An Improved High-Resolution Processing Method for a Frequency Domain Interferometric Imaging (FII) Technique

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ABSTRACT

Frequency hopping [also recently called range imaging (RIM) or frequency domain interferometric imaging (FII)] is a pulse compression technique used to improve the range resolution $\Delta r$ of Doppler radars limited by their minimum transmitted pulse length. This technique can be seen as an extension of the dual-frequency domain interferometry (FDI) technique, since it consists of transmitting more than two adjacent frequencies. Similarly to antenna array processing used for angular scanning, RIM/FII enables range scanning along the vertical line of sight to obtain a range profile (classically called “brightness” in the literature of the field of antenna array processing). The performances of RIM/FII can be improved by using high-resolution methods such as the maximum likelihood method (or the Capon method), the singular value decomposition method with the multiple signal classification (MUSIC) algorithm, and the newly introduced improved maximum likelihood method (the Lagunas–Gasull method). The applications of such methods would permit us to investigate in detail the small-scale dynamics within the stratified atmosphere where very thin structures, such as temperature sheets, coexist with thin turbulent layers. First, simulations are presented in order to compare the performances of the Lagunas–Gasull method with respect to the other methods already discussed by Palmer et al. and Luce et al. The second part of this paper is devoted to presenting some preliminary results with a 45-MHz miniradar profiler located at Toulon, France (43.78°N, 5.58°E), and to show other applications of the Lagunas–Gasull method on data collected with the VHF middle- and upper-atmosphere (MU) radar located at Shigaraki, Japan (34.85°N, 136.10°E). These results demonstrate the applicability of the Lagunas–Gasull method on two different VHF Doppler radars.

1. Introduction

The performances of atmospheric pulsed Doppler radars are limited by the range resolution (typically 150 m) related to the minimum pulse width. Consequently, they can only provide a coarse description of the very thin structures that have been observed by high-resolution in situ techniques (Dalaudier et al. 1994; Muschinski and Wode 1998). Indeed, experiments with these techniques have shown the ubiquitous existence of very thin layered structures, also called temperature sheets (typically 10 m thick), associated with sharp temperature gradients. It was shown that the temperature sheets contribute to the vertical echo power enhancements detected by VHF atmospheric radars (Luce et al. 1995). Only frequency modulated continuous wave (FMCW) radars (e.g., Richter 1969; Eaton et al. 1995) providing a high vertical resolution have the potential for detecting such thin layered structures, mainly within the first kilometers of the lower atmosphere. But, contrary to pulsed radars, FMCW radars are bistatic and are only used for lower-troposphere studies due to their limited range coverage and small antenna apertures. In the field of mesosphere–stratosphere–troposphere (MST) radar studies, a pulse-scanning technique was
The RIM/FII technique in its basic form simply differs from frequency hopping by the applications of high-resolution processing methods. The simplest form of range profile can be obtained from a discrete Fourier transform (DFT) of the signals received at the different frequencies. But its performances are poor because they depend only on the total radar system bandwidth, which is limited to few hundreds of kilohertz at VHF. However, they can be enhanced by applying high-resolution methods commonly used in the field of antenna array processing. In addition to methods already discussed by Palmer et al. (1999) and Luce et al. (2001a,b), that is, the maximum likelihood method [or the Capon method (Capon 1969)] and the multiple signal classification (MUSIC) algorithm (Bienvenu and Kopp 1983; Schmidt 1986), the improved maximum likelihood method (IMLM) [or the Lagunas–Gasull method (Lagunas-Hernández and Gasull-Llampallas 1984)] is introduced in the present paper for MST radar applications. The Lagunas–Gasull (LG) method is a filter-bank method based on a refined estimate of the filter bandwidth. Some theoretical aspects of the different methods are briefly described in section 2. From simulations shown in section 3, it is confirmed that the performances of the LG methods are better than those of the Capon method, especially for lower signal-to-noise ratio (SNR). This property is interesting since atmospheric echoes are often associated with low SNR. Furthermore, the LG method is also preferable to the MUSIC algorithm since the latter was only developed for the detection of discrete sources and does not give access to their intensity. However, we suggest that the combination of the filter-bank (LG) and subspace-based (MUSIC) methods, easy to apply, can give us complementary information that may be useful for a detailed overview of the clear air structures.

