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The Complete Data Fusion extended to two-dimensional products

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INTRODUCTION

The Complete Data Fusion (CDF) method has been applied for at least 10 years to vertical profiles or scalar products from both simulated and real measurements (one-dimensional analysis, 1D-CDF). During these years the method has been developed and improved to extend its application to an increasingly large number of atmospheric products.

In this study, the CDF algorithm, used so far only for 1D analysis, has been extended to two-dimensional products (2D-CDF). We applied the 2D-CDF to combine simulated ozone data of the Infrared Atmospheric Sounding Interferometer New generation (IASI-NG), a nadir looking sensor, with the Changing-Atmosphere Infrared Tomography (CAIRT), a limb sounder. CAIRT mission is one of the two candidates for ESA's Earth Explorer 11.

We will show results obtained with the rigorous approach of 2D complete data fusion for realistic simulations of CAIRT and IASI-NG.

THE CDF METHOD

The ***Complete Data Fusion*** [1] is an a-posteriori algorithm to combine independent measurements of the same profile from different instruments into a single estimate for a comprehensive and concise description of the atmospheric state.

The CDF solution $\mathbf{x}_f$ for the considered profiles $\hat{\mathbf{x}}_i$ (i=1,2,..,N) is given by:

$$\mathbf{x}_f = \left(\sum_{i=1}^{N} \mathbf{A}_i^T \mathbf{S}_i^{-1} \mathbf{A}_i + \mathbf{S}_a^{-1}\right)^{-1} \left(\sum_{i=1}^{N} \mathbf{A}_i^T \mathbf{S}_i^{-1} \boldsymbol{\alpha}_i + \mathbf{S}_a^{-1} \mathbf{x}_a\right), \qquad \boldsymbol{\alpha}_i \equiv \hat{\mathbf{x}}_i - (\mathbf{I} - \mathbf{A}_i)\mathbf{x}_{ai},$$

with the corresponding total error CM and AKM:

$$\mathbf{S}_f = \left(\sum_{i=1}^{N} \mathbf{A}_i^T \mathbf{S}_i^{-1} \mathbf{A}_i + \mathbf{S}_a^{-1}\right)^{-1} \qquad \mathbf{A}_f = \left(\sum_{i=1}^{N} \mathbf{A}_i^T \mathbf{S}_i^{-1} \mathbf{A}_i + \mathbf{S}_a^{-1}\right)^{-1} \sum_{i=1}^{N} \mathbf{A}_i^T \mathbf{S}_i^{-1} \mathbf{A}_i$$

$\mathbf{x}_{ai}$: a priori profile
$\mathbf{S}_i$: noise covariance matrices (CMs)
$\mathbf{A}_i$: averaging kernel matrices (AKMs).
for the i-th retrieval;

$\mathbf{x}_a$:a priori profile
$\mathbf{S}_a$: CM a priori
for data fusion.

2D DATA FUSION of LIMB and NADIR MEASUREMENTS

Instrument	CAIRT	IASI-NG
Geometry	Limb imager	Nadir spectrometer on MetOp-SG
Altitude range	5 - 115 km	0 - 60 km
Measurements sampling	horizontal sampling of 50 km along track, 25 km across track and vertical sampling of 1 km	across-track scan of 14 fields of regard (FOR), each measures an array of 4x4 pixels with 25 km distance between the centers of two pixels (for central FORs). Sounding point density: 25 km x 25 km
Spectral range	718-2200 cm^{-1}	645-2760 cm^{-1}
Synergy	The two satellites are assumed to fly on the same orbit, dephased of about 8 minutes in order to allow the nadir measurements to match the region of the limb tangent points.	

In the case of retrieval products that are 2D fields, the retrieved atmospheric parameter is given on a 2D grid, in this case the 2D field can be seen as a set of vertical profiles, each profile located at a different value of the coordinate along the line of sight.

The 2D data fusion of CAIRT and IASI-NG has been performed on the CAIRT 2D retrieval grid. On this grid, we combined multiple ozone measurements of CAIRT and four ozone measurements of IASI-NG for each along-track position, according to its expected spatial resolution.

