Assimilation of radar data in the AROME model at Météo-France

Eric Wattrelot,
Olivier Caumont, Thibaut Montmerle, Claudia Faccani, Marian Jurasek
and Günther Haase
(CNRM)
Outlines

- Context and Introduction.
- Basic theory of the two measurements: radial wind and reflectivity
- Sources of measurement errors: need for pre-processing radar data.
- The specific radar product for AROME
- Towards the assimilation of radial winds: observation operator, quality control and thinning
- Towards the assimilation of reflectivities: observation operator, specific methodology for reflectivities, quality control, and thinning
- Assimilation status for reflectivities: results through case studies.
- Assimilation status for radial winds: results and impact on short forecasts through case studies.
- Conclusions and perspectives
Outlines

- Context and Introduction.
- Basic theory of the two measurements: radial wind and reflectivity
- Sources of measurement errors: need for pre-processing radar data.
- The specific radar product for AROME
- Towards the assimilation of radial winds: observation operator, quality control and thinning
- Towards the assimilation of reflectivities: observation operator, specific methodology for reflectivities, quality control, and thinning
- Assimilation status for reflectivities: results through case studies.
- Assimilation status for radial winds: results and impact on short forecasts through case studies.
- Conclusions and perspectives
Context and Introduction

The AROME project …

- The mesoscale AROME model and its non-hydrostatic physic have the capability to simulate and to forecast dangerous mesoscale convective events as storms, wind bursts and therefore initial unexpected floods…

- However, previous studies have shown that good initial conditions were important in order to improve mesoscale convection forecasts (see presentation before by Pierre Brousseau…).

- Accordingly, there is need for using high density obervations…
  ⇒ Radar data from the french ARAMIS network can play a key role by providing information about the low level horizontal wind and the precipitating pattern within precipitating systems

Assimilation strategy: observation operator and 3DVar…

- Radial velocity observation operator is based on the horizontal wind field: impact studies have been carried out using the 3DVar AROME and long period of monitoring in pre-operational AROME model have been done

- Reflectivity observation operator needs a complete description of warm and cold hydrometeors: realistic simulation can be obtained only with AROME. But if reflectivities provide useful information, assimilation of rain is very difficult (not a model variable) and probably not very useful (rainfalls have a short shelf life). Therefore, there is need for a specific 1D+3DVar assimilation.
The ARAMIS radar network

Current status: high spatial and time resolutions…

- 24 radars from which 17 Doppler C-band Radars performing between 3 and 14 PPIs (Plan Position Indicator: constant elevation)/ 15’ and 1km horizontal resolution
- 1 double polarimetric (Trappes)

Expected at the end of 2008:

- All the radar network will be Doppler radars
- 4 with double polar (interesting for distinguish different shapes of hydrometeors.)
Outlines

- Context and Introduction.
- Basic theory of the two measurements: radial wind and reflectivity
- Sources of measurement errors: need for pre-processing radar data.
- The specific radar product for AROME
- Towards the assimilation of radial winds: observation operator, quality control and thinning
- Towards the assimilation of reflectivities: observation operator, specific methodology for reflectivities, quality control, and thinning
- Assimilation status for reflectivities: results through case studies.
- Assimilation status for radial winds: results and impact on short forecasts through case studies.
- Conclusions and perspectives
The radar antenna emits a horizontally polarized electromagnetic pulse.
The emitted energy is mostly confined into a narrow conical beam.

The basic theory of the Reflectivity measurement
The radiation hits some targets in the beam volume: beam volume defined in particular by the 3dbZ beamwidth (mostly confined energy) and the length of this volume which is $c.\Delta t/2$ where $\Delta t$ is the pulse duration (we can notice that $c.\Delta t/2 \sim 250m$ is smaller than model resolution (greater than 1km).
A part of the radiation is scattered in all directions and attenuated by the targets.

