Validation of torus mapping method for dealiasing Doppler weather radar velocities

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Aliasing of radial wind measurements

- Radial wind measured via phase shift of the scattered EM wave.
- Phase shift is circular on interval $[-\pi, \pi]$ $\Rightarrow$ there exists a maximal unambiguous measured velocity v_{ny} - Nyquist velocity.
- Phase shift measured between pulses:

$$v_{ny} = \frac{\lambda}{4\tau_p} = \frac{PRF \cdot \lambda}{4}.$$

- Observed velocities (v_o) larger than v_{ny} are folded (**aliased**) back to interval $[-v_{ny}, v_{ny}]$.
- Multiple aliasing can occur $\Rightarrow$ the real radial velocity v_r:

$$v_r = v_o + 2nv_{ny},$$

where n is an integer - Nyquist number.

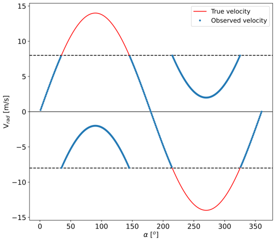
Torus mapping method

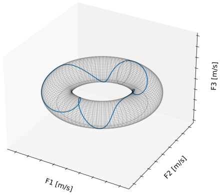
Assumes a smooth radial wind velocity field, linear in zonal and meridional speeds at a specific height:

$$v_r \approx v_m(u, v) = (u \sin \alpha + v \cos \alpha) \cos \phi.$$

Radial velocity as a function of azimuth has discontinuities because of aliasing $\Rightarrow$ map the function onto torus $\Rightarrow$ continuous curve:

$$F(\alpha) = \left(\left[R + \frac{v_{ny}}{\pi} \sin\left(v_o \frac{\pi}{v_{ny}} \right) \right] \sin \alpha, \left[R + \frac{v_{ny}}{\pi} \sin\left(v_o \frac{\pi}{v_{ny}} \right) \right] \cos \alpha, \frac{v_{ny}}{\pi} \cos\left(v_o \frac{\pi}{v_{ny}} \right) \right).$$





Torus mapping method

Express derivative of third component of torus function as:

$$D = \frac{\partial F_3}{\partial \alpha} = -au + bv,\ a = \cos\alpha\cos\phi\sin\left(v_o\frac{\pi}{v_{ny}}\right),\ b = \sin\alpha\cos\phi\sin\left(v_o\frac{\pi}{v_{ny}}\right).$$

Evaluate D from data by a numerical estimate, calculate a and b for all data points, find u and v for data subsets k by minimizing:

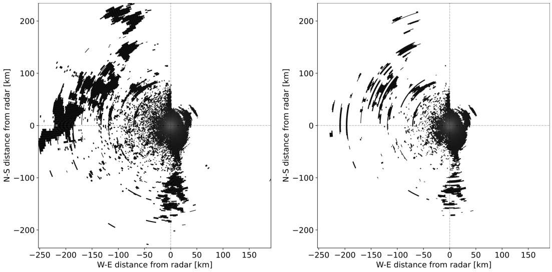
$$\{u, v\} = \min_{u,v}\sum_{k=1}^{N}\left[D_k - (-ua_k + vb_k)\right]^2,$$

Find Nyquist number by minimizing:

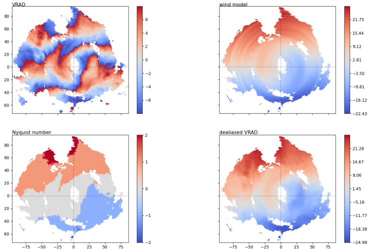
$$n = \min_{n}\left[\left|v_{o,k} + 2nv_{ny,k} - v_{m,k}\right|\right], n \in \mathbb{Z}.$$

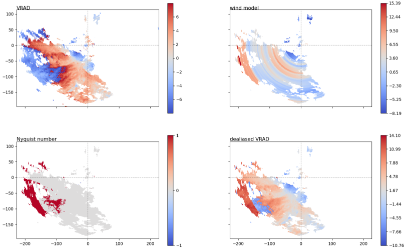
Algorithm implementation

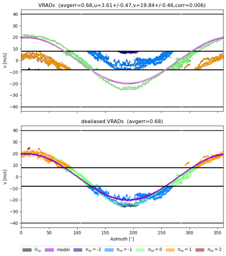
- Central differences used for numerical derivative estimation $\Rightarrow$ any measurement without two neigbours in azimuth direction rejected - mostly noise and edges,
- Dealiasing done on subsets within 100 m height intervals,
- Interval with < 500 points or value of $v_m > 60m/s$ rejected, to reduce nonconverged minimizations.

