A five-fold refinement in the spatial resolution of atmospheric radar using overlapped scanning?

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Program: Innovative Spontaneous Concepts

Project Objective:

One of the recurring criticisms of spaceborne radars designed to probe precipitation is their relatively coarse resolution. Because of the unknown fall speed of hydrometeors and their unknown distribution within the radar beam, the resolution is set by the real aperture of the system, i.e. the antenna size. The precipitation radars on NASA's most recent precipitation projects, TRMM and GPM, resolve ~ 5x5 horizontal kilometers, which is coarser than the spatial variability of condensed water within convective storms, arguably the most important type of precipitation for weather analysis and forecasting and for climate modeling. Ideally, one would want to achieve sub-kilometer resolution. One option to achieve such high spatial resolutions would be to increase the aperture size. Since this would increase mass, complexity and the requirement for correspondingly more complex supporting subsystems (hence the technological challenges and the cost), a less physically-demanding and more cost-effective solution would be highly desirable.

The objective of this project was to evaluate an option that consists in using the existing coarse intrinsic resolution, but with a scanning strategy with greatly overlapped oversampling, so that a given point on the surface falls in at least 5x5 contiguous radar beams. The problem is then to determine how well one can apply a deconvolution to sort out the contribution of fine-resolution columns to the overlapped coarse-resolution observations. The problem is not trivial, not least because the intrinsic radar measurements (of reflectivity factors) are unavoidably quite noisy, so the exact deconvolution problem has many mutually ambiguous solutions which may easily include unphysically large or small values for the reflectivity factors.

We recently developed and tested a disaggregation technique that successfully imposes two constraints on the deconvolution: the use of principal components instead of the unknown high-resolution quantities themselves, retaining only the principal components known to account for most of the observed variability (as a constraint to filter out noise); and the use of various first guesses as regularization terms in the deconvolution (representing as much of the a priori knowledge that is independent from the coarse-resolution observations as possible, so that the solution is forced to be consistent with the known physical constraints). The objective was therefore to adapt this technique to the radar case, and evaluate its success at reproducing known high-resolution airborne measurements, when ingesting coarsened-resolution overlapped simulated measurements that are synthesized from the airborne observations.

Results:

We adapted the variational approach of our passive-microwave study, namely the minimization of

$$(t'-t_b')^T B^{-1} (t'-t_b') + (A \cdot t'-O)^T R^{-1} (A \cdot t'-O) \qquad (*)$$

where t' denotes the unknown high-resolution values, t_b their a-priori values, B the mean-squared uncertainty in the a-priori knowledge, A the antenna pattern convolution matrix, O the coarse-resolution observations, and R the mean-squared uncertainty in the measurements. In the case of radar, the physical constraint on the disaggregation is obtained by deriving empirically the radar-reflectivity-factor vertical principal components (from analyses of the JPL airborne APR-3 radar measurements in different regimes), identifying the eigenvalues of the principal components that should be fixed before solving the minimization.

We tested the guided disaggregation approach on synthetic data, produced by averaging airborne APR-3 measured Ku-band reflectivities (at about 1-km horizontal resolution) on a regular 5x5 grid, translated by one beam (across- or along-track) at a time, to simulate satellite radar reflectivities (that would have been measured at a ~ 5-km resolution. Different options were tested:

- representing the unknown high-resolution reflectivity factors in power, or in dB, or in a non-linear transform (explained below) designed to enforce automatically the constraint that the reflectivities be within a prescribed range (we tested 0 – 55 db);
- using 2, 3, ... , 13 vertical principal components of the original 13 vertically layered 250m- thick bins (covering the 3120m from the melting layer down to about 1000m above mean sea level);
- specifying the uncertainty B for the a-priori first guess as the diagonal matrix whose diagonal entry is the eigenvalue corresponding to that principal component, or equal to the sample covariance of the interpolated observations within the low-resolution field of view;
- specifying the uncertainty R for the convolution term as a scalar multiple of the identity matrix (the scalar being the allowable error variance that can be tolerated in the convolution), or the diagonal matrix whose diagonal entries are the variances sz2 of the measured power (which does scale with the measured power).

