Humidity profile retrieval with the Clermont-Ferrand VHF wind profiler

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Abstract

The humidity profile can be derived from ST radars echo power and spectral width, provided the temperature profile, and one at least one humidity reference (either integrated or at a given altitude within the radar altitude range), are known. This technique has already been successfully implemented on VHF [3] [8] [12], and UHF radars [7]. To this purpose, several algorithms have been developed, as presented for example in [5], and [12].

In this project, we will use the particular topography of the Puy-de-Dôme Observatory to our advantage. The Laboratoire de Météorologie Physique (LaMP) Clermont-Ferrand VHF profiler is located a few kilometres from the Puy de Dôme, which culminates at an altitude close to the first range gate of the radar (1464 m). At its summit, continuous measurements are performed with a humidity sensor and a GPS station, which provides the integrated water vapour (IWV).

Hence, we will be able to test the different humidity profile retrieval approaches, and particularly the direct exploitation of the IVW data without the need of any assumption on the vertical distribution of the water vapour. This information, completed by reference data at the top (negligible humidity near the tropopause) and at the base of the profile (humidity sensor data) will give us a unique opportunity to fine-tune the retrieval algorithm and to cross check the measurement quality.

Finally, the humidity profiles retrieved with the VHF profiler will be validated by comparisons with the LaMP newly acquired water vapour Raman lidar.

1.Theoretical background

1.1 radar turbulence data: *η and ε*

Two main algorithms have been used to extract humidity gradients from the wind profiler data (WPR). The first one uses the refractive index gradient *M* [12], the second one the potential refractive index ϕ [11]. Both require the reflectivity and the turbulent dissipation rate values calculated respectively from the zeroth and the second moment of the radar signal on the spectrum.

Reflectivity η retrieval can be directly obtained from the signal-to-noise ratio of the radar spectral signal, using for example the classical equation [13]:

$$\eta = \frac{9\pi}{2}\,\frac{ckB\left(T_c + T_{rx}/\alpha\right)}{\alpha P_t F_r A_e \cos\beta}\left(\frac{z}{\Delta z}\right)\left(\frac{S}{N}\right) \qquad (1)$$

Where:

c = velocity of light
k = Boltzmann's constant
B = Bandwidth of the integrating filter
T_c = *Cosmic noise temperature*
T_{rx} = Receiver noise temperature
α = Efficiency of the antenna and transmission line
P_t = Peak transmitted power
F_r = Pulse repetition frequency
A_e = Effective antenna area
β = Antenna beam elevation angle
z = Range
Δz = Range resolution
S/N = Signal-to-noise ratio

The turbulence dissipation rate ε is deduced from the the spectral width σ after corrections due to wind shears and other contributions as described in [14]: being successfully tested by comparison with in-situ measurements [6]:

$$\varepsilon = \sigma_t^2 \left(4\pi/A\right)^{3/2} J^{-3/2} \qquad (2)$$

with: (3)

$$J = 12\,\Gamma\left(\frac{2}{3}\right)\int_0^{\frac{\pi}{2}} \sin^3\varphi \int_0^{\frac{\pi}{2}} \left[b^2\cos^2\varphi + a^2\sin^2\varphi + \left(\frac{L^2}{12}\right)\sin^2\varphi\,\cos^2\theta \right]^{1/3} d\theta\, d\varphi$$

where:
σ_t = Spectral width due to turbulence, corrected from wind shear and other factors
A = 1.53 to 1.68 (see [14])
Γ = Gamma function
φ, θ = Spherical coordinates
L = the product of the mean wind speed and the Doppler time series duration

$$a = \frac{r\theta}{4\sqrt{\ln 2}} \qquad (4) \qquad\qquad b = \frac{h}{4\sqrt{\ln 2}} \qquad (5)$$

r = range, q = elevation angle, h = pulse length

1.2 humidity equation

M is estimated from the general equation:

$$M = -77{,}6x10^{-6}.\frac{P}{T}\left[\frac{N^2}{g}.\left(1+15600\frac{q}{T}\right)-\frac{7800}{T}\frac{dq}{dz}\right] \quad (6)$$

