A New Tomographic Inversion Method Applied to Satellite-Ground Links to Obtain Atmospheric Components Distribution

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ABSTRACT - The principle of tomographic imaging for reconstruction of 2D vertical sections of atmosphere is here investigated. The proposed application is water vapor monitoring through attenuation measurements at 22 GHz.

INTRODUCTION

The distribution of atmospheric constituents in the lower atmosphere can be retrieved through satellite to ground beacons. Application of tomographic procedures to this issue is not straightforward due to the peculiar topology (i.e. the displacement of the measurement links respect to the object field). The main problems derive from: the limited angle view due to the unavailability of links at low elevation angles; the distance among the receiving ground stations (determined by the required horizontal resolution compared to the cost/effectiveness factor); the inhomogeneity of the object field, due to the dramatic changes in air density from the boundary layer up to the lower stratosphere. Furthermore, when a low number of angles is used at each ground receiving station, the problem becomes ill-conditioned. Therefore, a local basis function approach for tomographic inversion is here considered in order to avoid unbearable aliasing effects that would arise if a Fourier based inversion approach were applied.

TROPOSPHERIC COMPONENTS MONITORING THROUGH ATTENUATION MEASUREMENTS

In the last years the accuracy, and space-time resolution requirements for measures of atmospheric components increased mainly due to advances in atmospheric modeling requiring data at scales smaller than the mesoscale. In particular, when remote sensing of distributions of gaseous molecular species (i.e. water vapor, carbon monoxide etc) is concerned, several solutions may be applied. Advanced active systems relying on backscattering measurements are able to provide high resolution measures. The main drawback is the economic effort required. On the opposite, spaceborne passive remote sensing is cost-effective for monitoring of large scale features of global distributions, even if at low space resolution.

Atmospheric monitoring through exploitation of telecommunications systems grew significantly when satellite constellations for telecommunications became operative. An example of researches carried out in this context is the water vapor monitoring through phase delay measurements from GPS signals [1]. Furthermore, in the last decade, satellite-ground links were implemented at K band, making easily accessible the technology required to perform attenuation measurements around the 22.235 GHz absorption peak of water vapor. Though the inversion procedure discussed in this paper can be applied to any kind of monitoring system based on long path integral measurements (e.g. phase delay, IR attenuation, etc.), for ease of reference, the application to water vapor measurement through attenuation measurements around 22 GHz will be treated. Such, line is used in radiometric monitoring of atmosphere especially to retrieve estimates of Integrated Precipitable Water Vapor along vertical (or nearly vertical) directions across the atmosphere. When purely passive systems are adopted, the uncertainty on the background emissivity reduces the confidence on estimates. On the opposite, attenuation measurements are performed with a well known artificial source: little or no uncertainty about background emissivity affects measurements.

TOMOGRAPHIC RECONSTRUCTION

Tomographic approaches have been widely applied in ionospheric remote sensing and more recently in monitoring of atmospheric components at very low height [2], [3].

They rely on the possibility of inferring the 2D (or 3D) structure of a given object by exploiting a number of line integral measures across it. Among them, those facing the so called problem of limited-view tomography try to exploit at best the a priori information available about the object function in order to reduce the ill-conditioning due to the unavailability of measures along some directions [4].

Besides the cases when they are the only solution (e.g. medical applications), tomographic approaches are attractive for their good cost-effectiveness ratio and for the accuracy of integral measurements. For the proposed application the tomographic approach is adopted in order to retrieve water vapor distributions at a scale of few km's relying only on low cost systems. A baseline of receivers measures the attenuation affecting a signal transmitted by a spaceborne system. As shown in Fig. 1, the distance among receiving stations is by far smaller than the typical ground resolution of spaceborne passive systems. Indeed, given the minimum elevation angle α_0 (the angle below which refraction effects make attenuation measures unreliable for our purposes), distance among receivers depends linearly on the average height of the high resolution area within the monitored area.

Evidently, the network topology intrinsically lacks of vertical resolution since no measurements are made along directions corresponding to angles smaller than α_0. As discussed in [5], this problem can be faced either by means of ancillary data, when available, or of model based vertical profiles. In this paper we present a solution following the latter approach, and discuss how to exploit the effective information carried by the integral measures correlated to the turbulent structure of lower atmosphere. As in [6] and references cited therein, water vapor scaling along horizontal and vertical directions is here considered correlated. Hence test concentration fields were generated suitable to highlight the reconstruction capabilities of the system in the presence of nearly isotropic features.