The form of (*) and combination of options that gave the best results is

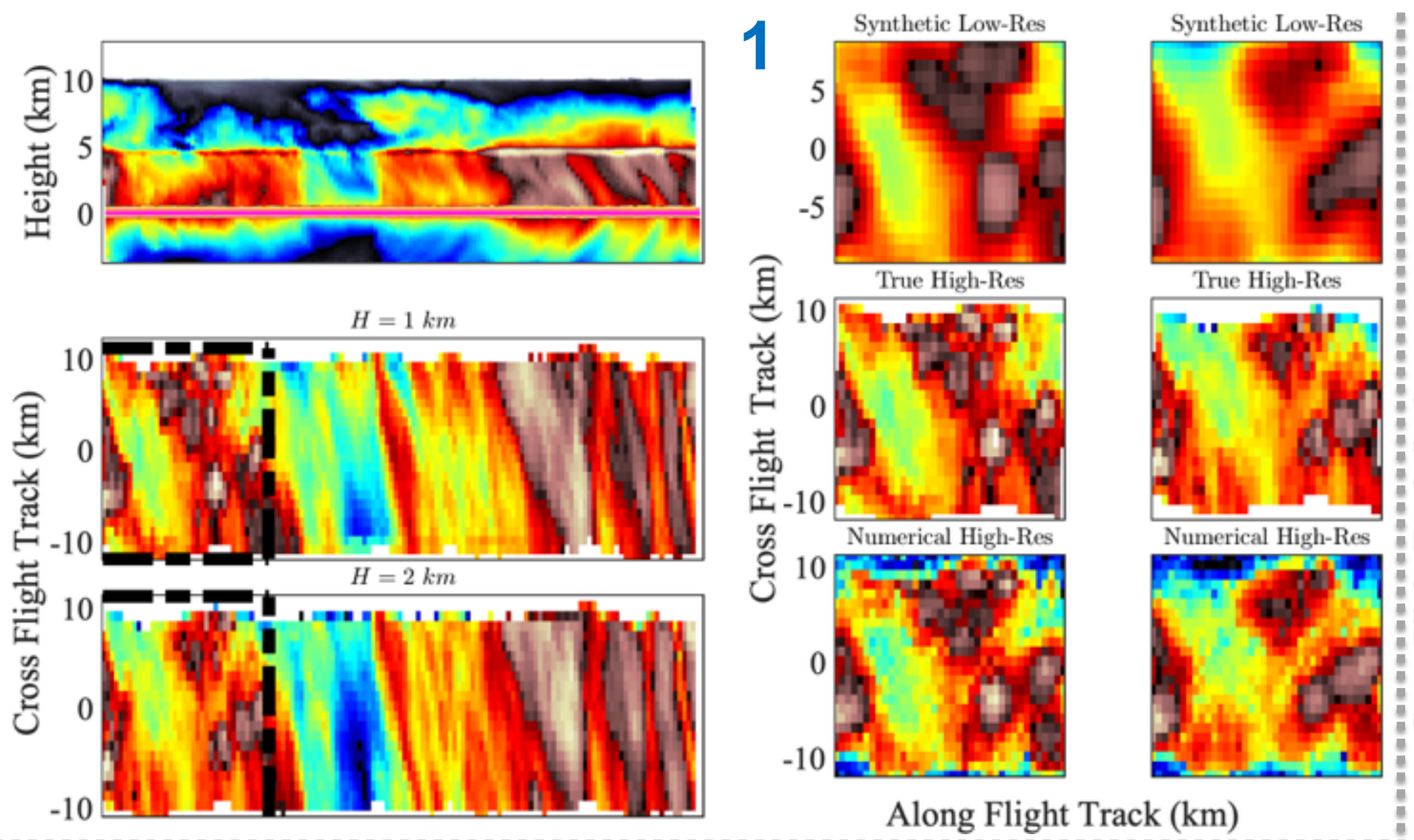
$$[\, z_{recon}(PC_8(z')) - z_{apriori} \,]^T B^{-1} [\, z_{recon}(PC_8(z')) - z_{apriori} \,] + [A \bullet z_{recon}(PC_8(z')) - O]^T R^{-1} (A \bullet z_{recon}(PC_8(z')) - O] \qquad (**)$$

in which

- z' denotes the transform $z' = tg[\, \pi ((z - z_{min})/z_{max})^g /2 \,]$ of the measured scalar reflectivity factors z, z_{min} the minimum physically plausible value for z, z_{max} the largest, and g is chosen so that the sample mean of $(z - z_{min})/z_{max})^g$, calculated from our aggregate airborne data, is 0.
- $PC_8(z')$ refers to the 8 principal components that capture most of the variability in the reflectivity profile
- $z_{apriori}$ is the interpolated value, at the given grid point, from the observations
- z_{recon} is the reflectivity (in power) reconstructed from the 8 principal components of z'