Section 4 presents preliminary applications on a low-troposphere VHF miniradar (Candusso et al. 1998; Candusso and Crochet 2001) and applications of the LG method on data collected with the more powerful VHF middle- and upper-atmosphere (MU) radar (Fukao et al. 1985). For the latter, datasets already presented by Luce et al. (2001a) have been reprocessed with the LG method and compared with the other methods. These preliminary results confirm the higher performances of the LG method with respect to the other filter-bank processes.

2. The processing methods used for RIM/FII

   a. Brief description of previously introduced methods

   As depicted in Fig. 1, the RIM/FII technique in its basic form (i.e., the frequency hopping) consists of a sequential

![Fig. 1. Schematic representation of the sequential frequency shifting.](image-url)
pulse-to-pulse transmitting/receiving frequency scanning, where $\tau$ is the pulse duration, $T_{\text{ipp}}$ the interpulse repetition period, and $f_n = f_0 + n\Delta f$ is the carrier frequency for the pulse number $n$ (where $n = 0, \ldots, N - 1$, $N$ being the number of frequencies used). Considering the scattering properties of the air refractive index irregularities classically assumed, the $\Delta f$ dependence of the signal amplitudes can be neglected if the maximum frequency shift $(N - 1)\Delta f$ is small compared to the nominal carrier frequency of the radar [e.g., see Luce et al. (2001a) for more details about the conditions of applications of RIM/FII].

All the methods described in the present paper require the determination of the Hermitian normalized cross-correlation matrix $\mathbf{R}$ (dimension $N \times N$):

$$
\mathbf{R} = \begin{bmatrix}
1 & \cdots & \rho(i\Delta k) & \cdots & \rho((N-1)\Delta k) \\
\vdots & \ddots & \vdots & \ddots & \vdots \\
\rho(-i\Delta k) & \cdots & 1 & \cdots & \rho(i\Delta k) \\
\vdots & \ddots & \vdots & \ddots & \vdots \\
\rho(-(N-1)\Delta k) & \cdots & \rho(-i\Delta k) & \cdots & 1
\end{bmatrix}
$$

(1)

Each component corresponds to the normalized cross correlation of the signals for a given frequency difference.

1) THE FOURIER METHOD

It is shown that the power distribution as a function of altitude that represents the Fourier range profile is given by

$$
P(z) = \mathbf{a}(z)^H \mathbf{R} \mathbf{a}(z),
$$

(2)

where the $\mathbf{H}$ represents the Hermitian operator. The vector $\mathbf{a}(z)$ is called the scanning vector and is defined by

$$
\mathbf{a}(z) = \frac{1}{\sqrt{N}} [1, e^{i\phi}, \ldots, e^{i(N-1)\phi}]^T,
$$

(3)

where $T$ is the transpose operator and $\phi$ is the phase shift between signals received at two adjacent frequencies. It is worthwhile to recall, that the condition $\Delta r \leq c/2\Delta f$ or $\Delta f \leq 1/\tau$ must be verified in order to avoid ambiguities when performing range scanning. The same condition must be verified when applying the dual-FDI technique in order to avoid ambiguity in position. Also, the resolving power (which defines the minimum distance of separation between two sources for being detected) achieved by the Fourier method is $c/2N\Delta f$, according to the definition given by Nathanson (1969) [which is slightly different than the definition given by Luce et al. (2001a)]. Consequently, the frequency shift $\Delta f$ must be adapted to the pulse length in order to scan the visible domain without ambiguities, whereas the resolving power depends on the total bandwidth $N\Delta f$ used. Similar conditions are obtained in antenna array processing for which the distance between adjacent antennas defines the ambiguity domain, and the total length of the array limits the resolving power. Figure 2 shows an example of range scanning with four frequencies separated by 250 kHz giving a maximum frequency shift of 750 kHz. In the present case, the pulse duration must be smaller than 4 $\mu$s to avoid ambiguity, leading to a resolving power of 150 m. For illustration, the observed altitude has been arbitrarily chosen to be 100 m below the center of a 300-m radar range gate. The effect of the radar range-weighting function already discussed by Luce et al. (2001a) is also represented.