With: θ = Potential temperature,
T = Absolute temperature,
P = Atmospheric pressure,
g = Acceleration of gravity,

Giving:

$$\frac{dq}{dz}-\left(\frac{2N^2}{g}\right)q = 1{,}652\frac{T^2}{P}M+\frac{T}{7800}\frac{N^2}{g} \quad (7)$$

Considering:

$$N^2 = g.\frac{d\ln\theta}{dz} = \frac{g}{T}.\left(\frac{dT}{dz}+\Gamma\right) \quad (8)$$

We finally obtain:

$$q(z) = 1{,}652\theta^2\int_{z0}^{z}\frac{T^2M}{P\theta^2}dz+\frac{\theta^2}{7800g}\int_{z0}^{z}\frac{TN^2}{\theta^2}dz+\theta^2\frac{q_0}{\theta_0^2} \quad (9)$$

With q_0 and θ_0:being the values of humidity and potential temperature respectively at the boundary height z_0.

For further developments, Eq (9) will be written as:

$$q(z) = a_0(z)+b_0(z)+c_0(z)q_0 \quad (10)$$

with:

$$a_0(z) = 1{,}652\theta^2\int_{z0}^{z}\frac{T^2M}{P\theta^2}dz \quad (11)$$

$$b_0(z) = \frac{\theta^2}{7800g}\int_{z0}^{z}\frac{TN^2}{\theta^2}dz \quad (12)$$

$$c_0(z) = \frac{\theta^2}{\theta_0^2} \quad (13)$$

Eq (8) directly provides the N^2 profile. Then θ profile is calculated by integrating $\theta(z) = \theta_0 e^{\int_{z0}^{z}\frac{N^2(x)}{g}dx}$ with $\theta_0 = T_0\left(\frac{1000}{P_0}\right)^{Ra/Cpa}$. P is deduced from $P = P_0\left(\frac{T}{T_0}\right)^{Cpa/Ra}$

The humidity equation can thus be solved if only M and T profiles, ground pressure and temperature, and humidity at a given range or over a larger layer are known.

The absolute value of the last parameter M is provided by the radar:

From [7] $$|M| = K L_0^{-2/3}\eta^{1/2} \quad (14)$$

From [1]: $$|M| = K' F^{1/2} N \varepsilon^{-1/3}\eta^{1/2} \quad (15)$$

With:
L_0 = Outer scale of turbulence
F = Filling factor of turbulence

In this process, attention should be paid to the sign ambiguity of M, because statistically, M can become positive in 10 to 20% of cases. This ambiguity can be solved in a first approximation if we notice that generally M becomes positive when N^2 is below a certain threshold of few 10^{-5} rad^2 s^{-2} [12].

The other algorithm [11], not described here due to lack of space, could be used, replacing M with the potential refractive index φ, bringing he same form of equation as Eq (10)

2. Algorithm implementation

2.1 One humidity reference point

Theoretically, only one humidity reference must be known in order to solve the equation. For a VHF radar reaching at least the upper troposphere, this condition is easily met, assuming negligible humidity at 9 km height for example.

$$q(zi) = a_0(zi)+b_0(zi)+c_0(zi)q_0 \quad (16)$$

From (16), $q0$ is deduced, allowing the direct resolution of (10)

2.2 Two humidity reference data

As already mentioned by Tsuda et al. [1], the radar-derived value of M may differ from the true one by a proportion coefficient. Moreover, calibration data may not always be much accurate or may change with time. Consequently, another unknown parameter K should be introduced in the term of M, changing (10) into:

$$q(z) = K.a_0(z)+b_0(z)+c_0(z)q_0 \quad (17)$$

For example, information on total humidity value qt would give us the extra parameter needed to solve (10). In that case, we would have the couple of two two equation with 2 unknowns (K and $q0$):

$$\begin{aligned} q(zi) &= K.a_0(zi)+b_0(zi)+c_0(zi)q_0 \\ qt &= K.A_0+B_0+C_0q_0 \end{aligned} \quad (18)$$

With A_0, B_0, and C_0, being the integrated value of a_0,, b_0, and c_0, respectively over the whole range of the profile.