Figures 1 to 3 show typical examples of the results. Figures 4 and 5 illustrate the cases where the disaggregation was least successful in faithfully recovering the high-resolution values in the original data. Figures 6, 7 and 8 summarize the quantitative performance of the approach according to three statistical measures of the success of the disaggregation, in estimating the actual values of the high-resolution radar reflectivities as well as in estimating their discontinuities in space at the fine scale.

1



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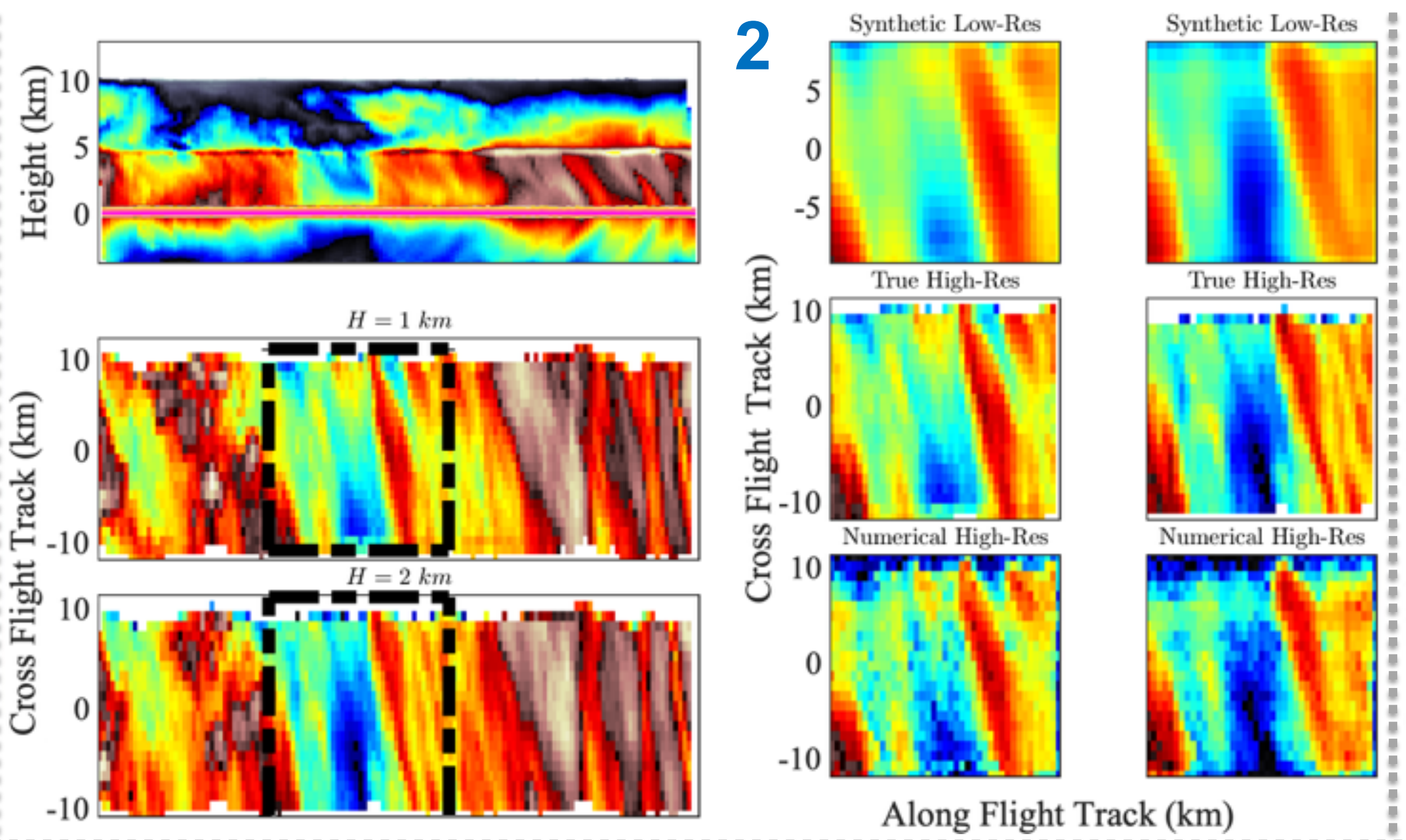

