS.

The WSDR study has drawn attention to this effect. It is important for Individual convective updraughts on the scale of about 1km (one pulse train). Such small scale features cannot be represented by the NWP models and their lifetime is much shorter than the revisit time, so such regions with high velocity gradients would be identified and flagged us unreliable by WIVERN.

WIVERN REFLECTIVITY COMPARED TO CLOUDSAT

APROXIMATE SENSITIVITY OF WIVERN BY SCALING CLOUDSAT'S DEMONSTRATED PERFORMANCE IN SPACE.

CloudSat: 3µsec pulses @ 4kHz: 1.2% duty cycle, 24W mean power
in 160msecs moves 1.1km along track, transmits 620 pulses.
Z sensitivity   -30dBZ

WIVERN: 40usec chirps with the V chirp 4usec behind H chirp.
Transmit chirps for 4.4msec – then 4.8msec silence for reception.
(to avoid simultaneous transmit and reception)
In 144msecs transmit 1600 pulses and move 51km around the arc.

	BASELINE	BROAD SWATH
a) Mean power, WIVERN 176W, CSat 25 W	+ 8.6dB	
b) Antenna WIVERN 2.9x1.8m, CSat 1.85m	+3.67dB	
c) WIVERN 650 km range, CSat 710km	+ 0.8dB	(1178km; -4.4dB
d) WIVERN 1600 pulses, CSat 620pulses	- 2dB	(720 pulses -0.3dB
e) WIVERN 144msec, CSat 160msec	- 0.45dB	(64msec -4dB
NET IMPROVEMENT OF WIVERN	+10dB	(BROAD SWATH +4dB

CloudSat was -30dBZ as it went 1.1km along track,
so WIVERN -40dBZ for 50km along track. (broad swath -34dBZ)

DOPPLER PERFORMANCE

APROXIMATE SENSITIVITY OF WIVERN BY SCALING CLOUDSAT'S DEMONSTRATED PERFORMANCE IN SPACE.

WIVERN: Transmits 1500 chirps in H and V every 135msecs while moving 50km around the scan circumference.

CloudSat was -30dBZ as it went 1.1km along track,
so WIVERN -40dBZ for 50km along the arc.
Doppler need the single pulse SNR about 0dB:
1600 pulses so SNR for single pulse down by 40 or 16dB
WIVERN single pulse SNR of 0dB for a Z of -24dBZ
Two pulses per km in height (extra 1.5dB)

GOOD DOPPLER (1 to 2m/s error)

	RESOLUTION	Z	No samples
	50km	-25.5dBZ	1500
single pulse train	1.6km	-19.5dBZ	100
single chirp	16m	-10dBZ	1

3. BIAS IN WINDS

ECMWF – MUST HAVE MINIMAL BIAS IN THE RETRIEVAL

'less than 0.5m/s' - random errors OK (within reason)

FOUR SOURCES OF BIAS:

Pointing error (dominated by satellite motion 7000m/s)

3.1 Error in elevation: scan is not symmetric about the zenith direction.

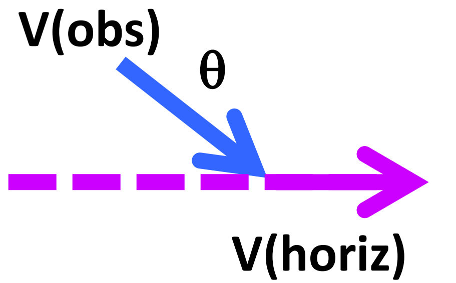
3.2 Azimuthal error: how do you know where you are around the scan

V(obs) = V(horiz) $\sin\theta$ and $\theta = 41°$ (zenith angle at ground)

and sin(41) = 0.75 so need V(obs) bias < 0.3m/s.

Component of satellite motion (7000m/s) as we scan:

V(obs) = V(sat) $\sin\theta$ $\cos\psi$ (ψ is azimuth angle from long track)



3.3 Terminal velocity V(t) will give a component V(obs) = V(t) $\cos\theta$

and an apparent V (horiz) = V(obs) /$\sin\theta$ = V(t) $\tan\theta$

tan 41 = .87, so need V(t) to 0.5/.86 = 0.6m/s.

3.4 Beamfilling ADM Aeolus correct for vertical gradient in return from molecules.

So wind velocity not from centre of gate for a non-uniform target

WIVERN: a) Vertical gradient of Z, so bias because wind not from mid-height of pixel.

b) Non-uniform beam filling of the 50km arc (7degs in azimuth).

POINTING KNOWLEDGE

Component of satellite motion (7000m/s) as we scan:

V(obs) = V(sat) sinθ cosψ **must be less than 0.3m/s**

(ψ is azimuth angle from along track, θ is zenith angle at the earth)

3.1 ELEVATION ERRORS: dV(obs, θ) = V(sat) cosθ cosψ dθ **must be <0.3m/s**

{cos ψ = 1, max error along track)

cos(41) = 0.75, so 0.3 = 7000 0.75 dθ : dθ to 1 part in 17,500 (0.0032°)

- or for a range of 650km a distance of 37m in elevation across the beam,

or an extra range of 37 tan(41) = 32m.

Should be able to detect this using the radar in altimeter mode?

3.2 AZIMUTHAL ERRORS dV(obs, ψ) = V(sat) sinθ sinψ dψ

{sin ψ =1 max error is across track}

sin (41) = 0.65 , so 0.3 = 7000 0.65 dψ: dψ to I part in 15,000 (0.004°)

- or for a range of 650km a distance of 43m across the beam in azimuth,

Beamwidth in azimuth is 1km so can't use position of landmarks!

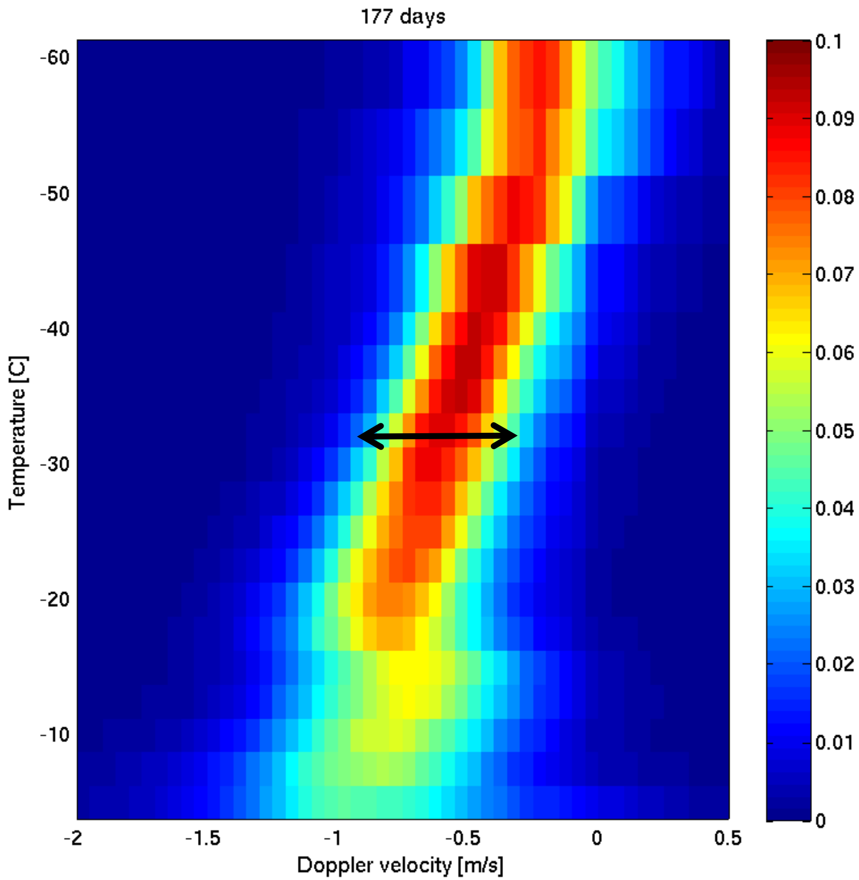
3.3 TERMINAL VELOCITY BIAS

must be less than 0.6m/s

ICE CLOUDS

Analysis of 177 days of ground based 35GHz vertically pointing radar at Chilbolton. Mean Doppler V as a function of Temperature.