The GPS instrument could provide the integrated water vapour (IWV) from the ground up to the satellite. It has been demonstrated that total humidity inside the radar range could be accurately estimated from previous radio soundings [8] or other other remote-sensing devices such as radiometer.

2.3 Three humidity reference data

In equations (14) and (15), L_0 and F are supposed to be constant with altitude. This assumption, already discussed [1], may involve non negligible errors as several studies have shown large height variations of L_0 even in the lower troposphere [2][9].

Consequently, a further variable K' should be introduced to express, at least at first approximation, the height variations which may occur for each profiling. The general humidity equation (17) thus becomes:

$$q(z) = (K+K'z).a_0(z)+b_0(z)+c_0(z)q_0 \quad (19)$$

In this case a third humidity reference would be necessary, for example, the value at a given height zj. This provides us with a new system of 3 equation for three unknown to solve (*q0*, *K* and *K'*):

$$\begin{aligned} q(zi) &= \left(K + K'z\right)a_0(zi) + b_0(zi) + c_0(zi)\,q_0 \\ q(zj) &= \left(K + K'z\right)a_0(zj) + b_0(zj) + c_0(zj)\,q_0 \qquad (20) \\ qt &= K.A_0 + K'.A'_0 + B_0 + C_0\,q_0 \end{aligned}$$

With A'_0 being the integrated value of ($z.a_{0)}$,) over the whole range of the profile.

Eq (20) needs to be solved before calculating the *q* profile from the equation (19).

3. Simulation with radio soundings

The two-month Mesoscale Alpine Project (MAP) Campaign in the region of Milan (Italy) [1] was used to test this technique. A large number of controlled measurements from the CNRM VHF radar were available and completed with nearly one hundred radio soundings launched in the vicinity.

The VHF radar belongs to the INSU/Meteo series [10], with only slight differences between the LaMP radar and the CNRM one which participated to the MAP Experiment, The characteristics are listed on the following table.

Table: *Main characteristics of the VHF radar*

	LaMP	CNRM
Frequency	45 MHz	
Antenna type:	Coaxial collinear	
Antenna area:	65x65m	85x130m
Beamwidth:	5.6°	4.3° - 2.8
Number of beams	5	
Peak power:	5 kW	12 kW
Pulse repetition period	156.25 µs	
Pulse width	10 µs (8 codes)	
Height resolution	375 m	
Nbr of spectral points	256	
Coherent integrations	128	
Incoherent integrations	7	

When the only reference point is a negligible humidity at 9 km height, the standard deviation (StD) from RS data largely extends over 1 g/kg below 5 km (Fig. 1)

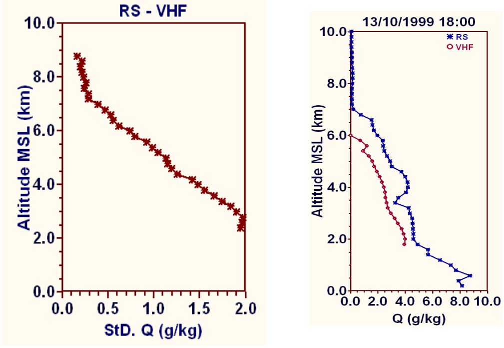

Figure.1 - Left: Standard deviation between radiosonde (RS) humidity measurements and VHF radar using zero humidity reference point at 9 km height. Right: Typical example of humidity profiles obtained with RS and VHF.

The results are much better when the total humidity reference value is added, in which case, 1g/kg StD is reached only below 3 km height (Fig. 2).