Another part of the energy of the radiation is backscattered in the direction of the radar and measured by the radar in reception mode. This quantity $P_r$ depends on the nature, the shape and the size of the targets but also on the characteristics of the radar...

We can know the location of the beam volume by measuring the time $T$ between the emission and the reception: $d = cT/2$ (distance between radar and hydrometeors).
The basic theory of the Reflectivity measurement

\[ P_r(r_0) = C \frac{z_e(r_0)}{r_0^2} \]

Equivalent reflectivity factor (in dBA):

\[ Z_e(r_0) = 10 \log \left( \frac{8 \cdot 10^{18} \lambda^4 \ln 2}{\pi^6 |K_w|^2 (\Delta \theta)^2} \int_0^{2\pi} \int_0^{\pi} f^4(\theta, \phi) \sum_{j \in \text{type}} \int_0^\infty \sigma_j(D, \rho_r r_j) N_j(D, r) dD \right) \times \exp \left( -2 \int_0^r \sum_{j \in \text{type}} \int_0^\infty C_{e,j}(D, \rho_r r_j) N_j(D, r) dD dr \right) \sin \theta d\theta d\phi \]
You will assimilate the Doppler radial winds!!

The first idea is to measure the « apparent » frequency modified by the displacement of a target but in our case of the radar…

Frequency = $10^{+9}$ Hz

=> $\Delta f << 10^{-5}$ this quantity cannot be measured by electronic of the radar antenna!!!
The basic theory of the Doppler measurement

A impulsed wave is emitted each period PRT (Pulse Repetition Time).

\( PRT = 3\text{ms} \)

The displacement of the target induces a variation of phase between the successive impulses \( \Rightarrow \) radial velocity measurement:

\[
V_r = \frac{dr(t)}{dt} = \frac{\lambda \Delta \Phi}{4\pi PRT}
\]

\( r(t) \) : distance radar-precipitation

\( \Lambda \) : radar wavelength
Aliasing of the speed

The signal is sampled at an emitted frequency PRF (Pulse Repetition Frequency). If the phase shift between two pulses exceeds $\pi$, the measure of speed can be ambiguous. The speed is folded or aliased in the interval $[-V_{\text{nyquist}}, +V_{\text{nyquist}}]$. Typically, $V_{\text{nyquist}} = 5\text{m/s}$.
The basic theory of the Doppler measurement

We can increase the non-ambiguous Nyquist velocity with a PRT very small: \[ V_r = \Lambda / (4 \text{PRT}). \] However, the range of reflectivity is directly proportional to the duration between two successives impulsed waves (because of need for location): \[ d = c \cdot \text{PRT}/2 \]

Accordingly, there is a compromise to find... and we can’t increase the maximum velocity.
- Map of 512km by 512km
- Resolution of 1km²
Folded radial wind map
The dual-PRT and triple-PRT method
(Tabary & al. 2005 et 2006)

The methods are to combine several pulses at two or three different PRT alternatively. The differences of aliasing velocities (for the different PRT) allow to estimate real radial velocity of targets...

Dual-PRT method

Triple-PRT method
Triple-PRT method

De-aliasing of the velocity

Dealiased velocity
Outlines

- Context and Introduction.
- Basic theory of the two measurements: radial wind and reflectivity
- Sources of measurement errors: need for pre-processing radar data.
- The specific radar product for AROME
- Towards the assimilation of radial winds: observation operator, quality control and thinning
- Towards the assimilation of reflectivities: observation operator, specific methodology for reflectivities, quality control, and thinning
- Assimilation status for reflectivities : results through case studies.
- Assimilation status for radial winds : results and impact on short forecasts through case studies.
- Conclusions and perspectives
The quality of the Doppler measurement depends on:

1. Number of samples available within the pixel (quantity linearly decreasing with range)

2. The signal-noise-ratio: 
   \[ \text{SNR(dB)} = Z(\text{dBZ}) + 20 \log_{10} \left[ \frac{100}{r(\text{km})} \right] \]