If use Z as well – even better.



RAIN:

C-BAND RAIN FALLS AT 6-7M/S.

94GHz max speed about 3m/s. (Mie scattering reduces the radar return from the larger drops).

WORK IN PROGRESS ON HOW GOOD IS THIS CORRECTION.

3.2 AZIMUTHAL POINTING KNOWLEDGE

400km radius - need to know position to 43m.
Scan speed 350km/sec, need to know time to 120usecs.
(Length of chirp, 40usecs and V/H pulse 4usec)

TWO POSSIBILITIES:

3.2.1 Cloud Targets – But if the clouds moves, then the position of the maximum and minimum velocity is slightly different to the along track direction.

3.2.2 Ground Targets Zero velocity across track. The ocean waves move, so only for land, but land targets depolarise the H and V returns.

3.2.1. CLOUD TARGETS: POSITION OF MAXIMA AFFECTED BY WIND.

When same target viewed fore and aft along track, the position of max velocity moves by angle ϕ away from true along track direction:

ϕ is proportional to the West (W) and South (S) components of the wind.

Amplitude of 7 second sine wave changes from V to

$V - W\cos(\alpha) - S\sin(\alpha)$ (where α is equator crossing angle).

So plot amplitude against ϕ – to get true along track angle
(probably best to limit to low latitudes)

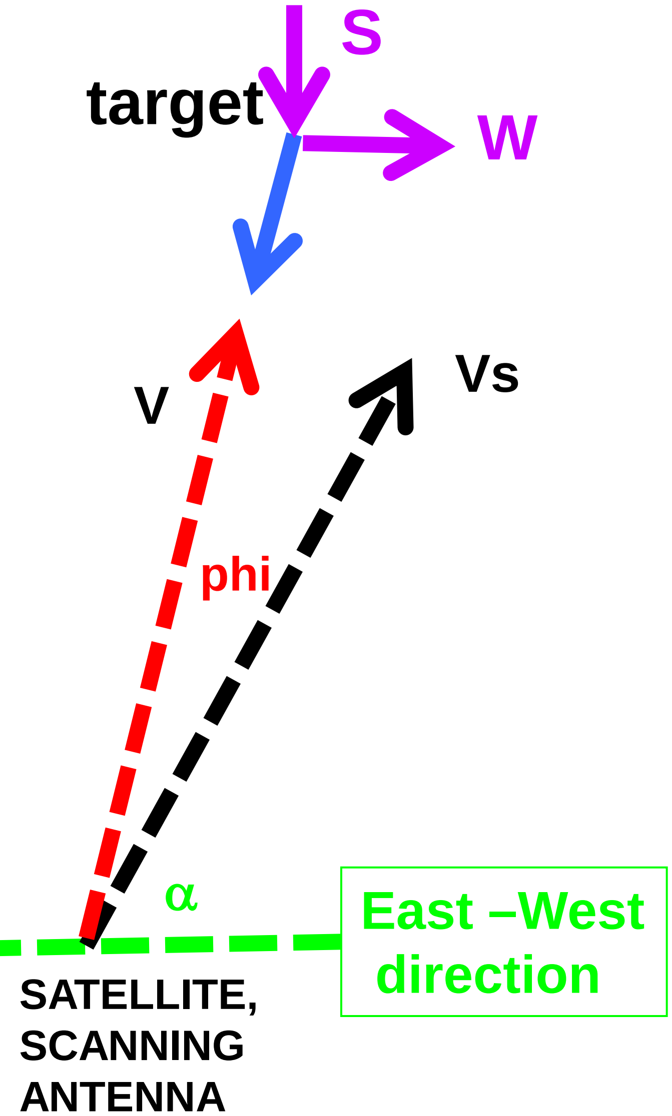
SEE FIGURE OVERLEAF FOR FULL EXPLANATION….

3.2.1 AZIMUTHAL POINTING KNOWLEDGE - CLOUD TARGETS:

Vs: velocity along track due to satellite motion.

W is the westerly component of the wind. S is northerly component

α angle crossing the equator, ϕ is the antenna scan angle away from true along track direction



Velocity, V, measured at angle ϕ from true along track direction – dashed red arrow.

$V = Vs \cos\phi - W\cos(\alpha + \phi) - S \sin(\alpha + \phi)$

ϕ for max V as a function of W:

$dV/\phi = -Vs \sin(\phi) + W \sin(\alpha + \phi) - S \cos(\alpha + \phi)$

So max when: $\phi = \{W \sin(\alpha) - S \cos(\alpha)\} / Vs$

(ϕ Is very small), & amplitude reduced to

$Vs - W \cos(\alpha) - S \sin(\alpha)$

Same ϕ shift and amplitude reduction for aft looking beam seeing the same target.

METHOD: FOR TARGETS VIEWED FORE AND AFT, at non-polar latitudes, PLOT angle (ϕ) of max V against AMPLITUDE, FIND ϕ CORRESPONDING TO AMPLTIUDE V.

Complicated – variable unknown winds, what is SNR of cloud returns for each chirp?

DOPPLER SENSITIVITY FROM SPACE

CLOUDSAT – In 160msec moves 1km along track.

Transmits 3usec pulses at 4kHz: 1.2% duty cycle.

Detects echoes down to -30dBZ

See nearly all ice clouds

RAIN at 2mm/hr is +30dBZ - one million times higher

WIVERN In 160msec moves 50km around the cycloid arc.

Transmits FM chirps - 10 times more mean power.

Detects echoes down to -40dBZ for 50km arc.

Sees all ice clouds and stratocumulus.

FOR 5km resolution – sensitivity -35dBZ

DOPPLER NEED GOOD SNR (15dB)

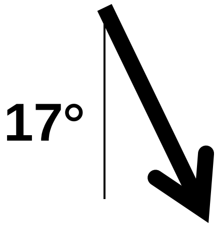
accuracy 1 to 2m/s for > -25dBZ: resolution 50km along cycloid

> -20dBZ: resolution 5km along cycloid

4. Rain and winds from Space

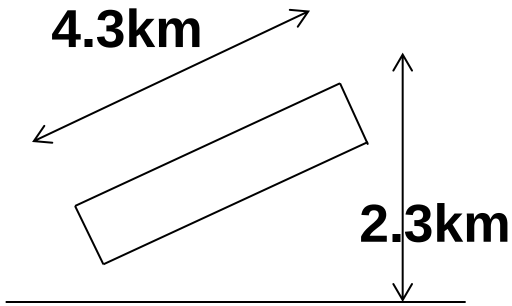
TRMM – first rain radar in space

Since 1997: TRMM 2m antenna, 13GHz (2.2cm), 350km orbit, ±35°N/S, 4.3 km footprint: 250m vert resolution
Sensitivity +23dBZ or 0.7mm/hr