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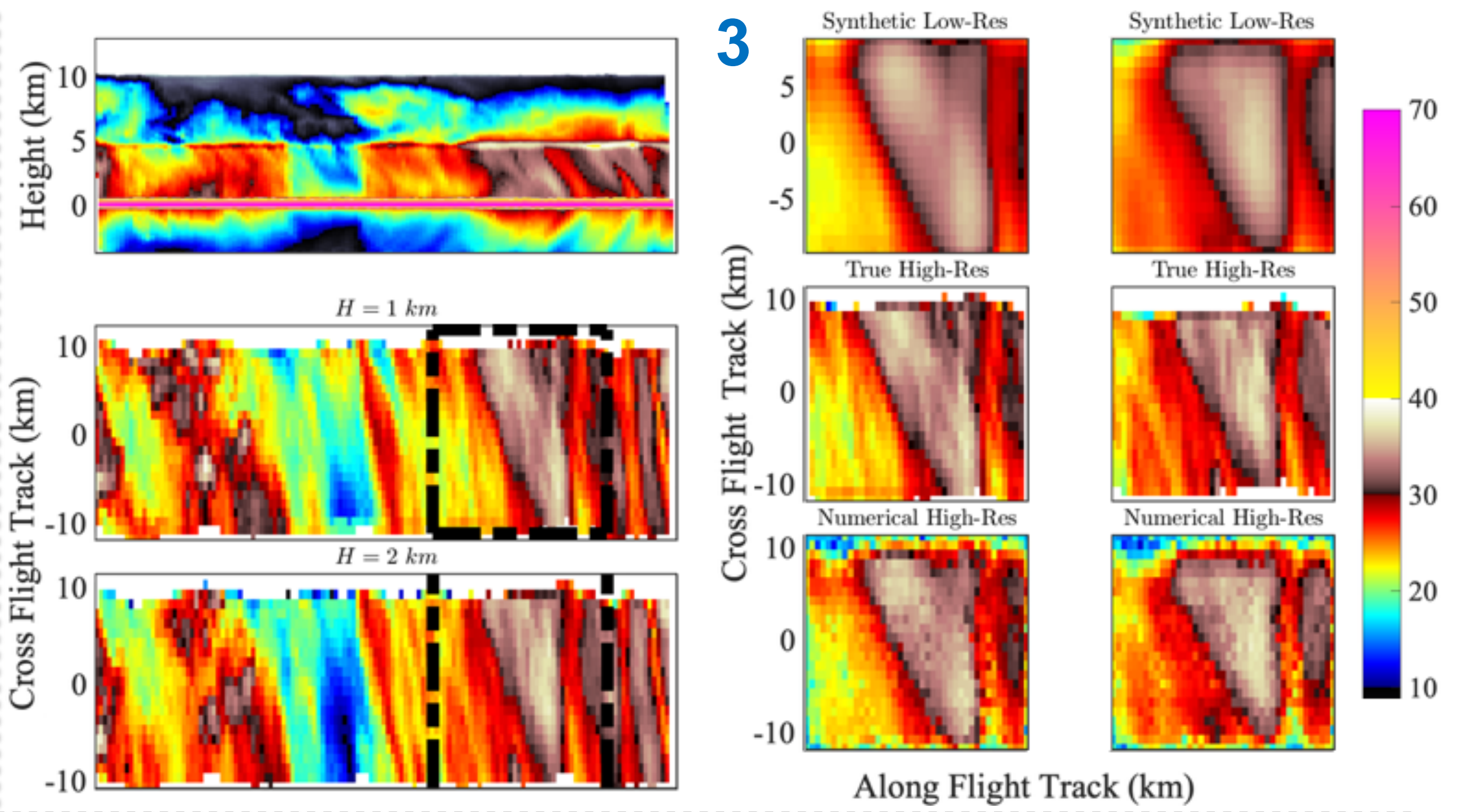