2) THE CAPON METHOD

The scanning vector of the Fourier method is data independent. The Capon method adapts it for each altitude $z_i$ by minimizing the contribution from the other altitudes. In this case, the problem consists of minimizing

![Fig. 2. Representation of the range scanning. The range weighting function (solid line) after frequency hopping processing is the product of the initial range-weighting function (dash-dot line) with the weighting function introduced by the frequency hopping (dashed line), numerically phased to observe 100 m below the center of the radar range gate.](https://example.com/fig2.png)
Fig. 3. Simulation of the different methods used in range profile estimation in order to compare their ability to separate two infinitely thin layers within a radar range gate of 300 m in thickness and an SNR of 20 dB. The normalized brightness represents the position of the layers within the radar range gate as a function of the distance between each other.

\[ P(z) = h(z)^\mu R_h(z) \]  \hspace{2cm} (4)

under the condition

\[ h(z)^\mu a(z) = 1, \]  \hspace{2cm} (5)

where \( h(z) \) describes the data-dependent bandpass filter of the adaptive method. It can be found by solving the constrained optimization problem owing to the Lagrangian multiplier methods reintroduced by Palmer et al. (1998) in the context of MST radar studies. The solution to (4) and (5) is given by

\[ h(z) = \frac{R^{-1}a(z)}{a(z)^\mu R^{-1}a(z)}. \]  \hspace{2cm} (6)

The Capon range profile is then given by

\[ P_{\text{Capon}}(z) = \frac{1}{a(z)^\mu R^{-1}a(z)}. \]  \hspace{2cm} (7)

Thus, the high-resolution range profile \( P_{\text{Capon}} \) depends on \( a(z) \) and the inverse normalized cross-correlation matrix \( R^{-1} \). Its resolving power depends on the SNR, not only on the total bandwidth as does the Fourier method. More simulation details are given in section 3.

3) The MUSIC Algorithm Based on an SVD Decomposition

The eigen system approach has been introduced by Bienvenu and Kopp (1983) for the detection of discrete sources. It consists of a singular value decomposition (SVD) of the normalized cross-correlation matrix into two orthogonal vector subspaces: the signal and noise vector subspaces. Thus, to estimate the source positions, the MUSIC algorithm (Schmidt 1986) is based on the fact that the eigenvectors of the signal subspace are orthogonal to the noise subspace eigenvectors. We obtain

\[ P_{\text{MUSIC}}(z) = \frac{1}{a(z)^\mu V_n V_n^\mu a(z)}. \]  \hspace{2cm} (8)

where \( V_n \) is a matrix with columns corresponding to the noise eigenvectors of the matrix \( R \). The dimension of this matrix \((N \times n)\) depends on the number of sources assumed. In theory, if \( R \) is calculated without estimation errors, the range profile \( P_{\text{MUSIC}} \) has infinite values at the position of the sources. In practice, only maxima are found. For our applications, it is thought that the MUSIC algorithm may be used for the detection of much thinner layers than the initial range resolution (e.g., temperature sheets). For the case of distributed sources, however,
Fig. 4. Comparison of the resolving power of the different methods used in range profile estimation as a function of SNR from 0 to 30 dB. The normalized brightness is represented for two infinitely thin layers separated by 75 m.

theoretical investigations showed that the MUSIC algorithm is able to give positions that are still representative of the position of the distributed source (e.g., Valaee et al. 1995). The peaks corresponding to the highest eigenvalues are confined within the domain covered by the distributed source.

b. The LG method

The range profile given by the Capon method is not a power spectral density (PSD) but has the dimension of a power that corresponds to the integration of the “true” PSD through the filter \( h(z) \):

\[
P_{\text{Capon}}(z) = h(z)^H R(z) = \int z |H(z)|^2 S(z) \, dz \quad (9)
\]

where \( H(z) \) is the transfer function of the filter centered on \( z \), and \( S(z) \) the true PSD. As explained by Stoica and Moses (1997, p. 188), a true PSD can be generated by multiplying the relation (7) or (9) by \( N - 1 \). The LG method, also an adaptive method, is a more subtle modification of the Capon method that applies a correcting factor that depends on the true filter bandwidth. By considering that \( S(z) \) is approximately constant within the bandwidth of \( |H(z)|^2 \) around \( z_i \), relation (9) can be approximated by

\[
P_{\text{Capon}}(z_i) = S(z_i) \int |H(z)|^2 \, dz = S(z_i) h(z)^H h(z). \quad (10)
\]