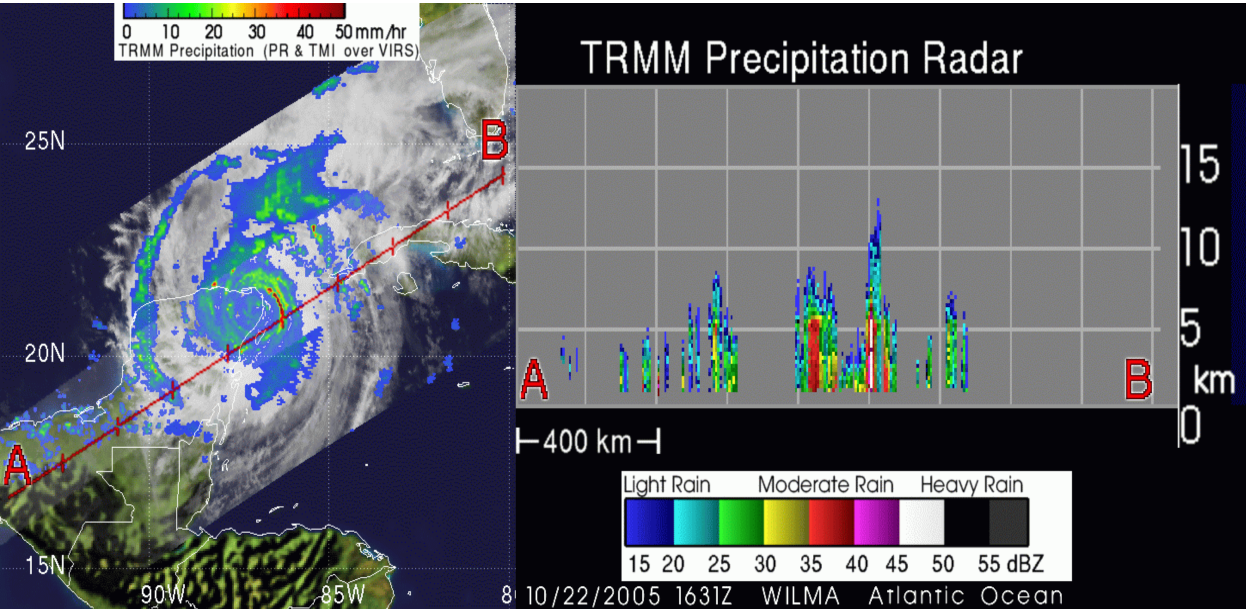


230km swath - off nadir 17°

BLIND ZONE



Hurricane Wilma 2005



5. Rain and winds from Space

GPM – (2014) Second rain radar in space

- **Improve TRMM – global and better rain rates over land.**
- **Dual frequency 14 and 35GHz – same swath as TRMM,**
- **Min Z is +18dBZ (5dB better than TRMM).**
- **Min Z is +12dBZ, but only over half the swath of TRMM and with 500m vertical resolution.**
- **Most snow has Z < 10dBZ.**

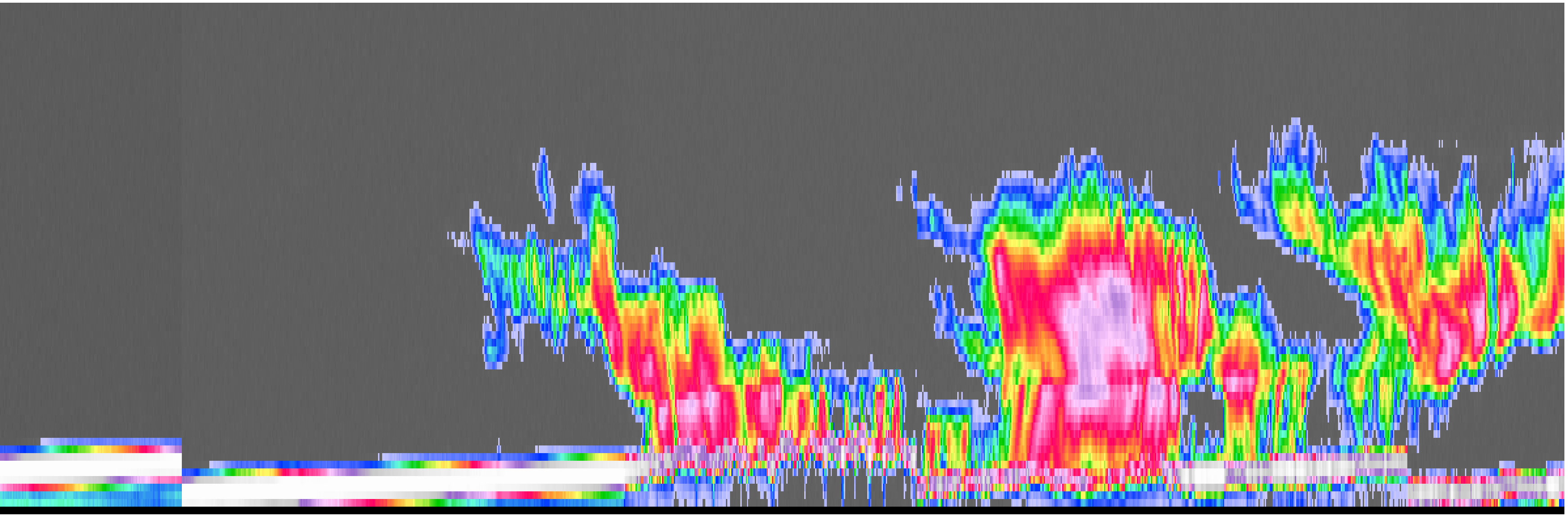
5. Rain and winds from Space

CLOUDSAT (2006)– first cloud radar in space

1.85m antenna, 94GHz (3.2mm) nadir pointing

700km orbit, 500m vert resolution:

Sensitivity -30dBZ but for a 1.4km wide swath



FIRST OVERPASS OVER THE UK IN 2006

94GHZ CPI Klystron still working fine after 7 years – spare unused

PRECIPITATION FROM SPACE?

Passive techniques: Rain causes increase in the upwelling microwave radiation from the sea surface. (Limited range/saturation/depth?)

ACTIVE:

TRMM: 230km swath. 250m vertical resolution.
Min Z 23dBZ (0.7mm/hr). Tropics only.

GPM: same swath as TRMM. Min Z (dual frequency mode 18dBZ, single frequency, 500m v resolution 12dBZ). Most snow <10dBZ.