Two different reconstruction algorithms belonging to the Algebraic Reconstruction Techniques (ART) have been applied. The first is a nearly standard ART (ART1 in the following). The object field is approximated as linear combination of 25 base functions with fixed position and width over a grid covering the monitored area, and whose weighing coefficients are determined through the iterative optimization of an error functional. Their initial guess values decrease exponentially with height: the two parameters of the exponential are calculated based on the average of specific attenuation measurements along each link (***k*** in the following), and on the average of surface water vapor concentration measures ($\boldsymbol{k_o}$ in Fig.2) performed at each receiver.

A second, newly developed, reconstruction technique (ART2 in the following) relies on 2D Gaussian base functions whose number, position and width, as well as weighing coefficient, are determined by means of a priori analysis of measured data and further minimization of an error functional. ART2 derives from the technique discussed in [2] and is outlined in Fig. 2.

In ART2 the inhomogeneity of the object field is modeled as follows in the reconstructed field:

$$\hat{k}(x,z) = \hat{k}_e(z) + \hat{k}_d(x,z)$$

where $\hat{k}_e(z)$ is the large scale vertical profile (calculated in the same way as that described for the first guess profile in ART1), and $\hat{k}_d(x,z)$ is the "local variation" estimated by means of tomographic reconstruction of $\boldsymbol{k_d} = \boldsymbol{k} - \boldsymbol{k_e}$, where $\boldsymbol{k_e}$ is the specific attenuation due to $\hat{k}_e(z)$; $\boldsymbol{k_d}$ is a zero mean vector.

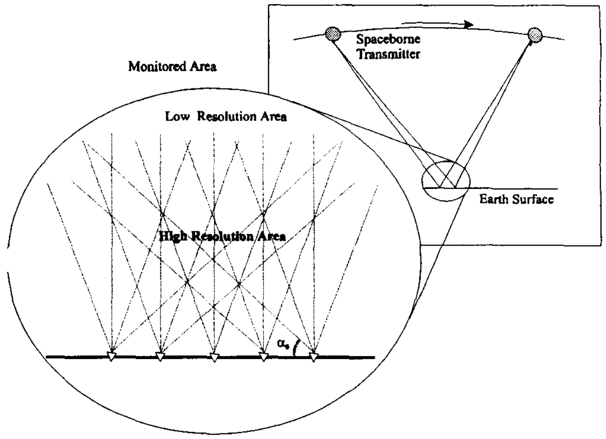

Fig. 1 - Sketch of the satellite-ground monitoring system

Each base function is characterized by four parameters : the center coordinates (X_c, Z_c), the width and weighing parameters (resp. W and H). The centers are determined one at a time by exploiting the spatial correlation among measurements. H and W of each new base function are searched in domains depending on Z_c (for H) and on local spatial resolution of the network (for W). After that, the contribution of the new i-th base function $\boldsymbol{k_{bf}}^{(i)}$ is used to update the attenuation vector as follows: $\boldsymbol{k_{res}}^{(1)} = \boldsymbol{k} - \boldsymbol{k_{bf}}^{(1)}$; $\boldsymbol{k_{res}}^{(i)} = \boldsymbol{k_{res}}^{(i-1)} - \boldsymbol{k_{bf}}^{(i)}$. The error functional to be minimized is: $J_d = \langle [\boldsymbol{k}^i_{res}]^2 \rangle / E_d$, where $E_d = \langle [\boldsymbol{k}_d]^2 \rangle$. Reconstruction ends when J_d falls below a threshold depending on noise power affecting measures, or when no further reduction of J_d is possible.

SIMULATIONS AND RESULTS

The reported results were obtained using a baseline of 6 receivers separated by 2 km and with angle views ranging from -45° to 45° (step 15°) off-zenith. Simulated concentration fields including only features at least as wide as ART1 base functions (i.e., 3 km) were reconstructed with good approximation by both ART1 and ART2 (area averaged normalized bias smaller than 0.01, and local relative error always smaller than 0.20). On the opposite, features at smaller scales led larger local errors on ART1 compared to ART2. As shown in Fig.3, the latter is instead able to reconstruct also features at scales that are comparable to the ground receiver distance. Although 'slab-like' features producing steep inversions in vertical profiles like that in the low-right area of the

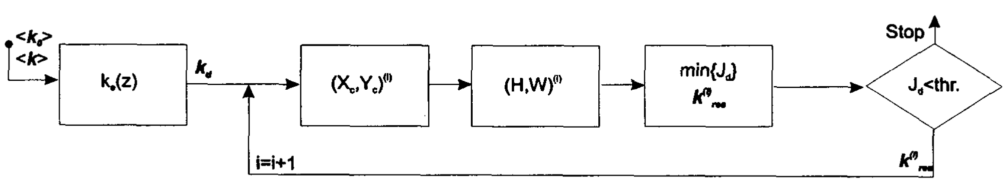

Fig. 2 - Scheme of the proposed tomographic reconstruction technique (Ref. to text for symbols)