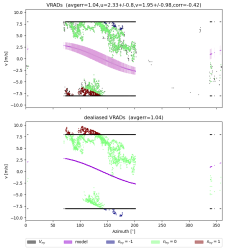


Dealiasing - individual cases





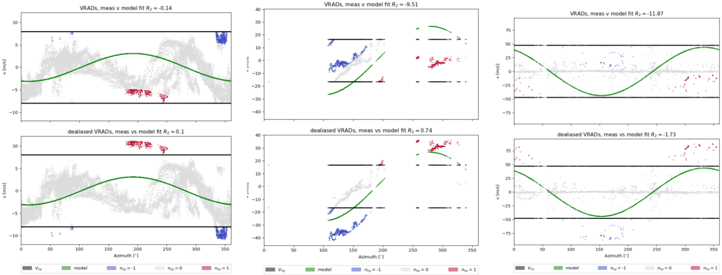




Dealiasing - minimization covergence

Minimization does not always converge to correct values, main reasons:

- linear wind assumption not satisfied in a single height interval,
- only a small portion of azimuth is filled,
- large amount of noise present in data.



Noise - main cause of wrong convergence, contains random values centered around zero ⇒ numerical derivative has big fluctuations. Some form of noise removal recommended before dealiasing.

Validation plan

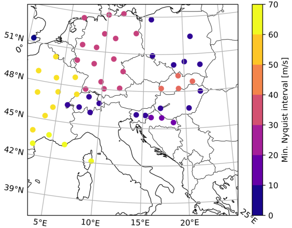
Goal: show that dealiased radar measurements are comparable to other established upper-air wind measurements and show usefulness for NWP data assimilation.

- Comparison of pair-wise colocated wind measurements from radars, radiosondes and aircraft. Maximum separation for colocation is 10 km in horizontal, 100 m in vertical and 10 min in time.
- Comparison against results from ALADIN NWP model.
- Analysis of effect of quality control in data assimilation in ALADIN.

Dataset

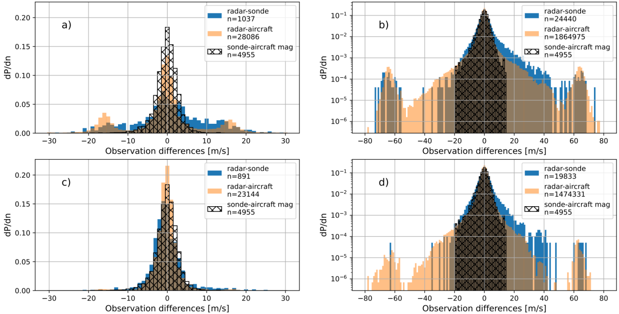
Measurements from whole year 2021, on used NWP domain.

- Radar - OPERA dataset, divided into 2 subsets:
  - Dataset A: Both Slovenian radars, minimum $v_{ny} = 8$ m/s. Only one value of small v_{ny} $\Rightarrow$ dealiasing effect clearer.
  - Dataset B: German, Slovakian and French radars, minimum $v_{ny} \gtrsim 30$ m/s. Study usefulness of dealiasing with bigger v_{ny}.
- Radiosondes - accurate, but sparse,
- Aircraft - Mode-S derived data - much larger statistics,
- NWP dataset - used ALARO operational configuration with 4.4 km resolution, 3h DA cycling. First guess departures calculated, with accompanying quality control flag.



Validation - colocated observations

Comparing distributions of differences of colocated observation values, using the sonde-aircraft distribution as reference.