CloudSat: (2006) very narrow swath (1.4km) Detection limit -30dBZ.
Good for snowfall,
For rain use attenuation of ocean return good up to 10mm/hr

EarthCARE: Even narrower swath 800m. Detection limit -34dBZ

BLIND ZONE for a single pulse

SURFACE RETURN, σ, FROM OCEAN @ 94GHz:

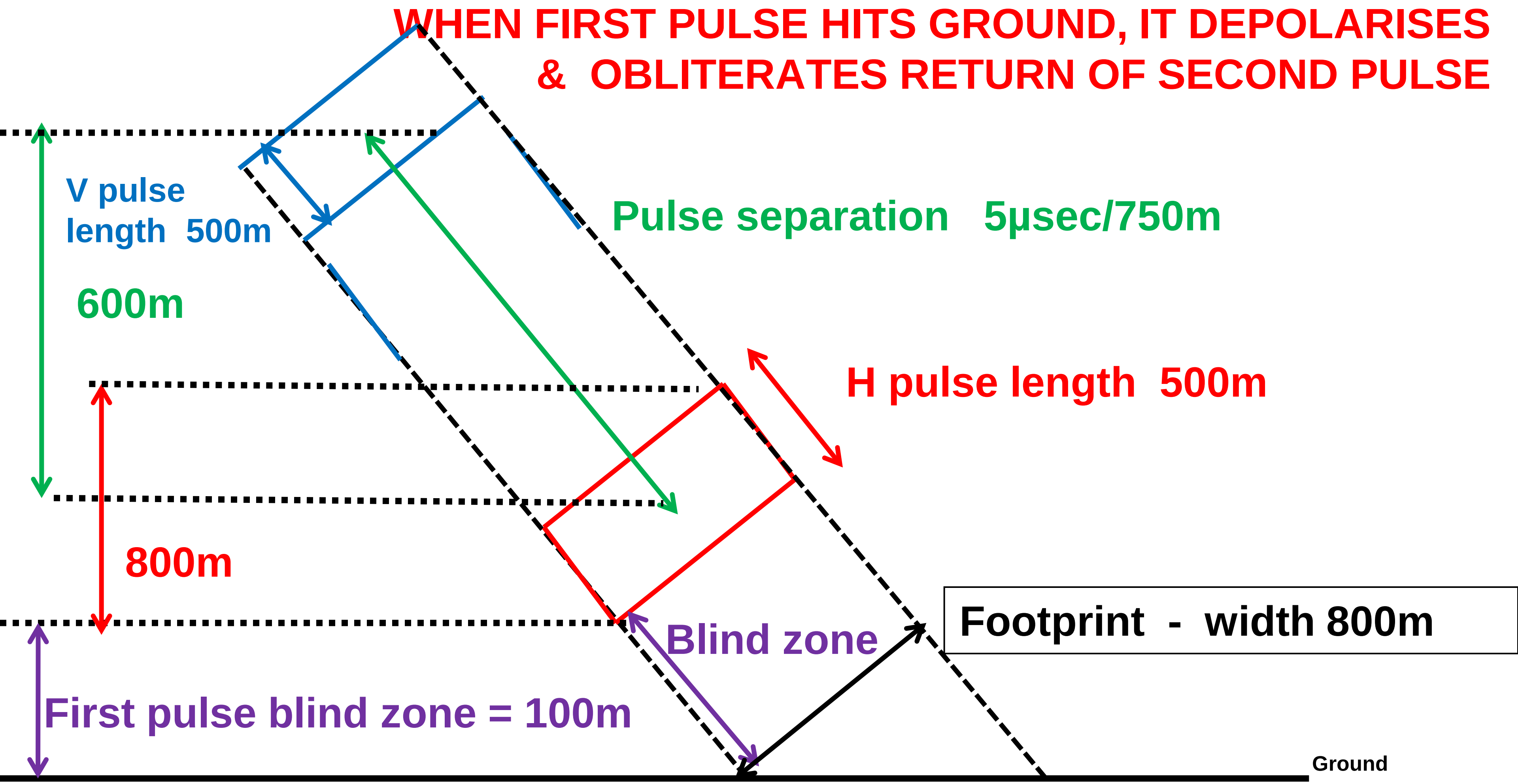
NADIR (LI ET AL, 2005) σ = +10dB (m^2 /m^2)
(Blind zone CloudSat 1.2km)

For a 500m radar pulse at nadir the surface return is equivalent to +37dBZ!

At 45° OFF NADIR (Plant, JGR, 2002)
SURFACE RETURN 30dB LOWER THAN AT NADIR.

Blind zone for nadir pointing CloudSat is about 1.2km, but for WIVERN ocean surface echo 30dB lower
- blind zone only about 100m

MUST HAVE 5µsec SEPARATION FOR 1km BLIND ZONE:



1. 5µsec pulses adds 600m to the blind zone.
2. position of V PULSE when red H PULSE hits the ground:

SO BLIND ZONE FOR DOPPLER = 600 + 400 + 100 ≈ 1100m.

H AND V PULSES – TARGETS > λ, MIE SCATTERING?

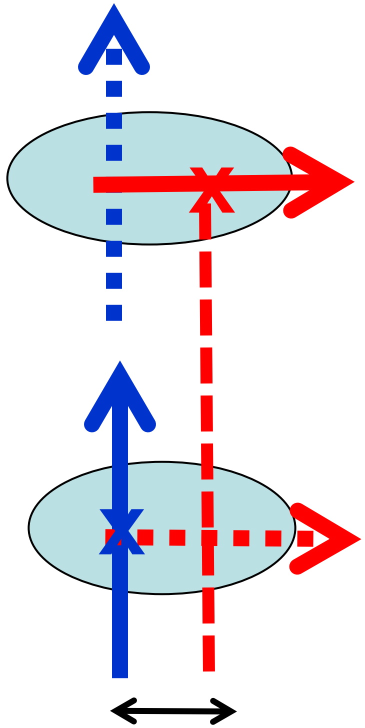
DIFFERENTIAL PHASE ON BACKSCATTER (δ)

APPARENT VELOCITY – EVEN IF STATIONARY

ASSUME H AND V PULSES IN PHASE (PROPAGATION THE SAME)

H pulse

V Pulse
5μ sec later



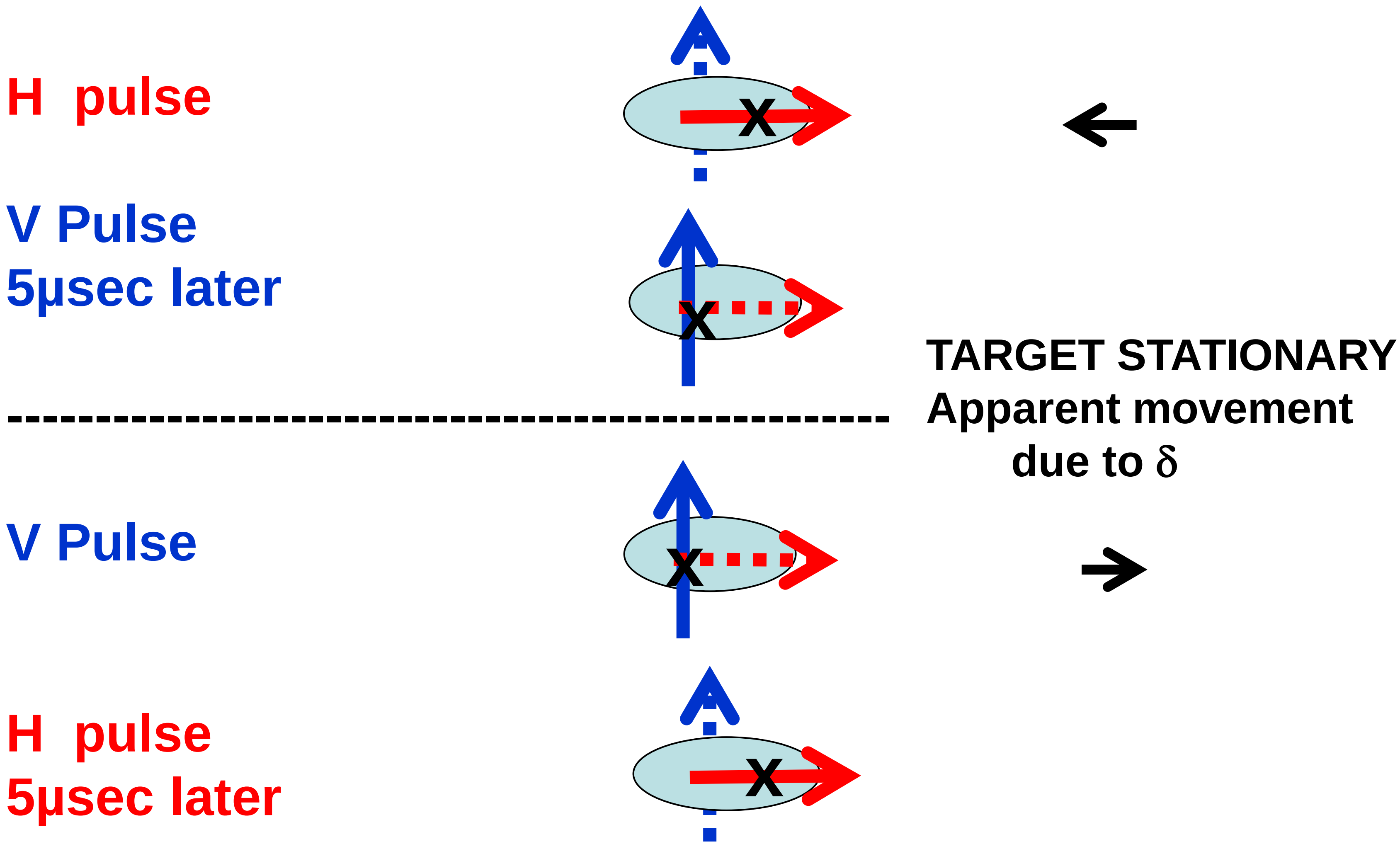
Apparent movement: δ a few degrees
(i.e. velocity of a few m/s)