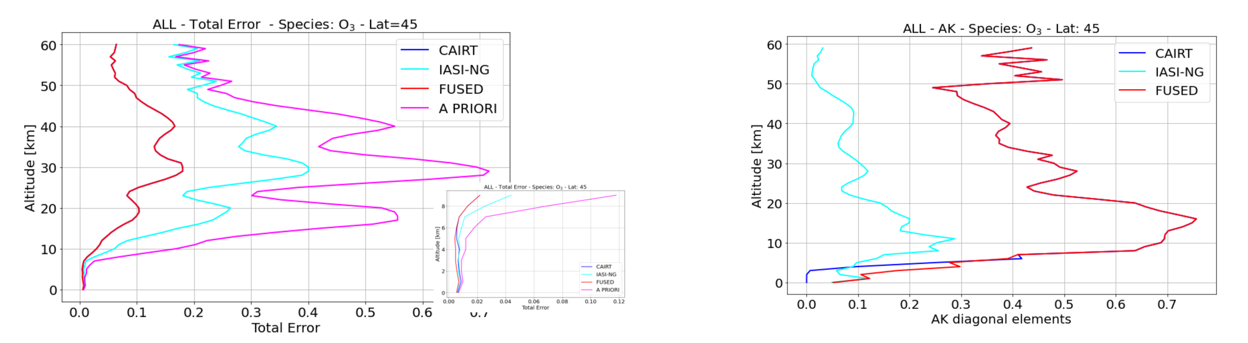
The simulated 2D distributions (2-indices quantity) for CAIRT and IASI-NG were arranged in a vector and the AKMs and CMs (4-indices quantities) have been arranged consequently in matrices. The 2D data fusion was performed applying the standard CDF formulation to these input vectors and matrices.

Results are presented for the 2D-CDF performance and for the improvement achieved with respect to the 1D-CDF in terms of total errors, degrees of freedom and Shannon information content.

1D CDF

In the 1D case study, we applied the CDF to one CAIRT e one IASI-NG simulated ozone profile. The total error profile of the fused product is superimposed to that of CAIRT and more than 50% smaller than that of IASI-NG from nearly 8 km up to 60 km. In this altitude range, also the AK diagonal profile of CAIRT and fused products show the same values (from 0.3 to 0.75) with a peak around 15 km. IASI-NG profile shows a similar vertical behaviour but with lower values (<0.3). Below 8 km the fused product demonstrates the higher quality.

Total Error   AK



Total error (left) and diagonal elements of the AKM (right) for CAIRT, IASI-NG and the fused product

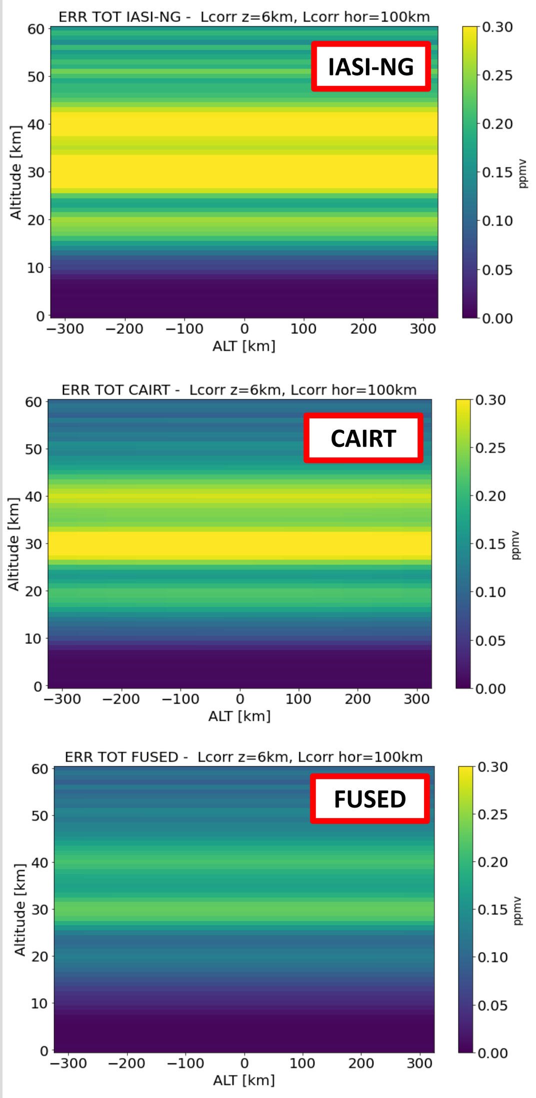
The Shannon information Content (SIC) and the Degrees Of Freedom (DOF) values are shown on the right and demonstrate the enhanced quality of the fused product.

