Improving GPM passive microwave retrieval and multi-sensor merging: a nonlocal formulation accounting for the 3D structure of rain

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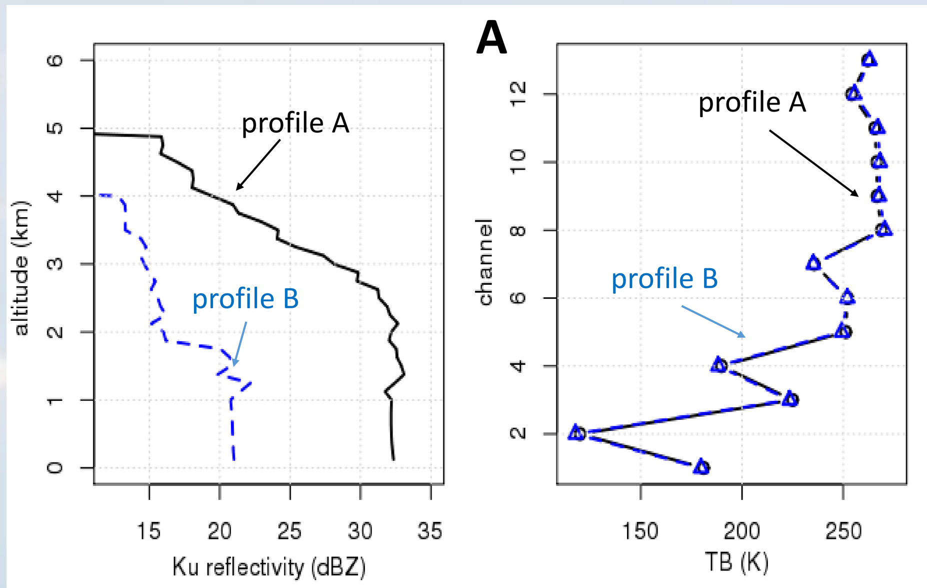
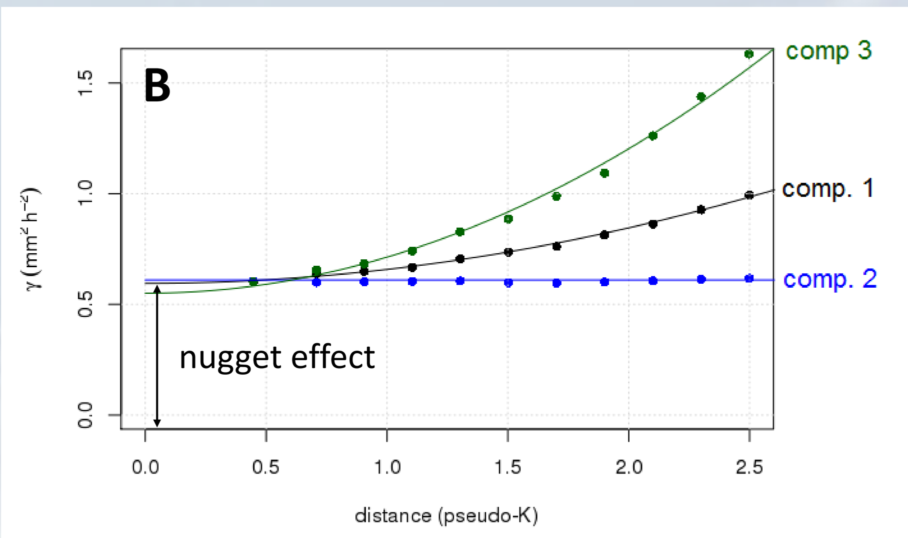
I) Limitations of the pixel-wise passive microwave retrieval of rain

- The retrieval is an *underdetermined inverse problem*, there is no one-to-one relation between the multispectral signature and the hydrometeor profile at the pixel level: two different hydrometeor profiles can have the same signature (Fig, A).
- The distance-based retrieval from a dictionary is an *interpolation problem in the TB space*, but the interpolation accuracy is mathematically limited by the fact that *the interpolated function R(TB) is irregular*:
  $|TB_1 - TB_2| \rightarrow 0$
  does not necessarily imply that
  $|R(TB_1) - R(TB_2)| \rightarrow 0$
  as illustrated by Figure B.
- The *uncertainty* associated with the non-regularity of *R(TB) cannot be reduced by increasing the size of the dictionary* and is independent of the distance metric or the interpolation method.