3. The spectral width (which is only just beginning to be calculated operationally)

4. The measurement is representative of the size of the beam volume: it increases with range, so the incertitude as well)

\[ v(r_0) = \int_0^{2\pi} \int_0^{\pi} \int_0^{\infty} \frac{[v_r \eta](r)(r)^2}{r^2} f^2(\theta', \phi') L(r) \sin \theta' \, d\theta' \, dr \, d\phi' \]
\[ = \int_0^{2\pi} \int_0^{\pi} \int_0^{\infty} \eta(r)(r)^2 \frac{f^2(\theta', \phi') L(r) \sin \theta'}{r^2} \, d\theta' \, dr \, d\phi' \]
Doppler velocity dealiasing method

Use of a staggered triple-PRT (Pulse Repetition Time) scheme

⇒ 3 different Nyquist velocities $V_{N_i}$

But still some noisy pixels…

⇒ Need for filtering

Pre-processing of the radial wind
Reference velocity... some noisy pixels: need for filtering

Dealiased velocity

Filtred dealiased velocity
Pre-processing of the radial wind
(Faccani & al, 2007)

- 5x5 Median filter
- 3x3 « cleaner » filter
(replacement of pixels with large error compared to the surrounding pixels by the median of the sorted values)
Quality of the reflectivity measurement

The quality of the reflectivity measurement depends on:

1. Clutter on orography and partial beam blocking behind mountains

2. Bright band: difficult to simulate

3. Altitude of reflectivities: possible problem for ground rain-rates but not for reflectivities. But error positionning increasing with altitude because of broadening of the beam and of a constant refractivity index along the ray path
4. Spurious echoes:

- attenuation by heavy precipitation
- Grounds clutter (due to variation of refractivity index along the ray path).

Pulse to pulse variability algorithm: low variability means clutter

This algorithm is not effective for clear sky echoes (birds, bugs…) whose variability is the same order to that of rain echoes.
Pre-processing of the reflectivities: Gross error removal

- Pre-processing of the reflectivities: Gross error removal
  - Raw data
  - Corrected data
  - Status flag
  - Dynamic ground clutter
  - Permanent ground clutter
  - Clear sky echoes

Maps showing reflectivity data with color scales for raw data and corrected data.
Outlines

- Context and Introduction.
- Basic theory of the two measurements: radial wind and reflectivity
- Sources of measurement errors: need for pre-processing radar data.
- The specific radar product for AROME
- Towards the assimilation of radial winds: observation operator, quality control and thinning
- Towards the assimilation of reflectivities: observation operator, specific methodology for reflectivities, quality control, and thinning
- Assimilation status for reflectivities: results through case studies.
- Assimilation status for radial winds: results and impact on short forecasts through case studies.
- Conclusions and perspectives
Radar product for AROME

- Data (Z, Vr, Status) provided in BUFR format at 1 km horizontal resolution for 24 Radars so far (Status= one byte decomposed in two parts of 4 bits: information on spurious echoe and attenuation)

\[ \Rightarrow \sim 120 \text{ elevations} \times (512)^2 \times 3 = 94,371,840 \text{ pixels for one assimilation time!} \]

\[ \Rightarrow \text{A lot of data and of headaches to manage!} \]
Radar product for AROME... in the model

~ 94,371,840 pixels for one assimilation time!
⇒ 6,291,456 columns in the model

Using columns of observations in model

- Radar observations considered as profiles in the model
- Altitudes of the pixels calculated considering a constant refractivity index along the ray path (i.e., using the approximation of the Earth’s effective radius: consistent with observation operator, see hereafter)
- This last approximation is also coherent with the non-horizontal integration of the beam because of parallel purposes (we cannot simulate anomalous propagation and attenuation!!)
Outlines