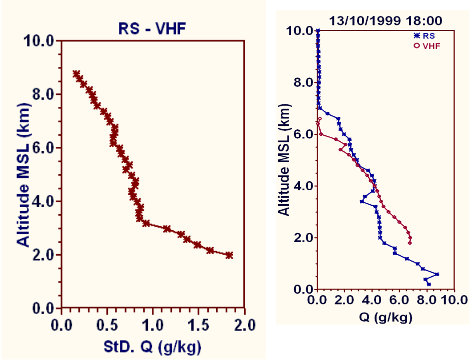

Figure.2 - Same as Fig. 1 using the total humidity inside the radar range as a second reference

A third reference point value at the base of the radar range (3 km in our example) considerably improves the statistics as shown on Fig. 3.

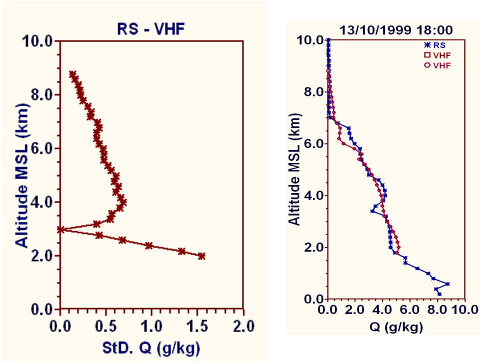

Figure.3 - Same as Fig. 2 using a known value at 3 km height as a third reference.

These preliminary results were very encouraging for implementing a three-reference humidity system at LaMP.

4. The LaMP project

4.1 The experimental set-up

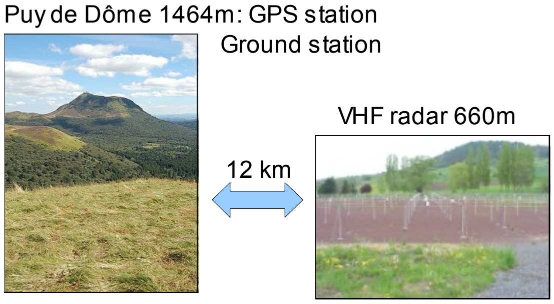

Figure 4- The instrumental set-up at LaMP

At its summit, continuous measurements are performed with a humidity sensor and a GPS station, which provides the integrated water vapour (IWV) corresponding practically to the range covered by the radar.

Hence, we will be able to test the different humidity profile retrieval approaches, and particularly the direct exploitation of the IVW data without the need of any assumption on the vertical distribution of the water vapour.

Finally, the humidity profiles retrieved with the VHF profiler will be validated by comparisons with the LaMP newly acquired water vapour Raman lidar.

This system, along with updated radar hardware, will be fully operational at the end of 2009 for a continuous operational profiling of wind and humidity.

4.2 Preliminary results

Preliminary experiment was made between 5 November and 7 December 2004 with the LaMP VHF radar completed with GPS IWV data and ground station measurements at Puy-de-Dome. At this time, the temperature profile was deduced from the standard value calculated from ground level measurements. Fig. 5 gives a synoptic view of the humidity evolution over the radar during the month-long experiment.

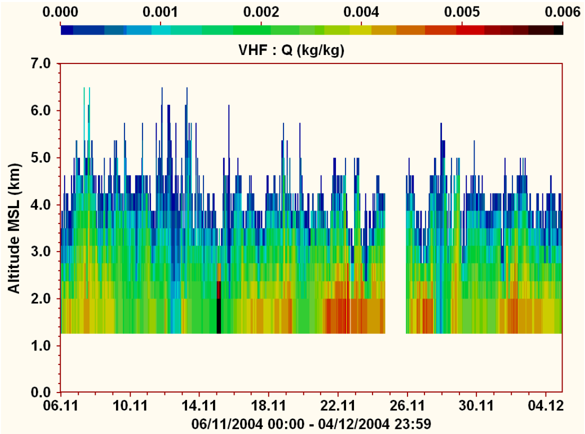

Figure.5 - *Evolution of humidity profile over the LaMP radar site during the 2004 experiment using the GPS and ground data at Puy de Dôme with the 3 reference point method.*

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