A: The profiles A and B are different but have quasi identical spectral signatures. The KuPR reflectivity profile is mapped along GMI's field of view.



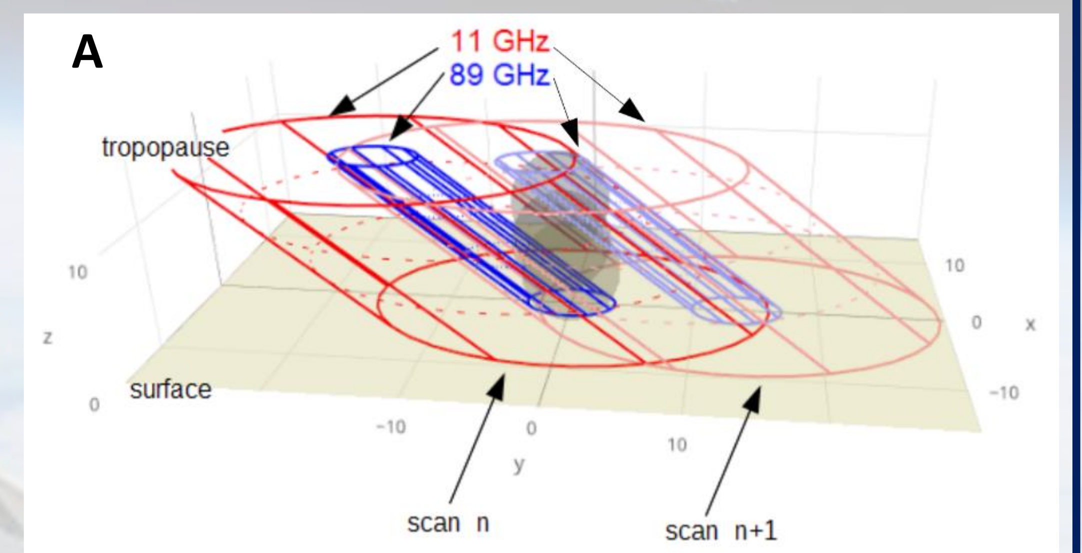
B: Local directional variograms of the function *R(TB),* where *R* is the surface precipitation rate. The three directions shown here correspond to the first three principal components estimated locally. The variograms are computed from a dictionary of collocated GMI and KuPR observations over oceans. The variance does not tend toward zero when the distance tends toward zero (nugget effect) indication the non-regularity of *R(TB).*

II) Nonlocal retrieval: extracting information from the neighboring TBs and the spatial patterns to reduce the uncertainty