THIS PROBLEM occurs for droplets and ice particles ≈ ≥ λ (3.2mm)

SOLUTION – SEND H-V PULSE PAIR, THEN V-H 'TWIN PAIR'

Average the two : δ - CANCELS OUT – true velocity

Propagation: provided H and V pulse arrive with the same phase



DOPPLER PERFORMANCE

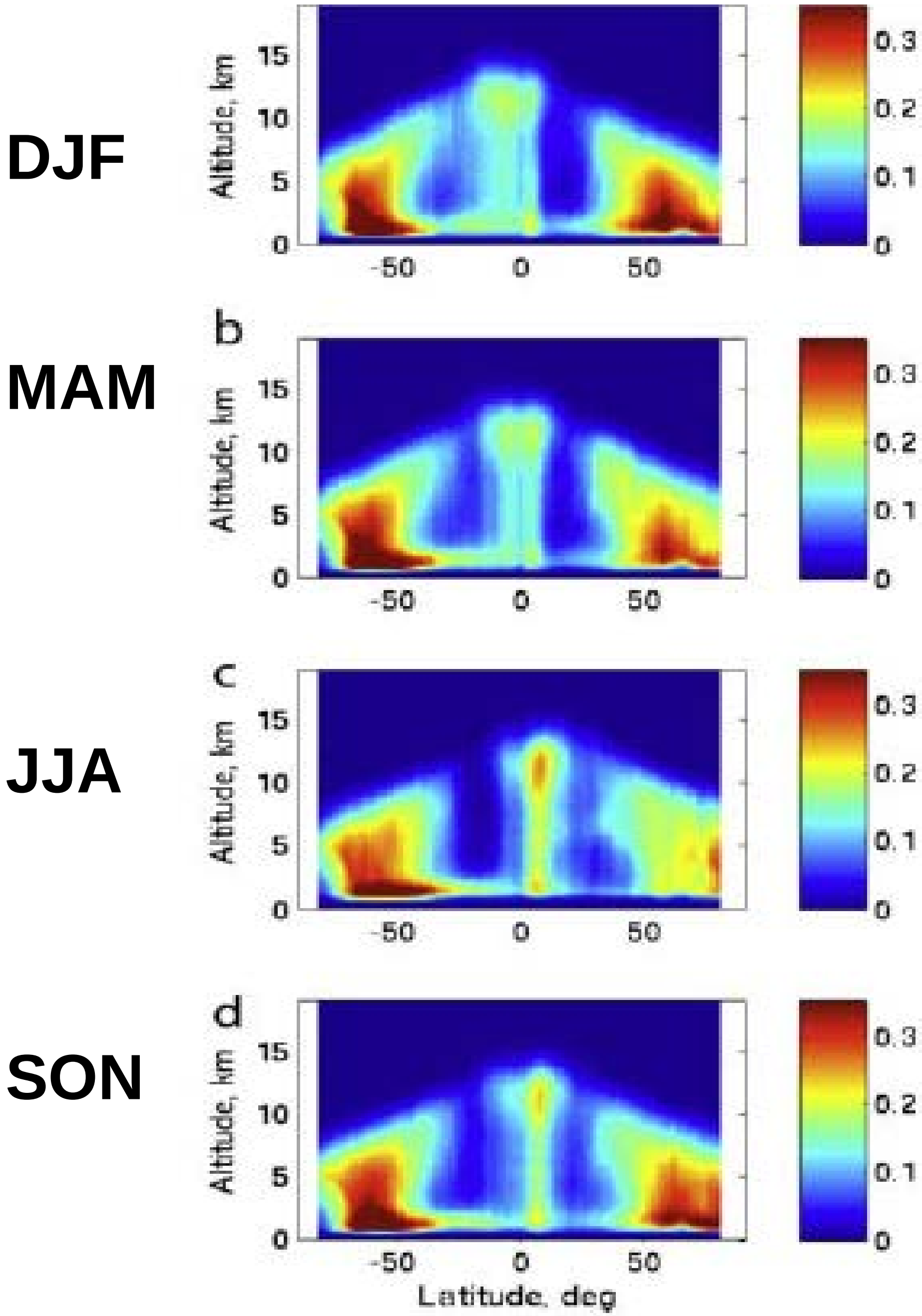
APROXIMATE SENSITIVTY OF WIVERN BY SCALING CLOUDSAT'S DEMONSTRATED PERFORMANCE IN SPACE.

CloudSat: 3µsec pulses @ 4kHz: 1.2% duty cycle, 24W mean power
in 160msecs moves 1.1km along track, transmits 620 pulses.
Z sensitivity -30dBZ

COMPARE WITH WIVERN

a) Mean power, WIVERN 176W, CloudSAT 25 W	+8.6dB
b) Antenna WIVERN 2.9x1.8m, CloudSat 1.85m	+ 3.67dB
c) WIVERN 731km range, CloudSat 710km	0dB
d) WIVERN 1600 pulses, CloudSat 620	-1.8dB
e) WIVERN 140msec, CloudSat 160msec	- 0.5dB
NET IMPROVEMENT OF WIVERN	+10dB

CloudSat was -30dBZ as it went 1.1km along track,
so WIVERN -40dBZ for 50km along track.
Doppler need to consider single pulse SNR:
1600 pulses so SNR for single pulse down by 40 or 16dB
WIVERN single pulse SNR of 0dB for a Z of -24dBZ
Two pulses per km in height (extra 1.5dB) SNR 0dB for Z -25.5dB



CLOUD OCCURRENCE ZONAL STATISTICS FROM CLOUDSAT WITH Z > -27.5dBZ

(Marchand et al, JGR, 2009, He only reported this threshold)

i.e. 20-30% of the time IN THE STORM TRACKS

GOAL:

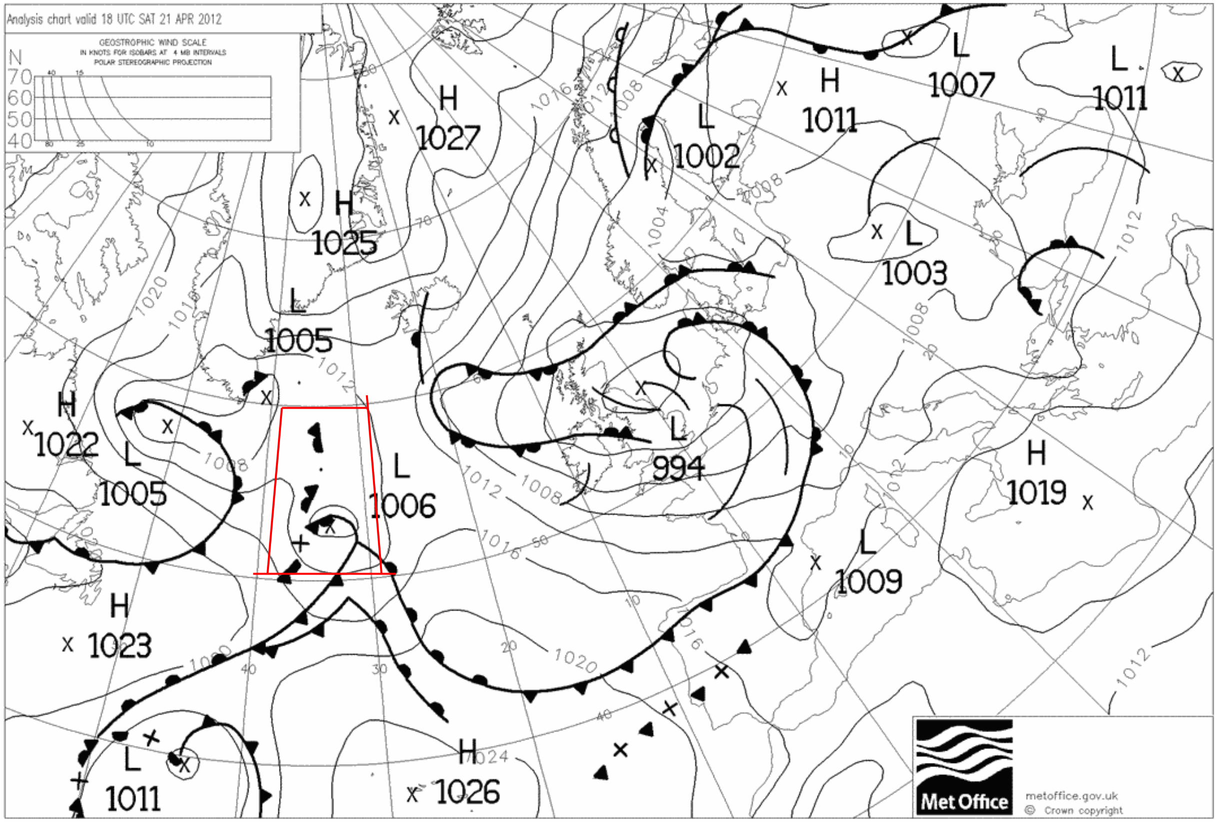
WE CAN GET DOPPLER TO 2m/s in-cloud 50km horizontal resolution 1km vertical resolution for a Z of -27dBZ.

Complements AEOLUS clear air profiles

Would more winds actually help?

China is installing 365 wind profilers,
Europe is cutting down on observations to save money.

E.G. SAT 21 April 2012 0Z: DISTURBANCE IN RED BOX 30-40W 50-60N FORECAST TO GIVE DEEP STORMY LOW OVER UK MONDAY

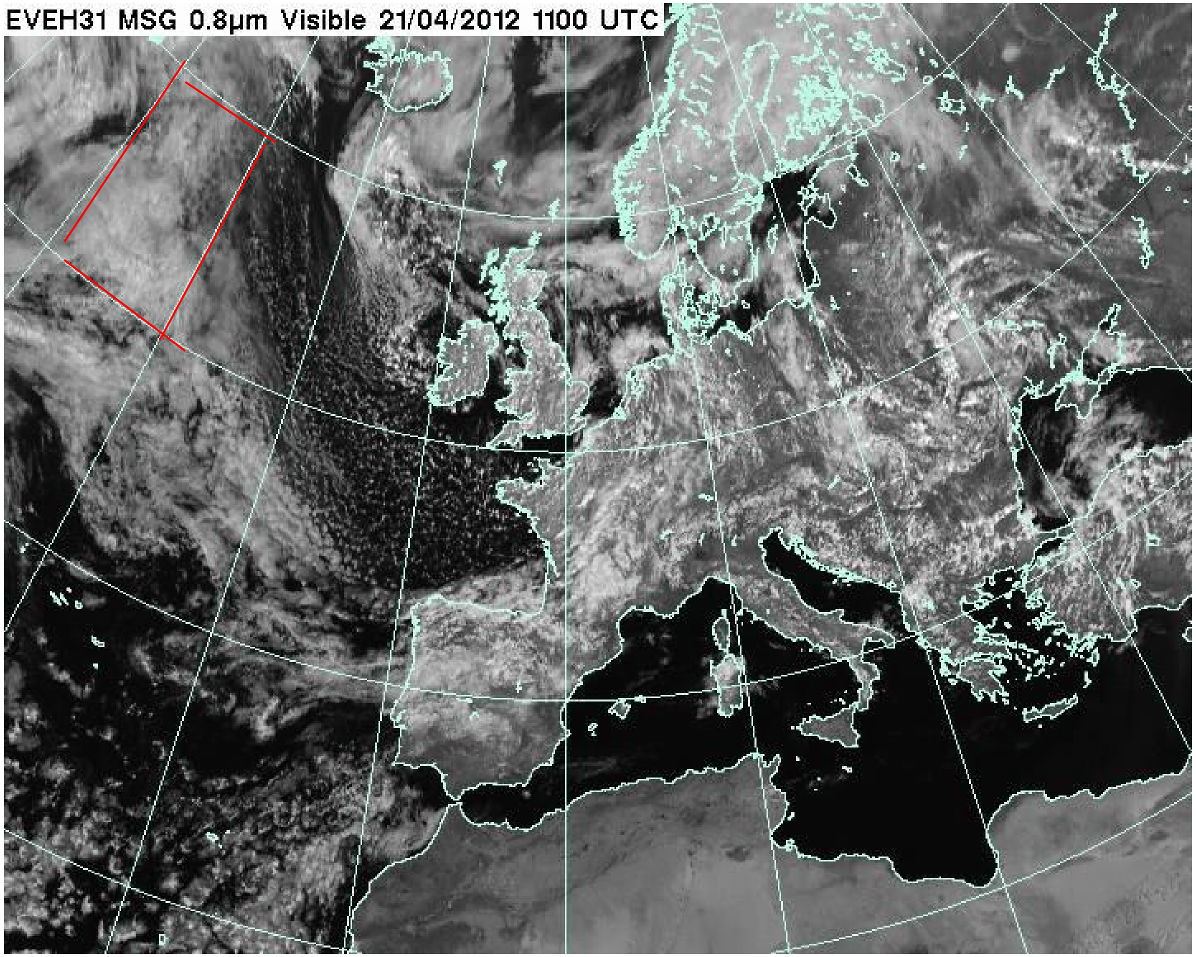


Archived by www.wetter3.de 21-04-12 18 UTC

VIS Sat 12Z Saturday 21 April

What are the winds in the red box?