PRODUCT	SIC O_3	DOF O_3
IASI-NG	23.07	5.97
CAIRT	70.62	26.60
FUSED	75.05	27.25

$$\text{SIC} = 0.5 * (\log_2|\mathbf{S}_a| - \log_2|\mathbf{S}_{tot,i}|)$$

$|\mathbf{S}_a|$ and $|\mathbf{S}_{tot,i}|$ determinants of a priori and retrieved profile VMCs

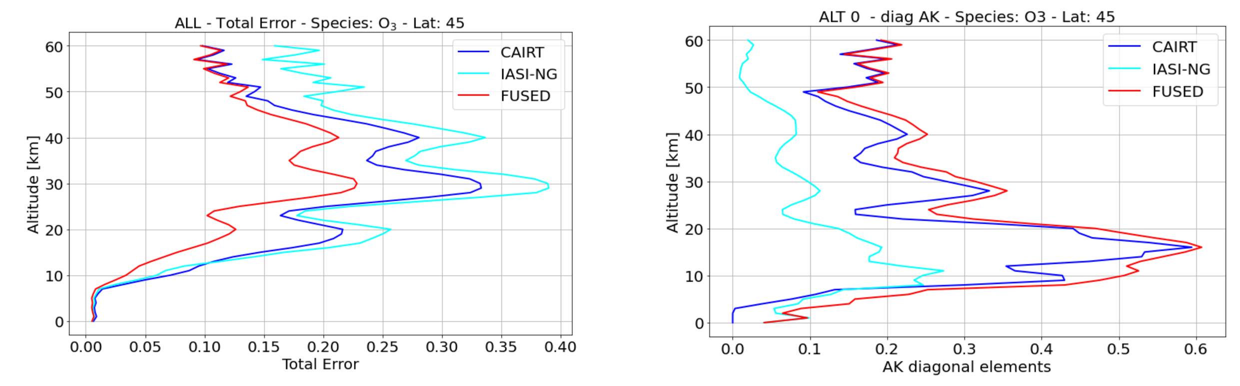
Total Error



Total Error in the CAIRT 2-dimensional retrieval grid for (from the top) IASI-NG, CAIRT and the fused product (ALT: along-track)

2D CDF

In the 2D case study, we simulated a 2D field of 51 CAIRT measurements and 4 IASI-NG measurements of ozone for each along-track (ALT) position, selecting an atmospheric region of 21 ALT (1000 km of horizontal extension), and we applied the CDF as described above. The maps for the 2D fields of the total error and AK diagonal elements, as well as the corresponding profile plots for the central ALT, show how the data fusion is able to enhance the information gain and reduce the total error in the fused product, in the whole altitude range.

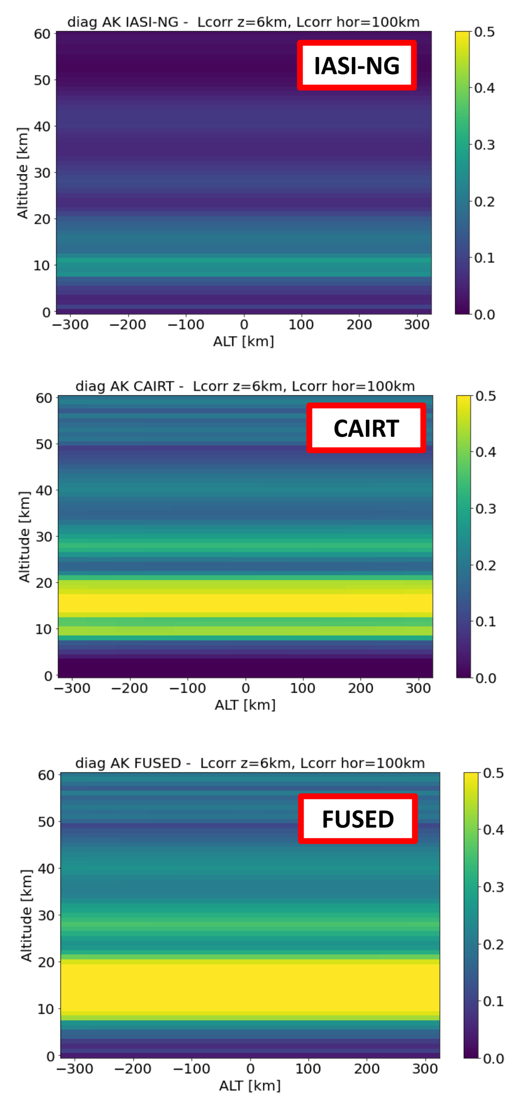


Total error (left) and diagonal elements of the AKM (right) of the **central along track position** for CAIRT, IASI-NG and the fused product.