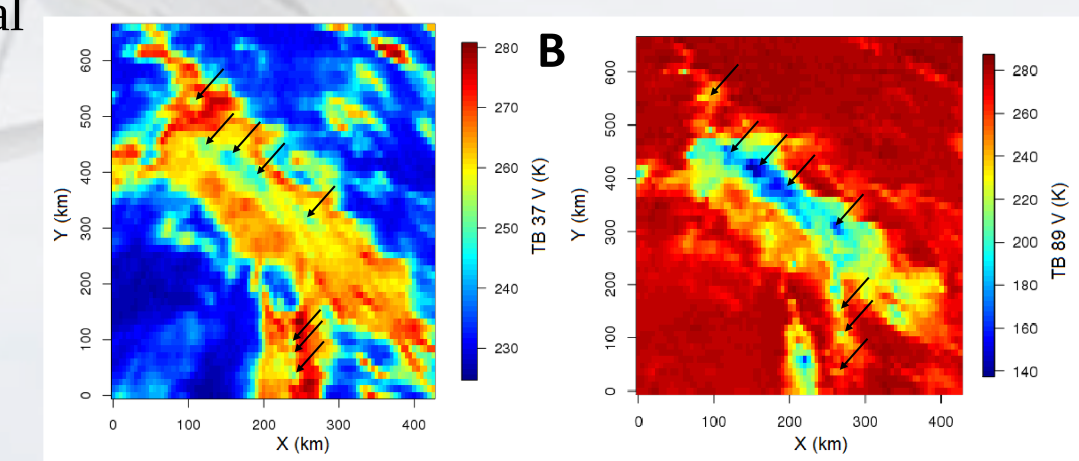
- The uncertainty associated with the irregularity of *R(TB) can only be reduced by adding new information* to the observation vector. This information may come from ancillary dataset (e.g. environmental variables such as the CAPE or the altitude of the 0°C isotherm from reanalysis, or information about the surface's radiometric properties).
- Our idea is that information can be extracted from the *neighboring TBs around the pixel of interest* and that considering a set of nearby TBs as a consistent ensemble and parametrizing their *multiscale spatial variations and covariations* allows to better retrieve the underlying three-dimensional structure of precipitation.

Rationale

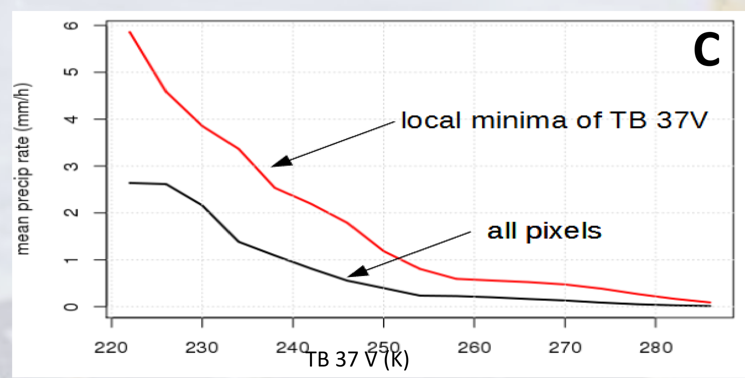
- The scanning geometry of GMI and of the other similar passive microwave images induces *overlapping fields of view* at various frequencies, and because of the *high incidence angle*, the observed volume associated with each individual beam is not a vertical column but is tilted (Fig A). With the various channels responding to the presence of hydrometeors at different altitude levels, *the spectral signature characterizing a specific vertical atmospheric column may be split across several pixels.*
- The response of a channel to the hydrometeors may be complex and *scale-dependent*. For example, channels around 40 GHz, sensitive to both liquid drops emissivity and ice scattering have a non-monotonic response to precipitation intensity, nevertheless the ice scattering and liquid emission signals have different "geometric signatures" (Fig B). Generally, it is found that the scattering signal dominates the fine-scale spatial variability of the 37 GHz TBs while the emission signal dominates the coarse-scale variability.
- Analyzing the *spatial patterns of the TBs* is expected to allow better identification of specific precipitation systems and features. For example, Figure C shows that identifying the local minima of the 37 GHz V TB allows refining the relation between TB and precipitation rate. For this example, the local minima likely indicate convective cells.



A: Considering the scanning geometry of GMI, a given vertical atmospheric column is always intercepted by at least two different beams for the high-frequency channels and by up to 13 different beams at 11 GHz.