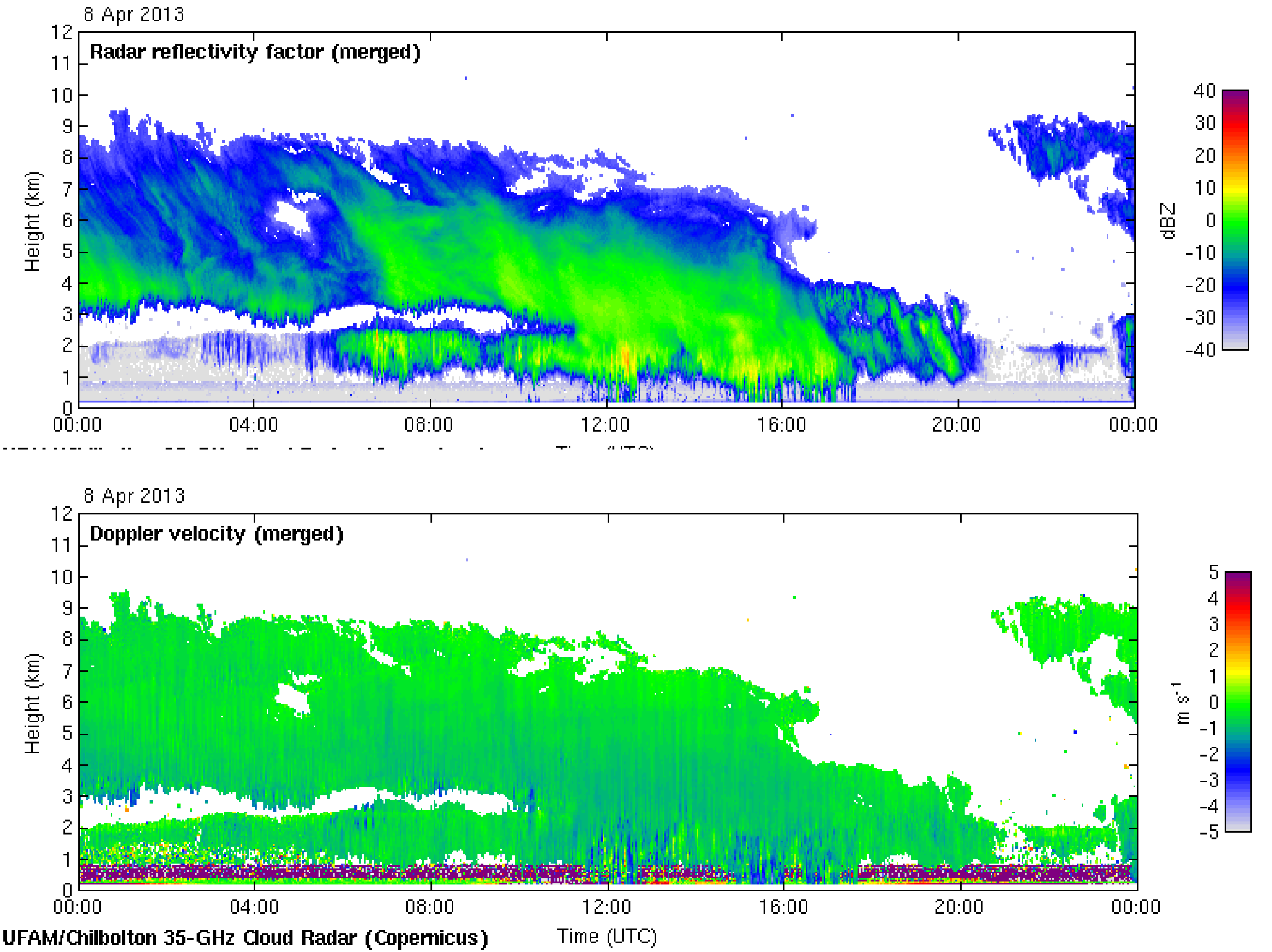
In fact, low did develop, but only 3mm rain in Reading



FSO Cardinali QJ 2009 (Forecast sensitivity to observations) technique can tell us the impact or each observation on improving the forecast.

Confirm that the winds from sondes are most valuable in reducing forecast errors.

YESTERDAY'S VERTICAL RADAR PROFILES OVER CHILBOLTON
LARGE ECHOE EXTENT > -27DBZ; NEGIGIBLE TERMINAL VELOCITIES



9. PERFORMANCE - SUMMARY

For 50km along the conical scan – 1km vertical resolution

dBZ sensitivity better than - 40dBZ:
will detect thin cirrus and stratocumulus

for Z > -27.5dBZ Doppler accuracy 2m/s

From Cloudsat: Doppler 20 - 30% of the time in mid latitude storm tracks.

For 1km resolution around the conical scan rather than 50km
Need signal higher by $\sqrt{50}$, a factor of seven, (8.5dB)

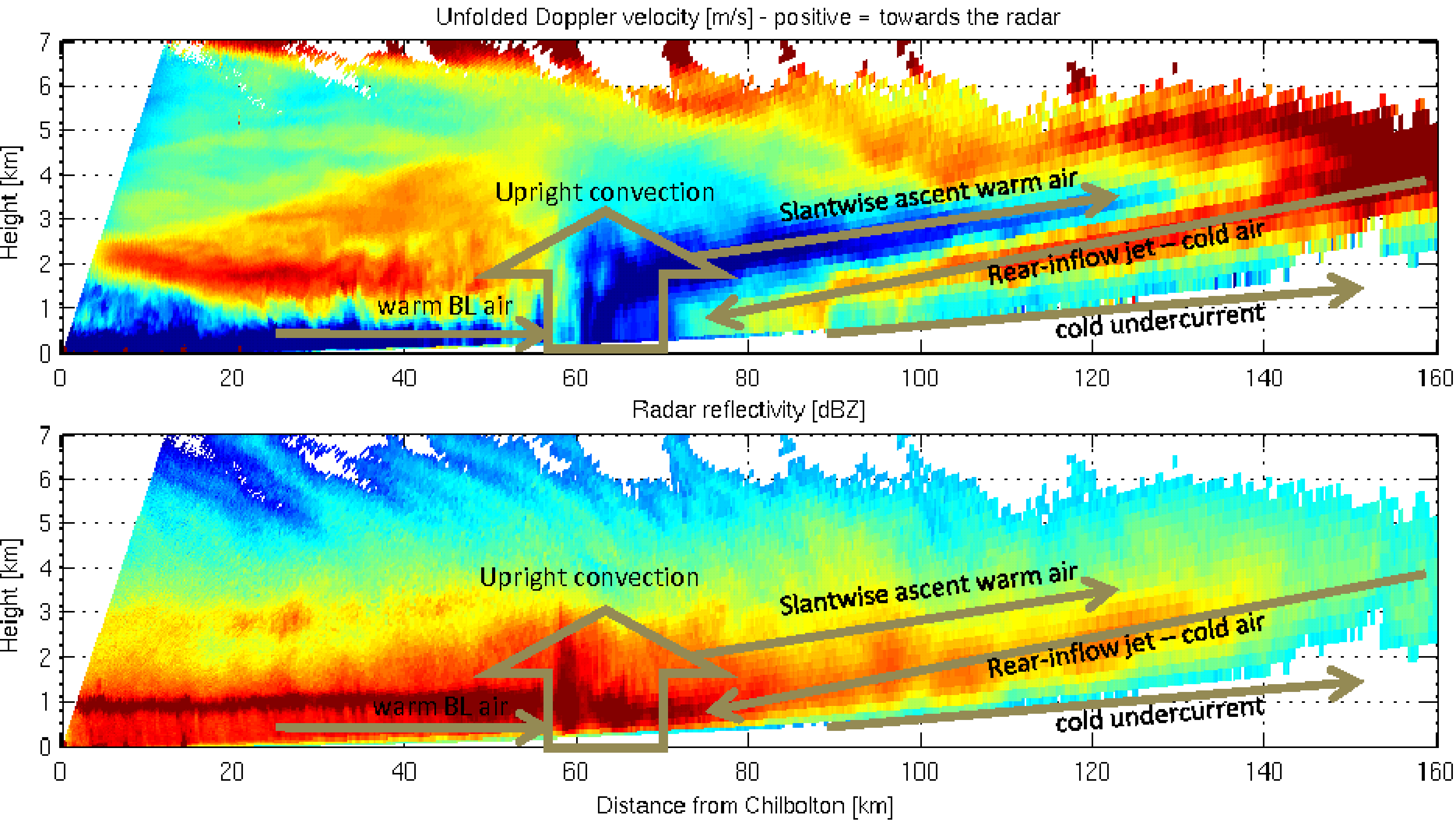
i.e dBZ sensitivity -31.5 dBZ to detect cirrus and stratocumulus