Thus,

\[
S(z_i) = \frac{P_{\text{Capon}}(z_i)}{h(z)^H h(z)}, \quad (11)
\]

which can be extended to all the altitudes in order to obtain the general expression of the LG range profile:

\[
P_{\text{LG}}(z) = S(z) = \frac{a(z)^H R^{-1} a(z)}{a(z)^H R^{-2} a(z)}. \quad (12)
\]

The LG method presents a better resolving power and a better white noise density estimation than the Capon method. Stoica and Moses (1997) also emphasized that the correction \( h(z)^H h(z) \) can be applied only if the function \( |h(z)^H a(z_i)|^2 \) for \( z_i = [z_i - \Delta r/2; z_i + \Delta r/2] \) has its maximum around the position \( z \). Otherwise, the LG range profile can be biased. More details are given by Stoica and Moses (1997, p. 199).

3. Simulations

In this section, we describe simulations performed in order to compare the resolving power of the LG method with respect to the Fourier, Capon, and MU-
SIC methods, by using four frequencies separated by 250 kHz around 45 MHz (corresponding to the radar carrier frequency). Since we are interested in the resolving power of the different methods, it is assumed that the signals received for each frequency are produced by $L$ infinitely thin scattering layers. Moreover, these signals are assumed to be affected by a white background noise of power $P_N$. The normalized cross-correlation matrix ($4 \times 4$) can thus be expressed as

$$R = \left[\sum_{i=1}^{L} P_i a(z_i) a(z_i) + P_N I\right] / \left(\sum_{i=1}^{L} P_i + P_N\right),$$

(13)
where $P_i$ and $z_i$ are the power backscattered by the layer $i$ and its altitude, respectively, and $I$ is the identity matrix.

The first simulation was devoted to comparing the resolving power performances of the different methods by assuming two infinitely thin layers embedded within a 300-m radar range gate. Figure 3 shows the normalized brightness as a function of the distance between the two layers varying from 0 to 300 m. In addition, without loss of generality, the signals received from both layers have the same power ($P_i = P$ for $i = 1, \ldots, L$), giving an SNR defined in decibels by $10 \log_{10}(\sum P_i/P)$ equal to 20 dB. As expected, the better resolving power is achieved by the MUSIC algorithm, which localizes both layers for the smallest distance (a few meters), while the worst performances are given by the Fourier method (in agreement with the theoretical value $c/2N\Delta f$). It is worth noting that the LG method resolves the two layers for a smaller separation ($\approx 25$ m) compared to the Capon method ($\approx 55$ m). These simple simulations thus confirm the better resolving power of the LG method with respect to the Fourier and Capon methods. In practice, it is then expected to obtain better performances with the LG method than the Capon method, at least for sufficient SNR.

In Fig. 4 the normalized range profile is shown within a radar range gate of 300 m, assuming two infinitely thin layers separated by 75 m as a function of SNR for values between 0 and 30 dB. This plot clearly shows that the Fourier method cannot separate the two layers, whatever the SNR may be (it does not depend on SNR if the cross-correlation matrix is not biased), whereas the resolving powers of the adaptive methods are improved as SNR increases. As already shown by the previous simulation, the resolving power performances of the LG method are better than those of the Capon method because it can resolve both layers at lower SNR (similar performances are obtained with the LG method when the SNR is reduced by about 7 dB). It is worth noting in Figs. 3 and 4 that the position of the two detected layers by the filter-bank methods can be biased (i.e., the two layers appear closer to each other) if the

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<th>Table 1. Experimental configuration used during the campaign with the VHF mini radar profiler.</th>
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<td>Beam direction</td>
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<td>Transmitted peak power</td>
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<td>Interpulse repetition period</td>
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<td>Pulse width</td>
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<td>Sampling</td>
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distance between the layers and/or the SNR is not sufficient. Of course, this problem is even more critical if distributed layers are considered. With the simulation configuration used, it is also noted that the results with the MUSIC algorithm present the best performances.