- Context and Introduction.
- Basic theory of the two measurements: radial wind and reflectivity.
- Sources of measurement errors: need for pre-processing radar data.
- The specific radar product for AROME.
- Towards the assimilation of radial winds: observation operator, quality control and thinning.
- Towards the assimilation of reflectivities: observation operator, specific methodology for reflectivities, quality control, and thinning.
- Assimilation status for reflectivities: results through case studies.
- Assimilation status for radial winds: results and impact on short forecasts through case studies.
- Conclusions and perspectives.
Follows closely HIRLAM’s:

- Bi-linear interpolation of the simulated \((u,v)\) (gate length smaller than model resolution: no horizontal integration)
- Projection of \((u,v)\) towards the radar \(v_h = u \sin \phi + v \cos \phi\)
- Projection of \(v_h\) on the slanted direction of the radar beam (using the earth’s effective radius model)
  \[ v_r = v_h \cos(\theta + \alpha) \]
  \[ \alpha = \arctan \left( \frac{d \cos \theta}{d \sin \theta + \frac{4}{3} a + h} \right) \]
- No fall speed correction
- Side lobes contributions neglected
- Broadening of the radar beam simulated by a Gaussian function (Probert-Jones, 1962)
- TL/AD
Exemple de vents radiaux simulés :

Blaisy – élévation 1°

Convention: Vr > 0 => vers le radar
Screening quality control:

- error with range and broadening of the main lobe with range: \( \sigma_o \) depends linearly on the range
- check only the departures (observation minus guess) between +/- 20 ms\(^{-1}\)
**Thinning**

- To avoid observation error correlations between adjacent pixels
- Sorting criterion: # of elevations, (minimum cumulated innovation)
Outlines

- Context and Introduction.
- Basic theory of the two measurements: radial wind and reflectivity
- Sources of measurement errors: need for pre-processing radar data.
- The specific radar product for AROME
- Towards the assimilation of radial winds: observation operator, quality control and thinning
- Towards the assimilation of reflectivities: observation operator, specific methodology for reflectivities, quality control, and thinning
- Assimilation status for reflectivities: results through case studies.
- Assimilation status for radial winds: results and impact on short forecasts through case studies.
- Conclusions and perspectives
• Bi-linear interpolation of the simulated hydrometeors \( (T, q, q_r, q_s, q_g) \)

• **Compute radar reflectivity on each model level**

\[
\eta(r) = \sum_{j=\text{rain,snow...}}^{\infty} \int \sigma_j(D,r).N_j(D,r)dD
\]

Backscattering cross section: Rayleigh (attenuation neglected)

Microphysic Scheme in AROME

• **Simulated Reflectivity factor in « beam volum \( bv \)»**

\[
Z_e = 10 \log \left( \int_{bv} \eta(r).f^4(\theta, \varphi).dr.d\theta.d\varphi \right)
\]

Resolution volume, ray path: standard refraction (4/3 Earth’s radius) and gate length is 250m, smaller than model resolution

Antenna’s radiation pattern: gaussian function for main lobe (side lobes neglected)
Exemple: cold front, reflectivities 160 kms around different radars on the north of France

Counterpart of simulated Reflectivities by AROME:
Radar reflectivities assimilation

Basic theory of 1D+3DVar method (Caumont & al. 2006):

- Observed reflectivities → 1D Bayesian inversion → Columns of pseudo-observations (only humidity for the moment) → 3DVar Arome → analyse

\[
y_{\text{po}}^\mu = \frac{\sum_{j \in \text{neighbours}} x_j^\mu \exp\left(-\frac{1}{2} \|y_z - H_z(x_j)\|^2\right)}{\sum_{j \in \text{neighbours}} \exp\left(-\frac{1}{2} \|y_z - H_z(x_j)\|^2\right)}
\]

- \(y_{\text{po}}^\mu\): column of pseudo-observed relative humidity,
- \(y_z\): column of observed reflectivities,
- \(x_j^\mu\): column of relative humidity,
- \(H_z(x_j)\): column of simulated reflectivities.
Radar reflectivities assimilation

Basic theory of 1D+3DVar method:

- Observed reflectivities → 1D Bayesian inversion
- Columns of pseudo-observations (only humidity for the moment) → 3DVar Arome
- Analyse

Quality control which takes into account:
- The reflectivities departures
- The pseudo-observations relative humidity departures
- Consistency between the reflectivities departures and the humidity retrievals departures (test of convergence of the 1D Bayesian inversion)
before QC and thinning

after QC

OBS

AROME
after QC

OBS

AROME

humidify

Dry up

1D inversion

Relative Humidity innovations

After thinning
Outlines

- Context and Introduction.
- Basic theory of the two measurements: radial wind and reflectivity
- Sources of measurement errors: need for pre-processing radar data.
- The specific radar product for AROME
- Towards the assimilation of radial winds: observation operator, quality control and thinning
- Towards the assimilation of reflectivities: observation operator, specific methodology for reflectivities, quality control, and thinning
- Assimilation status for reflectivities: results through case studies.
- Assimilation status for radial winds: results and impact on short forecasts through case studies.
- Conclusions and perspectives
1st décembre 2007
simulated reflectivities

**r00 – 1 hour forecast**

**AROME - CTRL**

**AROME - REFL**

**AROME - DOPP**

**MOSAIC**
r00 – 3 hour forecast

AROME - CTRL

AROME - REFL

AROME - DOPP

MOSAIC

METEO FRANCE
Toujours un temps d’avance
Analysis - Divergence at 850 hpa

Mosaï – 00h

Optimal vertical sampling between 50 et 100 kms
Checking with « MUSCAT » software which consists of independant reconstructed wind fields with several superimposed radars (Bousquet al. 2008)

Convergence line well analyzed on analysis with assimilated reflectivities
The cold front is indeed well located on the 3-hour forecast from the analysis with reflectivities...
Good drying up on the front of the main rainfalls with reflectivities assimilated.

Good quantity of rainfalls on this area with reflectivities assimilated.
In particular better humidification on the « Massif Central area » on the analysis with reflectivities (5 cycling)...

And better setting on the NorthEast (dry on Alsace/Lorraine region).
Better scores on REFL run between P6 and P9.
Positif impact until 12-hour forecast!

Decreasing of False Alarm and increasing of detection for all the thresholds.
20 November 2007
19/20 Nov. 2007 – 1. Radar observations (OBS) AGAINST simulated reflectivities from the AROME model:

2. From the reference run from 21h (r21h) with 3 assimilation cycles: RUC 3h (CTRL)
Humidity 900 hpa

With assimilated reflectivities: guess is already humid on the North region.

Analysis with radar increases further humidification.

But is drying on the Centre France...
Instantaneous reflectivity field: 1h forecast

r21 – after 3 cyclages
Instantaneous reflectivity field: 2h forecast

r21 – after 3 cyclages
Instantaneous reflectivity field: 3h forecast

r21 – after 3 cyclages
Verification: cumulated rain against rain-gauges

But difficult to dry up on the South-west
Consistency between actually assimilated active data and humidity increments...

MOSAÏC of assimilated radars at 21h (in theoretical terms! Because some radars are missing: see active data above...)

Non sampled part !!!

Clear sky!!!
1 décembre 2007:

- Good moving and setting of the cold front, capability of modifying the dynamic of the system.

- Visible impact on short range forecasts and also 12 hour forecast after initial time

- Better scores of humidity and cloud cover until 15 hour forecast

20 novembre 2007:

- Under a good sampling, capability of the assimilation method of reflectivities of creating precipitation and capability of drying up.

- Little impact or non impact on rain forecasts after 12 hour forecast (for this case, not shown here)
Outlines

- Context and Introduction.
- Basic theory of the two measurements: radial wind and reflectivity
- Sources of measurement errors: need for pre-processing radar data.
- The specific radar product for AROME
- Towards the assimilation of radial winds: observation operator, quality control and thinning
- Towards the assimilation of reflectivities: observation operator, specific methodology for reflectivities, quality control, and thinning
- Assimilation status for reflectivities: results through case studies.
- Assimilation status for radial winds: results and impact on short forecasts through case studies.
- Conclusions and perspectives
Doppler Winds assimilation
15 august 2007
Case of 15 August 2007: heavy rain on cold front

- **CNTRL**: AROME with 3h-RUC, 1st analysis on 15 August at 9h
- **RADAR**: CNTRL with Doppler winds assimilated observed by 16 radars.