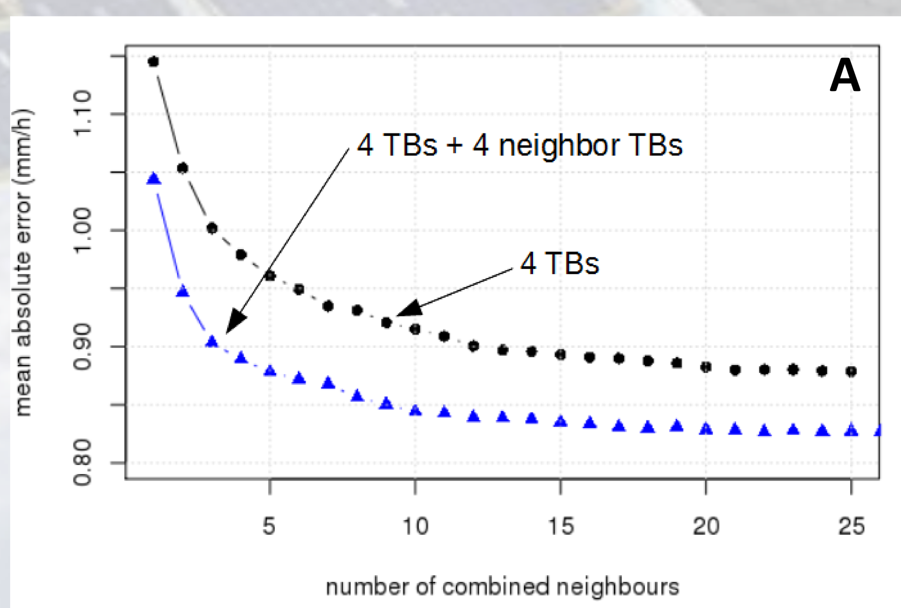
B: A local depression of the 37 GHz TB inside an area with high 37 GHz TB is a typical signature of a convective cell, the depression is caused by the ice scattering.



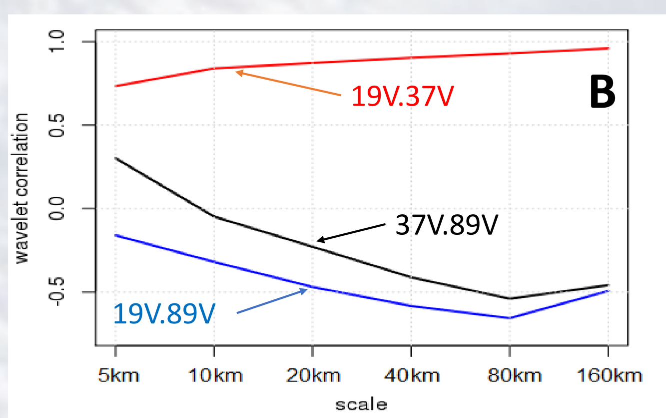
C: By adding a condition derived from the neighbor pixels (that is, all the adjacent pixels have a higher TB) we find a very different statistical relation between the 37 GHz V TB and precipitation in the pixel of interest.

III) Preliminary results toward the implementation of the nonlocal retrieval

- The most straightforward way to include nonlocal information in the retrieval is to add the neighboring TBs in the observation vector. However this approach is prone to dramatically increase the dimension of the inverse problem, rendering the distance-based dictionary retrieval ineffective. The main challenge is to find *a parsimonious representation of the neighboring information* for the retrieval.
- Figure A shows that adding the information from *only 4 channels in one selected pixel* allows to *significantly improve the retrieval*. This improvement is attributed to the ability to account for the parallax shift effect: because of the scanning geometry, the ice-scattering signature may be spatially shifted relatively to the emission signature of up to 18 km in the azimuthal direction of the beam (Guilloteau et al. 2018).
- The *wavelet transform* is a powerful tool allowing the parsimonious representation of the spatial variations and covariations of the TBs in the neighborhood around the pixel of interest. Moreover it allows accounting for the *scale-dependence of the relations between TBs and precipitation* (Fig B).
- *Dimensionality reduction* methods such as empirical orthogonal functions (EOF) also allow parsimonious representations. Accounting for the scale-dependence of the relations between TBs and precipitation can render the dimensionality reduction more effective.