4. Implementation and preliminary results

a. Applications on a mini VHF radar

In order to test the efficiency of the different methods to real radar data, a short multifrequency experiment was conducted in November 2000 with a 45-MHz VHF miniradar profiler developed in Toulon, France. This VHF miniradar is devoted to operating at low altitudes (low troposphere), which are not accessible by more classical VHF ST radars. It uses a set of 16 half-wavelength dipoles in squared configuration (4 × 4), giving an antenna array of 100 m² (Candusso et al. 1998; Candusso and Crochet 2001) and a −6 dB angular full width of the two-way antenna pattern of 26°. As can be deduced from the discussion by Luce et al. (2001a), such a large radar beamwidth can be a serious drawback for the application of interferometric techniques. Indeed, the effects of the wavefront curvature must be ignored in order to consider the processing problem as one-dimensional. This is possible for more classical VHF ST radars (which are characterized by a beam aperture of a few degrees only), whatever the anisotropy of the scatterers may be at the Bragg (half radar wavelength) scale. For large beamwidths, the normalized cross correlations depend on both the horizontal correlation length \( l_x \) of the refractive index irregularities and the beamwidth, except in the case where \( l_x \) becomes very large compared to the first Fresnel zone. Indeed, in this case, the main contributions come from directions close to the zenith only; that is, the apparent radar beamwidth becomes very narrow. Thus, we must keep in mind that the results with the present VHF miniradar might be substantially affected by this problem if the refractive index fluctuations associated to the studied layers are not strongly anisotropic; the apparent thicknesses might be overestimated no matter what the filter-bank methods may be.

1) EXPERIMENTAL CONFIGURATION

The November 2000 experiment involved the VHF mini radar with four carrier frequencies (44.625, 44.875, 45.125, and 45.375 MHz), equally spaced around the nominal radar frequency (45 MHz). The frequencies were switched after each interpulse period of 80 μs. Because the minimum frequency spacing was 250 kHz, the pulse
duration must be smaller than 4 $\mu$s [see relation (15)] in order to avoid altitude ambiguity. Thus, a radar pulse length of 2 $\mu$s was used with a sampling interval of 1 $\mu$s to obtain an overlap in the range of 150 m. Overlapping was applied in order to test the compatibility of the results between successive overlapped gates. Fifty gates were sampled between 2250 and 9600 m. Coherent integration was performed 1000 times for each frequency, and, to account for the frequency switching, the effective sampling frequency was 3.125 Hz. Since the experiment was performed using a vertical beam only, the aliasing velocity of 5.21 m s$^{-1}$ was appropriate. Unfortunately, measurements in oblique directions, useful for a coarse estimate of the anisotropy of the scatterers, are not available. The overall radar parameters used during this experiment are given in Table 1.

2) RESULTS

The data were collected during a 30-min experiment from 0010 to 0040 LT 10 November 2000, during which layered structures were detected. The range profiles were calculated for each record (44 records of time series of 128 points collected every 41 s) with an arbitrary range sampling of 1 m, providing 301 points within each radar range gate.

Figures 5a and 5b show the time evolution of the range profiles estimated with the Fourier, Capon, LG
RIM/FII experiment


- dual FDI
- Fourier
- Capon
- Lagunas–Gasull
- MUSIC (2 sources)

Fig. 9. Adaptation of Fig. 5 of Luce et al. (2001a) showing an example of applications of the different processing methods on the 45-MHz MU radar, including the LG/IMLM method for four successive gates. More details are given in Luce et al. (2001a).

(identified as IMLM on the figure), and MUSIC methods for the radar range gate number 7 (3150 m) and number 21 (5250 m), respectively. The results, assuming one and two sources, are given for the MUSIC algorithm. The power associated with the peaks detected by the MUSIC algorithm corresponds to the global echo power measured at the considered altitude. The black line with circles corresponds to the positions of maxima given by the dual-FDI technique using the 0.5-MHz frequency difference.

As suggested by one of the reviewers of the paper, we verified with the present dataset the condition of application of the LG method related to the quality of the bandwidth of the Capon filter and described by Stoica and Moses (1997, p. 199).