dBZ above -17.5dBZ for good Doppler

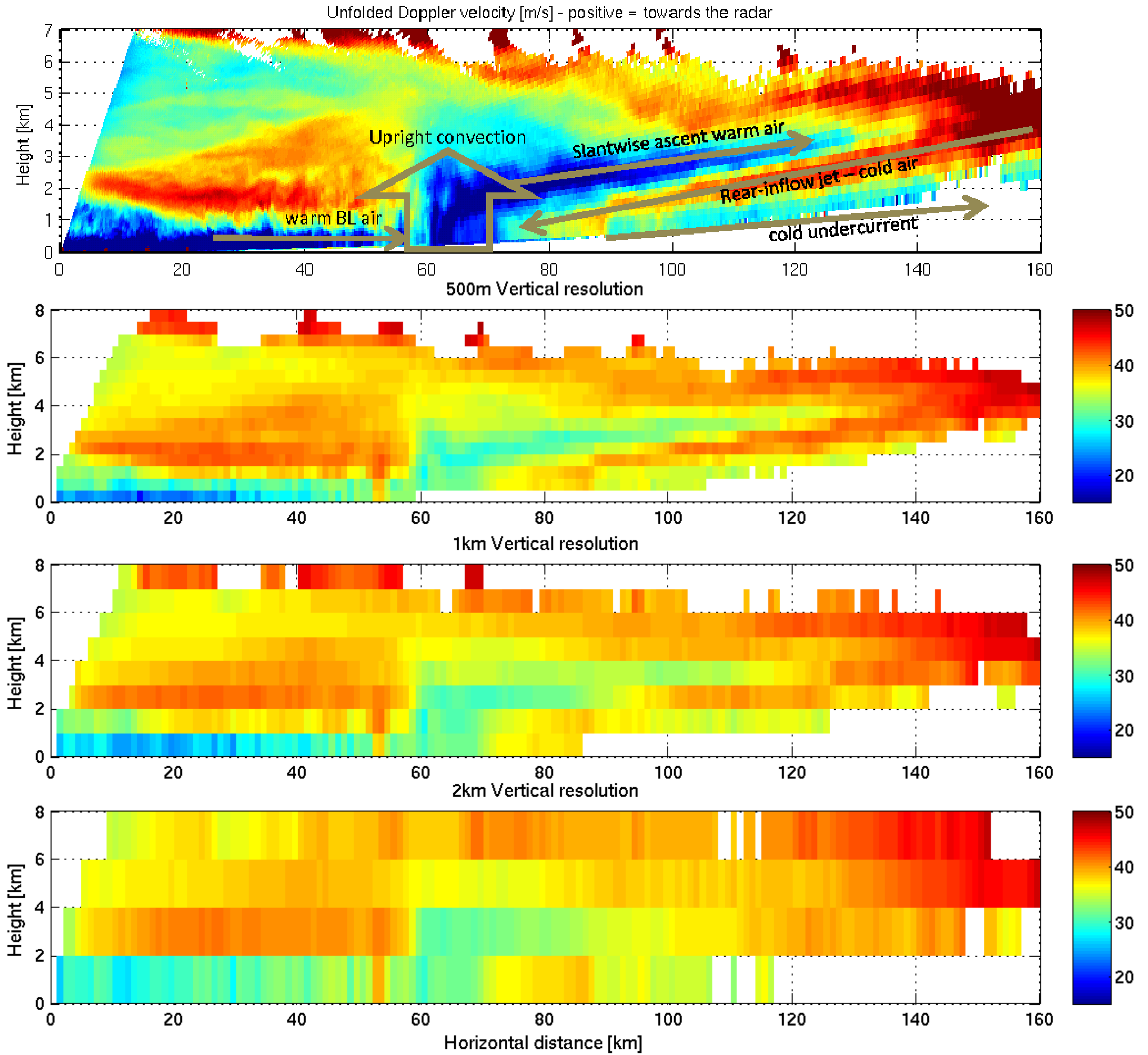
Remember drizzle 0.1mm/hr has a Z >0dBZ: very good Doppler.

Effect of vertical resolution?

3 May 09 cold front: RHI by high resolution Chilbolton radar



Courtesy Chris Westbrook, U of Reading



Unfolded Doppler velocity [m/s] - positive = towards the radar
Upright convection
Slantwise ascent warm air
Rear-inflow jet – cold air
warm BL air
cold undercurrent
Height [km]
500m Vertical resolution
1km Vertical resolution
2km Vertical resolution
Horizontal distance [km]

POINTING ACCURACY REQUIREMENT?

MAX COMPONENT OF SATELLITE VELOCITY 5000m/s for 1m/s accuracy need pointing knowledge 1 in 5000 or 200µrads

EarthCARE – vertical dwell pointing accuracy 120urad
remove harmonics as go round orbit of about 100urad
leaves 20µrads (0.1m/s vertical velocity) – yet to be demonstrated.

200µrads not possible with star trackers on the spinning WIVERN. The asymmetry of the spinning axis around nadir should change very slowly around the orbit and over time, but could also nutate.

a)Use radar as altimeter: 200µrad at 1000km slant range, is 200m, look for asymmetry in range to sea surface as satellite spins.

b)Can NWP recognise biases of 1 or 2m/s on left and right hand side of satellite?

SUMMARY AND QUESTIONS

DOPPLER: For 50km along the conical scan – 1km vertical resolution
for Z > -27.5dBZ Doppler accuracy 2m/s (but not in v heavy ppn cores)
From Cloudsat: Doppler 20 - 30% of the time in mid latitude storm tracks.

1.800m vertical resolution sufficient?
Improvement difficult – need antenna > 3m, can't use Vega rocket

2. Blind zone 1km over the ocean – acceptable. Worse over land?

3. Two visits a day poleward of 50degs? Worth losing 5dB sensitivity?

4. Gaps in tropical coverage acceptable?
- non sun synchronous orbit much more difficult to engineer.

5. Pointing accuracy – can this be monitored (and corrected) from change in wind bias as go round conical scan?