PRODUCT	SIC O3	DOF O3
IASI-NG	452.41	117.82
CAIRT	642.46	307.44
FUSED	949.66	366.49

The SIC and DOFs values demonstrate that in the 2D case study the fused product quality is further enhanced.

AK

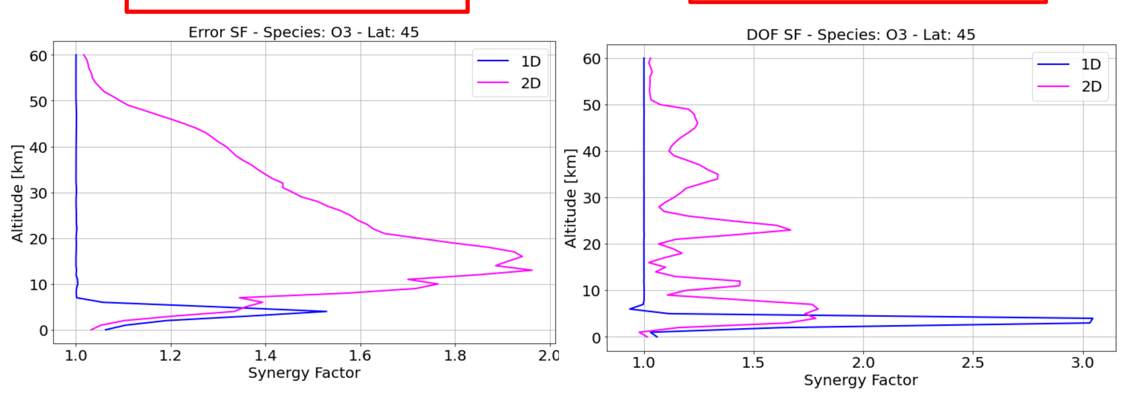


Diagonal elements of the AK in the CAIRT 2D retrieval grid for (from the top) IASI-NG, CAIRT and the fused product (ALT: along-track)

1D vs 2D: Synergy Factor

The performance of the synergy can also be evaluated in terms of the synergy factor (SF), which quantifies the level of synergistic advantage of two or more independent measurements. The SF is equal to 1 when the combined measurements are complementary and greater than 1 when a synergy between the two individual data sets really exists. We calculated the error SF (SF_{err}) and the DOF SF (SF_{DOF}) as described below:

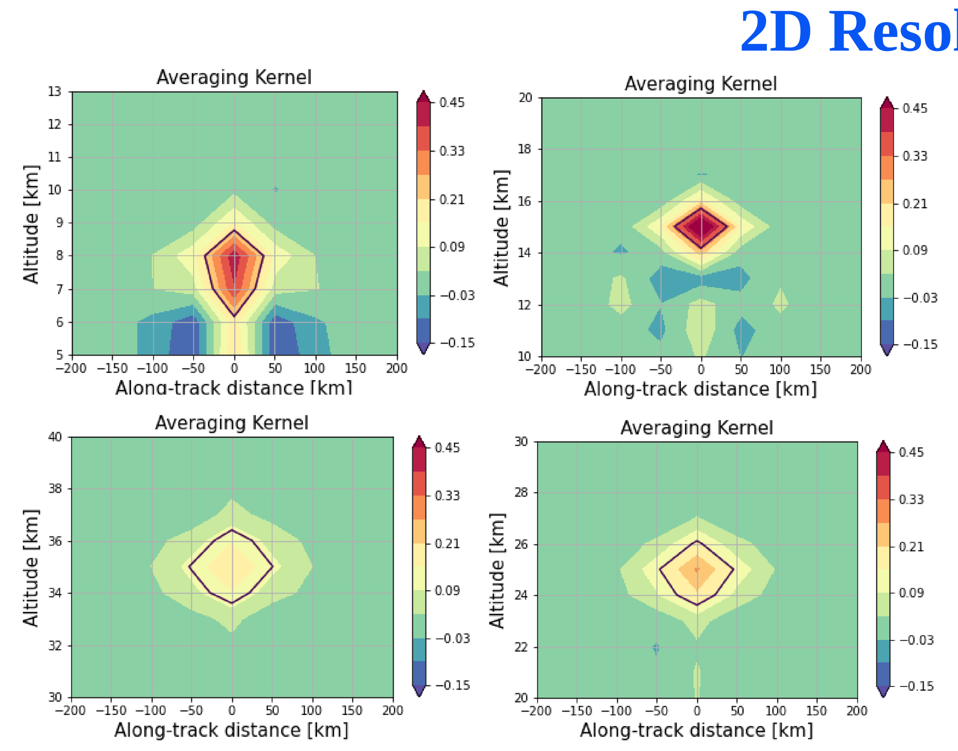
$$SF_{err}^{(j)} = \frac{\min_{i=1,2,...,N} \sigma_{tot,i}^{(j)}}{\sigma_{tot,f}^{(j)}} \qquad SF_{DOF}^{(j)} = \frac{diagA_f^{(j)}}{\max_{i=1,2,...,N} diagA_i^{(j)}}$$