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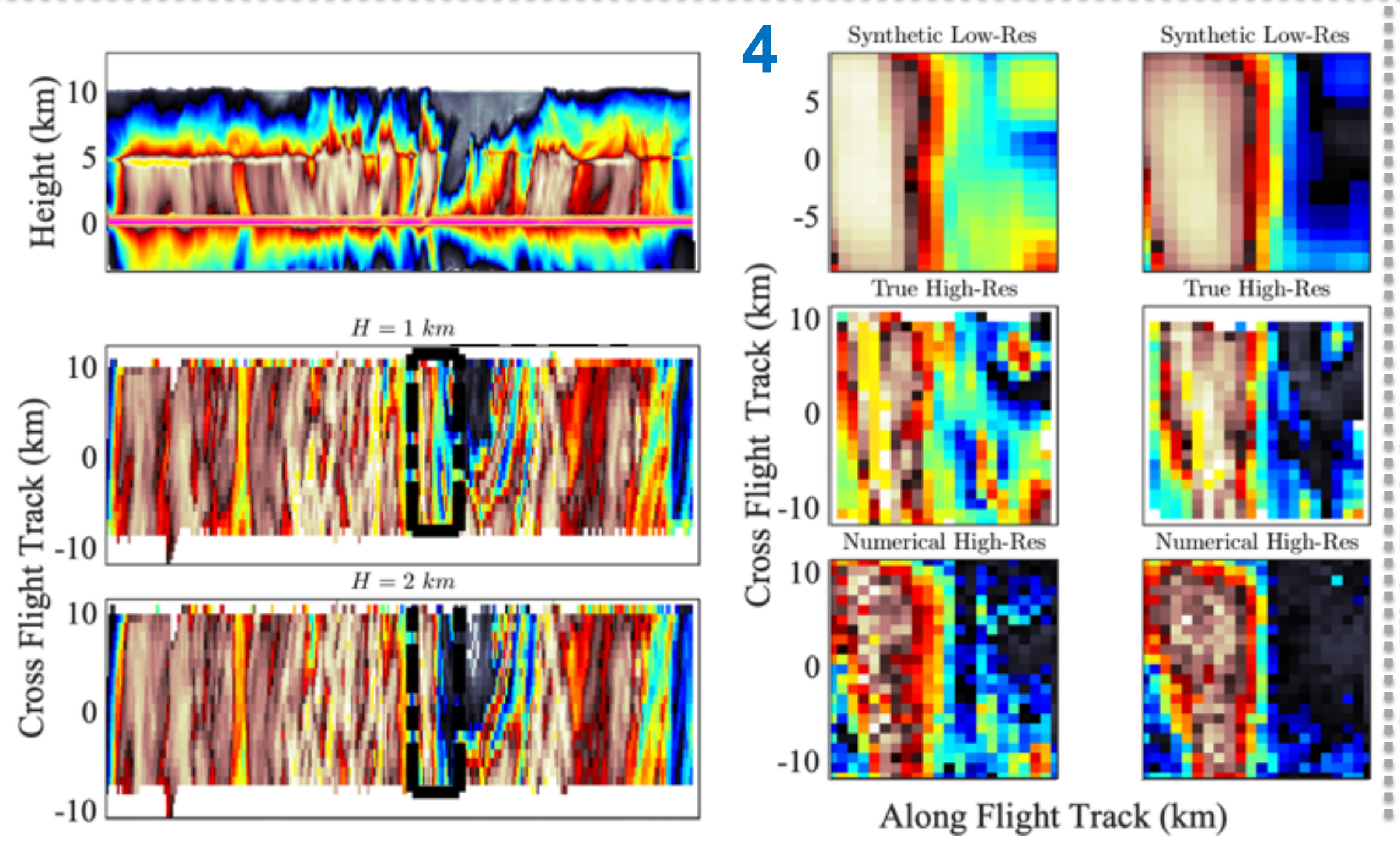