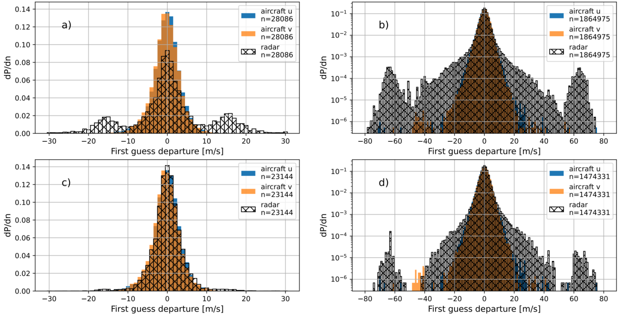


Case	N	avg [m/s]	std [m/s]
Aliased data			
ASD A	4955	-0.19	2.89
RAD A	28086	-0.76	10.23
RSD A	1037	0.73	9.51
ASD B	4955	-0.19	2.89
RAD B	1864975	0.06	5.66
RSD B	24440	0.69	6.48
Dealiased data			
ASD A	4955	-0.19	2.89
RAD A	23144	-0.26	3.71
RSD A	891	-0.11	4.52
ASD B	4955	-0.19	2.89
RAD B	1474331	-0.06	3.28
RSD B	19833	0.27	4.73

Spread reduced in both datasets, peaks corresponding to $n = \pm 1$ reduced by an order of magnitude, dealiased distributions comparable to reference.

Validation - NWP first guess departures

Comparing distributions of FGD for aircraft and radar colocated pairs.

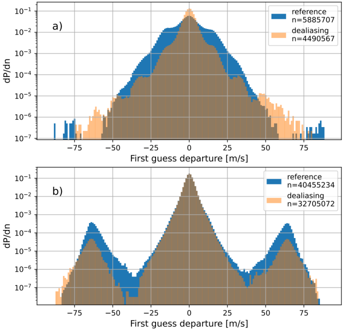


Case	N	avg [m/s]	std [m/s]
Aliased data			
aircraft u FGDD A	28086	-0.19	3.44
aircraft v FGDD A	28086	-0.33	3.43
radar FGDD A	28086	0.66	10.33
aircraft u FGDD B	1864975	-0.01	2.78
aircraft v FGDD B	1864975	0.12	2.7
radar FGDD B	1864975	0.02	5.72
Dealiased data			
aircraft u FGDD A	23144	-0.17	3.4
aircraft v FGDD A	23144	-0.35	3.45
radar FGDD A	23144	0.12	4.18
aircraft u FGDD B	1474331	-0.02	2.83
aircraft v FGDD B	1474331	0.12	2.74
radar FGDD B	1474331	0.14	3.49

Effect of dealiasing very similar to effect in colocated observations.

Validation - NWP first guess departures

Comparing distributions of FGD for aircraft and radar for all available measurements in SI and DE radars.



Aliased data

Case	N	avg [m/s]	std [m/s]
SI dataset	5885707	-0.44	9.7
DE dataset	40455234	0.09	5.39

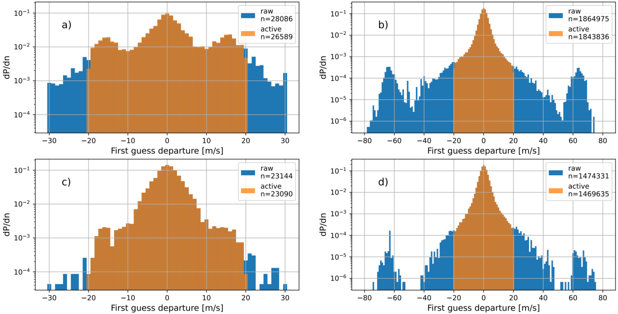
Dealiased data

Case	N	avg [m/s]	std [m/s]
SI dataset	4490567	0.12	4.7
DE dataset	32705072	0.1	3.29

More statistics ⇒ we can see peaks corresponding to multiple Nyquist numbers, all reduced by an order of magnitude.

Validation - NWP DA quality control

Checking interaction of dealiasing and DA quality control ⇒ a threshold imposed on first guess departures.



Acceptance rate is increased by correction of values by dealiasing, although for data with smaller v_{ny}, a stricter threshold would be required.

Conclusions

First systematic evaluation of the torus mapping algorithm on a large dataset over Europe over a time period of one year.

- Torus mapping algorithm is a robust procedure, although dependent on noise,
- dealiasing significantly improves the quality of radial wind measurements,
- about 90% of dealiased data is correctly dealiased (a rough estimate),
- radar observation quality is increased to the level of aircraft and radiosonde data,
- dealiasing is useful even for radars with larger v_{ny},
- for DA, it increases the acceptance rate, we propose a stricter quality control threshold for data with smaller v_{ny}.

Algorithm is already available as part of HOOF on ACCORD wiki pages.