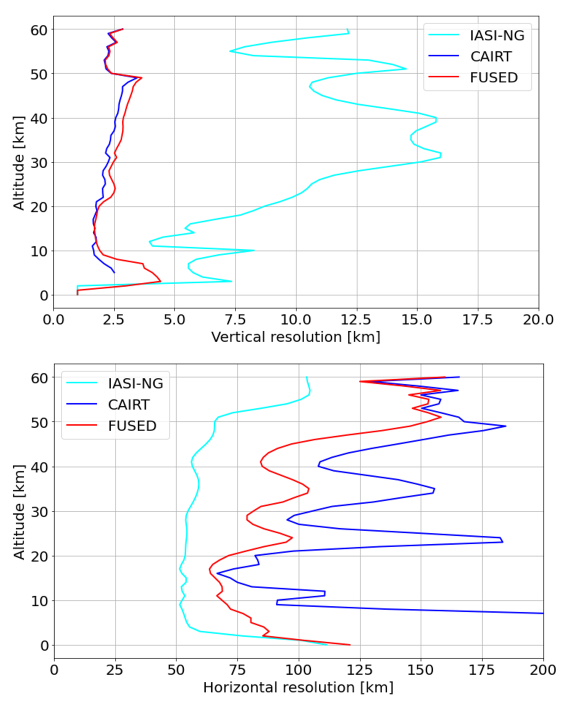
For **1D** analysis, it is possible to take advantage of the **synergy only below 8 km**

For the **2D** analysis **the synergy is fully exploited over the whole altitude range.**

2D Resolution



Maps of the 2D AKM rows (fused product) that correspond to the sensitivity of the retrieved vector to the true state at the central along track position and different altitudes: 8, 15, 25 and 35 km from top left clockwise.
The black contour on the images shows the FWHM value.



Vertical (top) and horizontal (bottom) resolutions for IASI-NG, CAIRT and the fused product.

The 2D vertical and horizontal resolutions are calculated as the FWHM of the corresponding averaging kernels. The resolution of the fused product exploits the complementarity of the limb (high vertical resolution) and nadir (high horizontal resolution) geometries. In this case, the fused vertical and horizontal resolutions, show their peak in the range 10-20 km of altitude.

Conclusions

In this study, we showed that the first application of the CDF-2D method to simulated CAIRT and IASI-NG products provides fused products with enhanced quality. We compared the results of the CDF method application to 1D and 2D products. The analysis of the total error and AK diagonal (profiles and maps of 2D fields), of the SIC and DOFs values demonstrates that, in both cases:

- the fused product quality is enhanced with respect to that of the individual products, in terms of total error reduction and information gain.

The analysis of the SF_{err} and SF_{DOF} shows that:

- only the CDF-2D is able to fully exploit the synergy between the measurements of the two sensors through the entire vertical range considered.

ACKNOWLEDGMENTS

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REFERENCES

[1] S. Ceccherini, B. Carli and P. Raspollini, *Equivalence of data fusion and simultaneous retrieval*, Optics Express, **23**, 8476-8488 (2015).