Précipitations cumulées sur 3h (analyse à 21 UTC)

The wind assimilation allow to dry up the AROME model…
Cumulated precipitation on 3h (analysis at 00 UTC on 16 August)

P3-P0

RADAR CNTRL SPIN-UP

zoom...
Divergence analysis (925 hPa) analysis at 00 UTC on 16 August

+ Active data first elevations

Observations of the first elevations too high...

Multiple Doppler observations...

1h - Cumulated precipitations (P1-P0)
3h Cumulated precipitations (analysis at 00 UTC the 16 august)

Scores P12-P0
(RR3h)

Better scores until 12 h
For cumulated rain > 5 mm/h
The convergence structures at low level of the atmosphere are only sampled near the radar.
Case of 13 may 2007: squall line

- **CNTRL**: AROME with 3h-RUC, first analyse the 13 mai at 9h
- **RADAR**: CNTRL with Doppler winds assimilation observed by the radars of Trappes, Falaise, Abbeville, Avesnes, Blaisy, Troyes, Montclar
Divergence analysis (925 hPa) 12 UTC

Convergence line at low level too far off the radars to be sampled

Convergence line near the radar of Trappes and perpendicular to the radial winds gradient: convergence at low level well analyzed

Convergence line nearly parallel to Vr (+ radar of Bourges non available): radial wind gradient too little to analyse the low-level convergence

+ Données actives 1ères élev.
Realistic forecast with radar, but: the forecast from 9h is not good because of distance with low level convergence

Squall line analyzed too late on Paris

The potentially positive impact of the assimilation of Vr for predicting convective systems depends heavily on the remoteness of radar systems and orientation gradients of Vr compared to structures convergence at low level
A positive impact on forecasting precipitating patterns of convective systems has been observed when the convergence at low level is well sampled.

Realistic analysis of these structures of low level convergence have been obtained when:
- these structures are near a radar
- they are oriented perpendicularly at the radial wind gradient
- they are sampled by several radars

Large period of monitoring to assess the impact on the system currently under progress: promising results.
Monitoring and adjustments...

CTRL

Vr<250

Winds: scores to analysis

CTRL

Vr<100
Outlines

- Context and Introduction.
- Basic theory of the two measurements: radial wind and reflectivity
- Sources of measurement errors: need for pre-processing radar data.
- The specific radar product for AROME
- Towards the assimilation of radial winds: observation operator, quality control and thinning
- Towards the assimilation of reflectivities: observation operator, specific methodology for reflectivities, quality control, and thinning
- Assimilation status for reflectivities: results through case studies.
- Assimilation status for radial winds: results and impact on short forecasts through case studies.
- Conclusions and perspectives
Radial winds:

- Continuous assimilation (over period of 1.5 mois) of doppler winds with an pre-operational assimilation AROME (each 3 hour, interesting for a systematic monitoring of doppler radars and AROME model).

- Many positive cases (QPF scores), neutral objectives scores, but some few negatives cases (subjective check): several adjustments to be done (decreasing the range, increase error statistics...).

- Results are sufficiently positive to predict winds will be incorporated into the first operational version of AROME.

Reflectivities:

- Assimilation of reflectivities (separately) with cycling over periods of 4 or 5 days: cases studies and adjustments of the 1D+3DVar assimilation method.

- Method giving very often positive results (QPF scores), but currently sub-optimal, since removal of inverted profiles from the 1D method in cases of "bad convergence" (method fails because of a model "too far" from reality "radar"): work under progress to optimize the method.