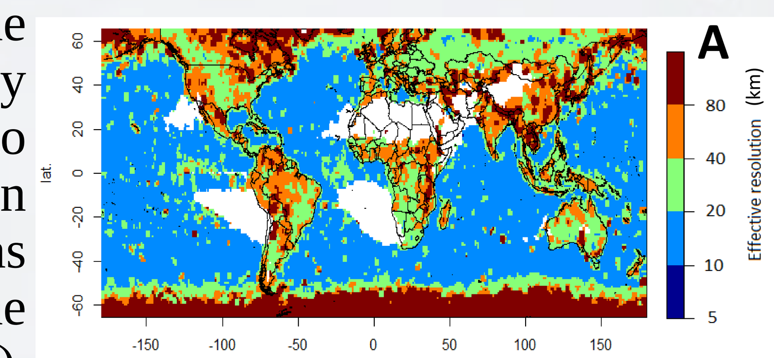
A: Mean retrieval error over land using a distance-based dictionary retrieval as a function of the number of combined dictionary elements. Using nonlocal parameters, -here the 37 GHz and 89 GHz TBs in the pixel next to the pixel of interest (in the azimuthal direction of the beam)- allows to reduce the mean retrieval error.



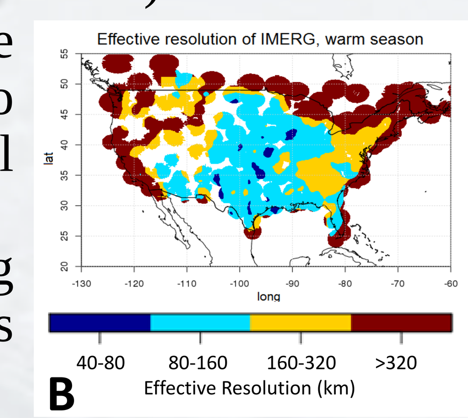
B: Linear correlation between GMI TBs in the wavelet domain (2D Haar wavelet) as a function of the scale, inside precipitating areas over tropical oceans. Analyzing the relations between TBs at various scale in the wavelet domain reveals the scale-dependence of their covariations. Even the sign of the linear correlations may change depending on the scale.

IV) Nonlocal approach for validation and multisensor merging

- The nonlocal approach is also pertinent for the validation of the retrieved precipitation fields. By comparing the satellite retrieved precipitation fields to reference fields in the wavelet spectral domain we can define the *effective resolution* (ER) of the retrieval as the finest scale at which the spatial variations of the reference field are accurately reproduced (Fig. A and B)
- Here, we consider that a scale is resolved if the spectral energy of error (difference relative to the reference) is less than half the spectral energy of the reference (Guilloteau et al. 2017).
- Considering *correlated errors*, characterizing the retrieval uncertainty in a spectral domain is also *beneficial for multisensor merging*.



A: ER of GMI-GPROF (V5) evaluated against the DPR (instantaneous)



B: ER of IMERG (Final v5) evaluated against MRMS gauge-adjusted radars (hourly-cumulated)

Conclusions

- Considering relations between TBs and precipitation only at the pixel level is limiting.
- By considering the TBs in a neighborhood around the pixel of interest, allowing the exploitation of nonlocal scale-dependent relations between TBs and precipitation, we can extract more information from the TBs to improve the retrieval.

Guilloteau, C., Foufoula-Georgiou, E., & Kummerow, C. D. (2017). Global multiscale evaluation of satellite passive microwave retrieval of precipitation during the TRMM and GPM eras: effective resolution and regional diagnostics for future algorithm development. *Journal of Hydrometeorology*, 18(11), 3051-3070.

Guilloteau, C., Foufoula-Georgiou, E., Kummerow, C. D., & Petković, V. (2018). Resolving surface rain from GMI high-frequency channels: limits imposed by the three-dimensional structure of precipitation. Journal of Atmospheric and Oceanic Technology, 35(9), 1835-1847.

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