In Fig. 5a, a layered structure has been clearly detected by the Fourier, the two adaptive methods, and with the MUSIC algorithm assuming a single source for the first 15 min before disappearing. It should also be noticed that the disappearance of the continuous structure after the first 15 min is related to a very small SNR (see Fig. 6). It was verified that this SNR decrease did not result from an increase of the cosmic noise level but is rather due to a signal power decrease. A similar event occurs at 5250 m (Fig. 5b), where a layer suddenly appears after minute 12. Unfortunately, we do not have complementary measurements for the interpretation of these phenomena, but it can be speculated that the echoes were related to atmospheric structures advected by the wind and limited in extent horizontally (e.g., the top of clouds associated with strong humidity/temperature gradients). The sudden disappearance or appearance of the echoes would then be correlated to their passages through the radar beam.

As expected, the LG method attains better resolution performances than the Fourier and Capon methods by increasing the contrast of the range profile. The MUSIC algorithm provides positions with a very remarkable agreement compared to the filter-bank methods, especially when a single source is assumed. This result clear-
Fig. 10. Applications of the different processing methods, as in Fig. 6b of Luce et al. (2001a), with the LG method added on a 30-min dataset collected with the MU radar at 9750 m.

ly indicates that the MUSIC algorithm does not break down. When two sources are assumed, they are often close to each other, that is the case before minute 10, for example, in Fig. 5a, and at minute 24 in Fig. 5b. The MUSIC algorithm detected two distinct structures during three consecutive records in Fig. 5a when the echoing layers appeared thicker with the filter-bank methods. Even the LG method was not able to resolve the double structures. Interestingly, two maxima separated by about 200 m have been identified around minute 18 in Fig. 5a by the adaptative methods and also by the MUSIC algorithm assuming two sources. This double structure was not found by the Fourier method (because of its poor resolving power) and cannot be observed using the dual-FDI technique.

The same analysis as Fig. 5a is given in Fig. 6, but the positions (corresponding to the maxima of the range profiles) and thicknesses estimated from the different methods are compared to each other. In this figure, results obtained with the dual-FDI technique using a frequency difference of 0.5 MHz are also included. Also, only the “MUSIC position” for one source is given, since usually only a single layer has been detected by the other methods. The structure thickness has been defined as the half-power width of the range profiles for all the methods, but this definition fails when the dynamics of the range profile is not sufficient. This is the case after minute 15, and the results should not be considered.

The layer positions given by the different methods agree very well with each other when the layer is well defined. It is interesting to note that the dual-FDI technique indicates positions that are extremely similar to those found with the RIM/FII technique. This result suggests the existence of an isolated dominant structure in the radar volume. Indeed, the absence of significant differences between the FDI and RIM/FII positions seems to exclude the presence of several dominant layers [not resolved by the high-resolution (HR) methods] within the range gate. However, it does not exclude the existence of a quite homogeneous background, since the FDI processing indicates a thicker layer than the two adaptive methods. It is important to recall that, in absence of complementary information, we can discuss only the variations and not the absolute values of thicknesses because of the effects of the large beamwidth of the mini VHF [see discussion in section 4a(1)].

As expected from the simulations, it is to be noted that the smallest thickness estimates (about 50 m around minute 10) are given by the LG method, while the largest ones are given by the Fourier method. The time variations of the layer thickness are similar for the four methods during the first 15 min and are clearly related to the SNR fluctuations. These time variations in thickness can be partly due to real variations of the atmospheric structure thickness but, because the SNR values are quite small, they might also result from the sensitivity of the methods to the SNR as shown by the simulations for the adaptative methods. We cannot conclude without more information, so this relationship will be studied in more detail in future works.

Figure 7 shows specific vertical range profiles around minute 28 given by the Fourier, Capon, and LG methods for the odd and even gates (blue and red lines, respectively). Since the processing is performed independently for the even and odd gates, it is interesting to investigate the compatibility between both results. These profiles agree well, as more thoroughly described later, for two consecutive gates at 5100 and 5250 m. This result confirms that the collected data and the processing are reliable. Also shown is the echo power profile at the initial range resolution of 300 m superimposed on the range profiles. It is remarkable to note the gain of dynamics of the HR range profiles with respect to the echo power profile just above 5000 m. Clearly, the peak detected at a range resolution of 300 m was smoothed by the range-weighting effects.