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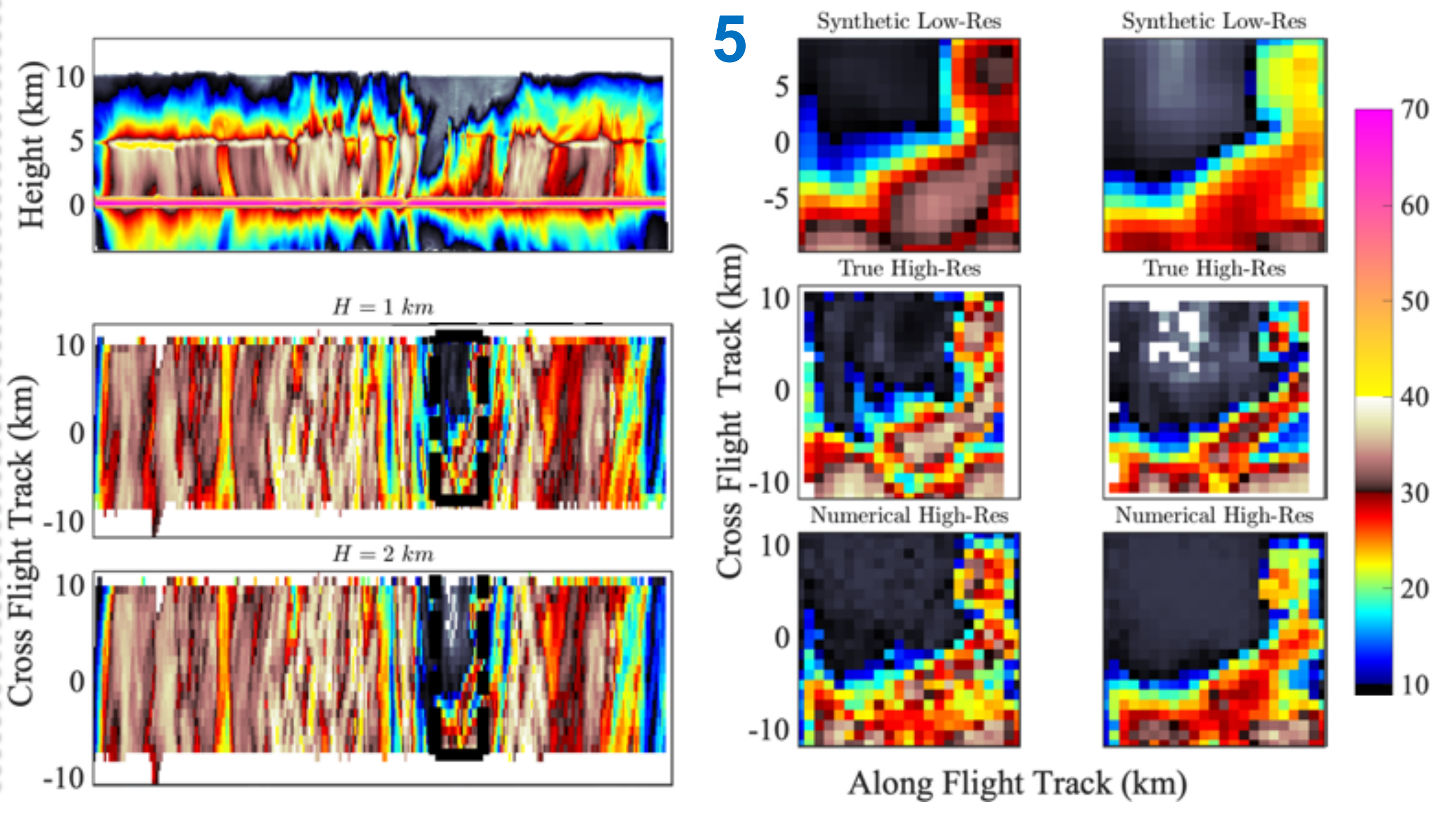