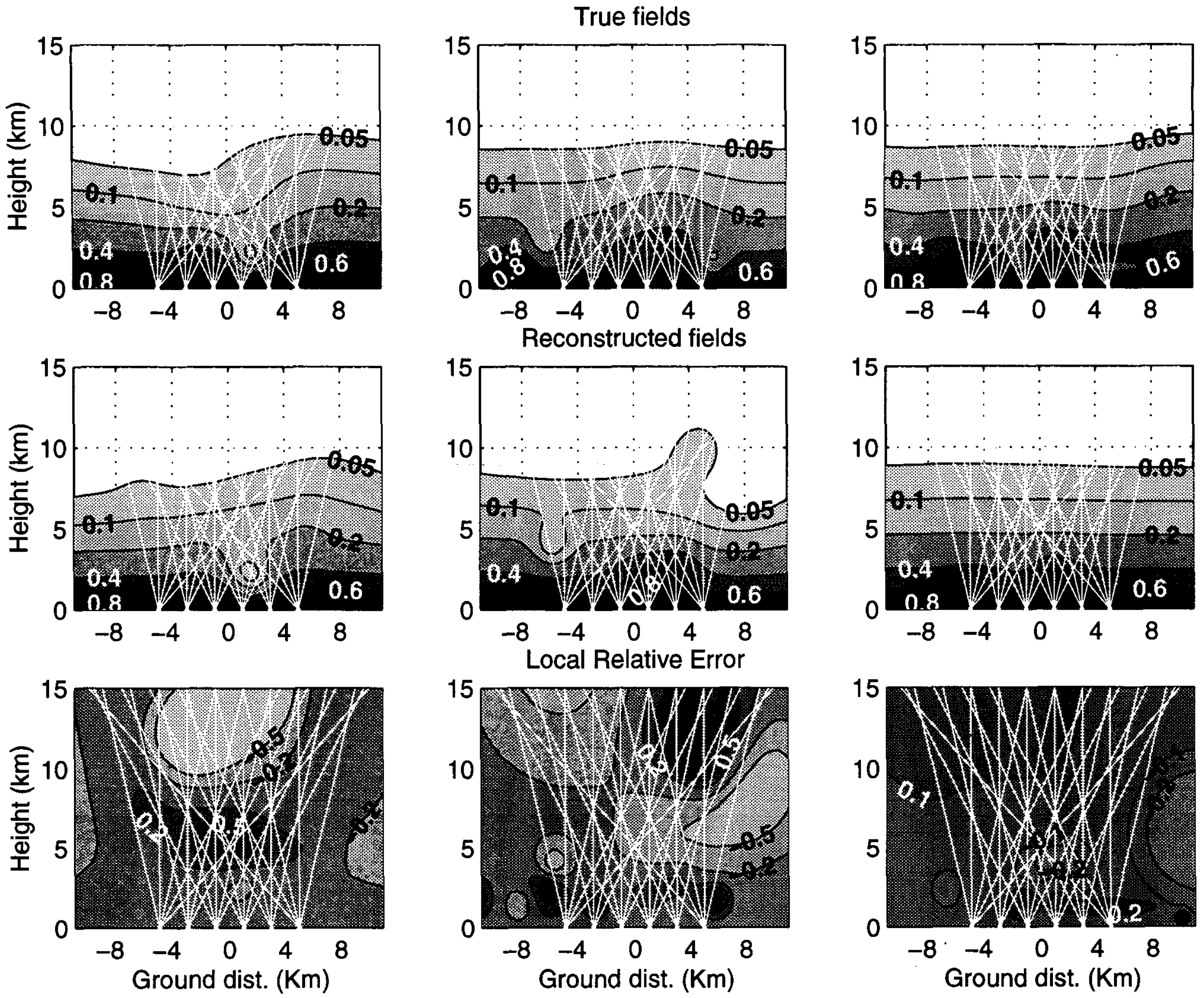

Fig.3 - Three examples of reconstructions through ART2

third field may not be reconstructed, they do not corrupt significantly the reconstruction in the remaining area. It can be noticed that within the monitored area, the lack of vertical resolution is highlighted by the band-like height-dependent shape of the local relative error. It is envisaged that integration with vertical profile measurements (through multifrequency radiometric measurements) would increase significantly the accuracy of reconstructions.

ACKNOWLEDGMENTS

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