Figure 8 shows range profiles using the Fourier, Capon, LG, and MUSIC methods for two 300-m consecutive overlapped gates at 5100 and 5250 m (gates 20 and 21). As clearly indicated in the figure, the range profiles given by the four methods are very similar at 5100 and 5250 m, with a maximum around 5180 m,
confirming the high performances of the processing used. It can also be noted that the range profiles also indicate an enhancement near 5000 m, probably indicating the presence of another (less intense) scattering layer.

b. Applications on the MU radar

Data analyzed previously by Luce et al. (2001a) have been reprocessed with the LG method in order to compare its performances with the other methods using a more powerful radar with a smaller beamwidth (3.6°). The objective is to confirm the reliability of results obtained with the mini VHF radar. The data presented here have been collected during a short experiment on 7 May 1999 with the Japanese 45-MHz MU radar (Fukao et al. 1985). The maximum frequency difference used was 0.5 MHz for an initial range resolution of 300 m and an oversampling of 150 m. Three pairs of frequency intervals (0.167, 0.333, and 0.500 MHz) were cycled such that the time interval needed to build the cross-correlation matrix was 90 s. More details on the data processing specific to the MU radar and on the radar configuration itself are given in Luce et al. (2001a).

Figures 9 and 10 are similar to Figs. 5 and 6b of Luce et al. (2001a), for which the results from the LG method have been added. Figure 9 shows the range profiles from the first record for four successive gates from altitudes 9.75 to 10.20 km associated with high SNR (from 19.3 to 13.0 dB) using the dual-FDI technique with Δf = 0.500 MHz, the Fourier, Capon, MUSIC, and the newly introduced LG methods. For the MUSIC method, two sources have been assumed. Figure 10 shows a time evolution of the range profiles at 9.75 km within the 300-m range gate during 30 min when SNR was high (see Fig. 4 of Luce et al. 2001a) and using the same methods as in Fig. 5. It is particularly noticeable that the LG method indicates thinner layers than the Capon method, confirming the simulations and the results obtained with the VHF miniradar. It is also interesting to note that the LG method confirms the presence of two sources at 9.75 km (Fig. 9) given by the MUSIC method, while the Capon method was not able to resolve them because of their small separation distance.

5. Conclusions

In addition to high-resolution methods already proposed by Palmer et al. (1999) and Luce et al. (2001a,b) for RIM/FII, we have introduced the Lagunas–Gasull (LG) method, which is also called the “improved maximum likelihood method” in more specialized literature. With the help of simulations, it is shown that the LG method can be considered as a trade-off between the Capon method and the MUSIC algorithm. Indeed, the LG method presents a better resolving power than the Capon method at lower SNR (but not too low) and gives access to the intensity level and also to layer thickness, contrary to the MUSIC algorithm, which was developed only for source localization.

In order to evaluate and compare the performances of the different methods, the multifrequency technique with four frequencies was implemented on a VHF mini-radar profiler located in Toulon, France. A short experiment was conducted successfully, and the different processing methods were applied. The basic range profiles obtained with the Fourier method present the worst performances because of its poor resolving power resulting from the narrow frequency bandwidth of the radar receiver. Besides, this Fourier method does not give better results than the FDI technique concerning the layer thickness estimation but is more robust (more information is used) and permits us to avoid layer repetition in consecutive gates inherent to the FDI technique. It is confirmed that the adaptive methods also present better resolving powers, and it was demonstrated by using both simulations and applications on real data on two different radars that the newly introduced LG method presents the best performances. Although the MUSIC algorithm was developed at the origin for the localization of discrete sources, it was confirmed that its application indicates positions that are in very good agreement with those given by the other methods and sometimes indicates the presence of several layers not resolved by the filter-bank methods. Thus, it is suggested that the MUSIC algorithm should be used in complement with the other methods.

These preliminary results of the four methods are in good agreement, even though the physical interpretation needs more thorough investigation, which is also necessary to validate the range profiles given by the different processing methods by performing new experiments using in situ measurements (e.g., by balloon).

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