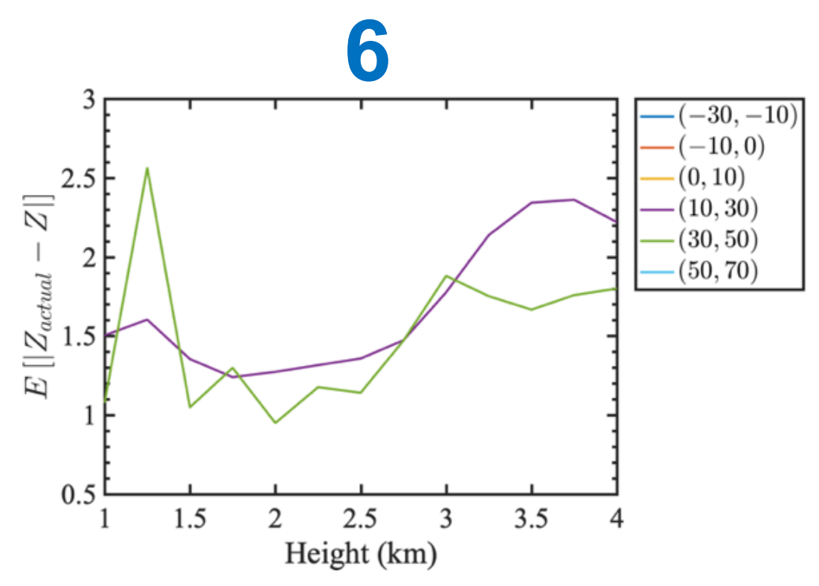

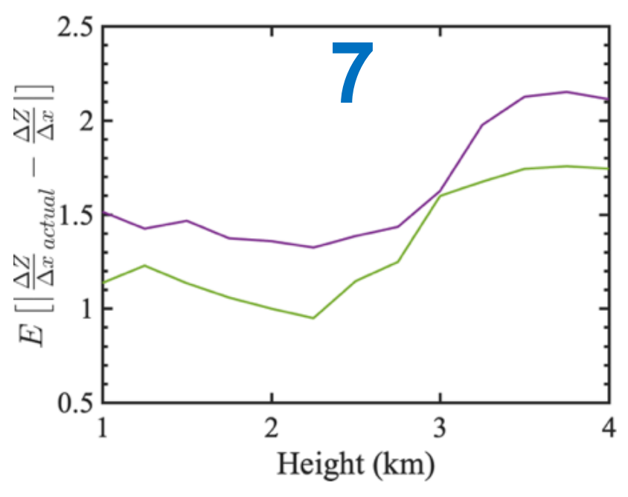

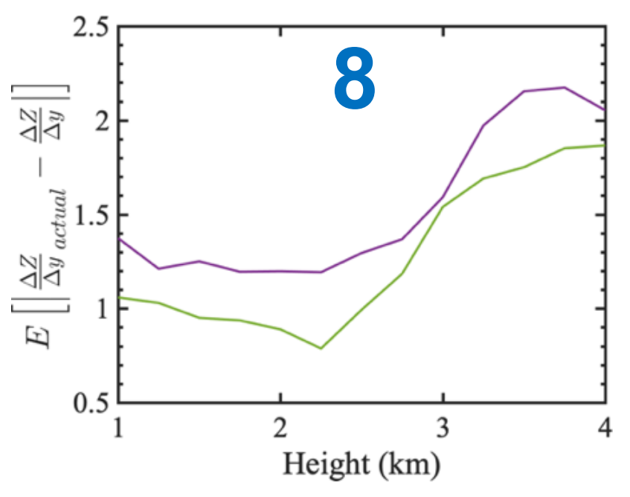

Benefits to NASA and JPL (and significance of results):

The ability to use overlapped measurements to produce consistently accurate estimates of the high-resolution radar reflectivity factors, would lay the theoretical basis for a new precipitation-radar observation strategy, that would use oversampled across- and along-track scanning and a vertical-principal-component guided disaggregation approach to drastically refine the horizontal resolution *in software*, with the currently-used relatively small aperture sizes, without having to consider a physical increase in the antenna size.

The results so far show that there is indeed a combination of choices in the formulation of the disaggregation (the arctangent transform, the a-priori regularization term, and the reduction in terms of 8 Principal Components) that leads to reasonably small errors in the disaggregation, but also that the errors can be further reduced. Further improvements should be possible by coarsening the resolution of the final estimates – or, equivalently, increasing the spatial frequency of the oversampling – , as well as by improving the a-priori regularizing background, and definitely by increasing the size of the domain -- and retaining only the innermost portion of the disaggregated solutions.

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