Studies around the optical asphericity of the atmosphere

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Background

We explore the use of spherical fits to the *NWP atmosphere*, instead of the sphere that is osculating to the ellipsoid, as an approach to handle and assimilate RO data when 3D asphericity is present.
These NWP fits can be produced at moderate cost, and can describe a large fraction of the NWP structure unrepresentable as spherical layers over the osculating sphere.
This work is intended to lead to proposals for use of atmospheric best-fit spheres, both at provider level and at user level.

Introduction

GPSRO is a 1D vertical measurement (1 measurement / height level). Atmospheric structure is much more pronounced vertically, justifying the traditional approach of reducing all structure to only vertical (a.k.a. spherical symmetry). This near-symmetry has not only been applied to assimilation; also to data reduction. Although horizontal structure is not negligible, GPSRO is primarily used as a source of information on atmospheric vertical structure. Horizontal structure (in the atmosphere, but also in the ionosphere), is a small perturbation to that main goal.
2D and 3D approaches have been developed, that account not only for the major vertical structure, but also for horizontal heterogeneity, for instance [1, 2, 3], and some strategies have found operational use, for instance [4].
Since, however, symmetry is key to algorithms of considerable simplicity, we explore the possibility of extending the use of existing tools based on spherical symmetry, through spherical fits *to the atmosphere*, modifying the center and radius of curvature wrt the osculating sphere to the WGS84 ellipsoid. Shifts of center and radius of curvature, when fit to the atmosphere instead of the ellipsoid are typically within about 10 km of the osculating values.

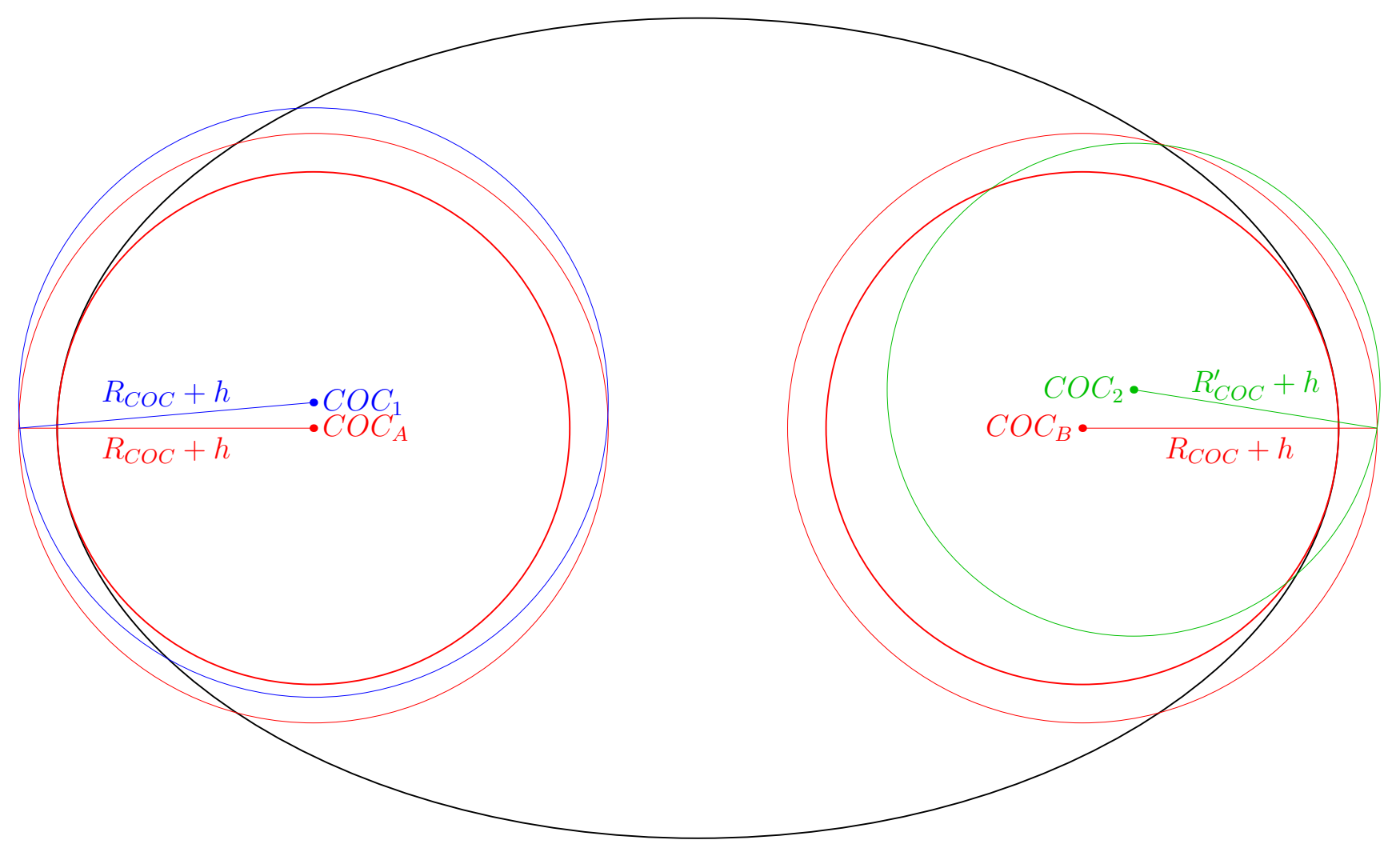

Figure 1: Examples of osculating spherical fits to an ellipsoid (red). Another fit departs locally linearly from it (left, blue), i.e. another sphere of the same radius but shifted center. On the right, a fit departs locally quadratically (green) from the osculating sphere. This "quadratic" departure is another sphere of both different radius and shifted center. Scale is very exagerated: typical tilt in the atmosphere is about 0.1-1 mrad. The center of curvature may, either due to the inclination of the isorefractive surfaces, or their curvature, displace typically by 1-10 km from the osculating center.

We find that these fitted spheres can represent a large fraction of the asphericity of the atmosphere, and are therefore useful. We explore both the provider-side data reduction process, and the user-side.
When required, we use the operational fields of Environment Canada's NWP system.

Mathematical expressions

Atmospheric structure in the vicinity of an occultation is in general a 3D field, $n_{3D}(\vec{x})$. Processing and end use work with representations that try to (compactly) express, manipulate and improve this field. We explore several expressions, **all of which use spheres** and are compact, but which allow an increasingly complex ability to approach the target 3D field.

- Classical osculating sphere (Figure 1, red):

$$n_{3D}(\vec{x}) \simeq n(r) \tag{1}$$

- With local linear gradient, spheres of fixed radius, but free center (see Figure 1, blue):

$$n_{3D}(\vec{x}) \simeq n(r) + \sum_{i\in(x,y)} g_i(r) \cdot x^i \tag{2}$$

- With local quadratic gradient, spheres of free radius and center (Figure 1, green):

$$\begin{aligned} n_{3D}(\vec{x}) \simeq & n(r) + \sum_{i\in(x,y)} g_i(r) \cdot x^i + \\ & \frac{1}{2} \sum_{ij\in(x,y)} C_{ij}(r) \cdot x^i x^j \end{aligned} \tag{3}$$

All are imperfect, with different balances of accuracy vs compactness. To quantify the ability of each to represent the 3D field, we produce test fits to a NWP atmosphere. Test fits are local, about the horizontal size of an occultation. Fit residuals represent the insufficiency of each fit (see Figure 1). Expanding the representation beyond the classical osculating sphere quickly improves the accuracy of the fit.

Fit residuals

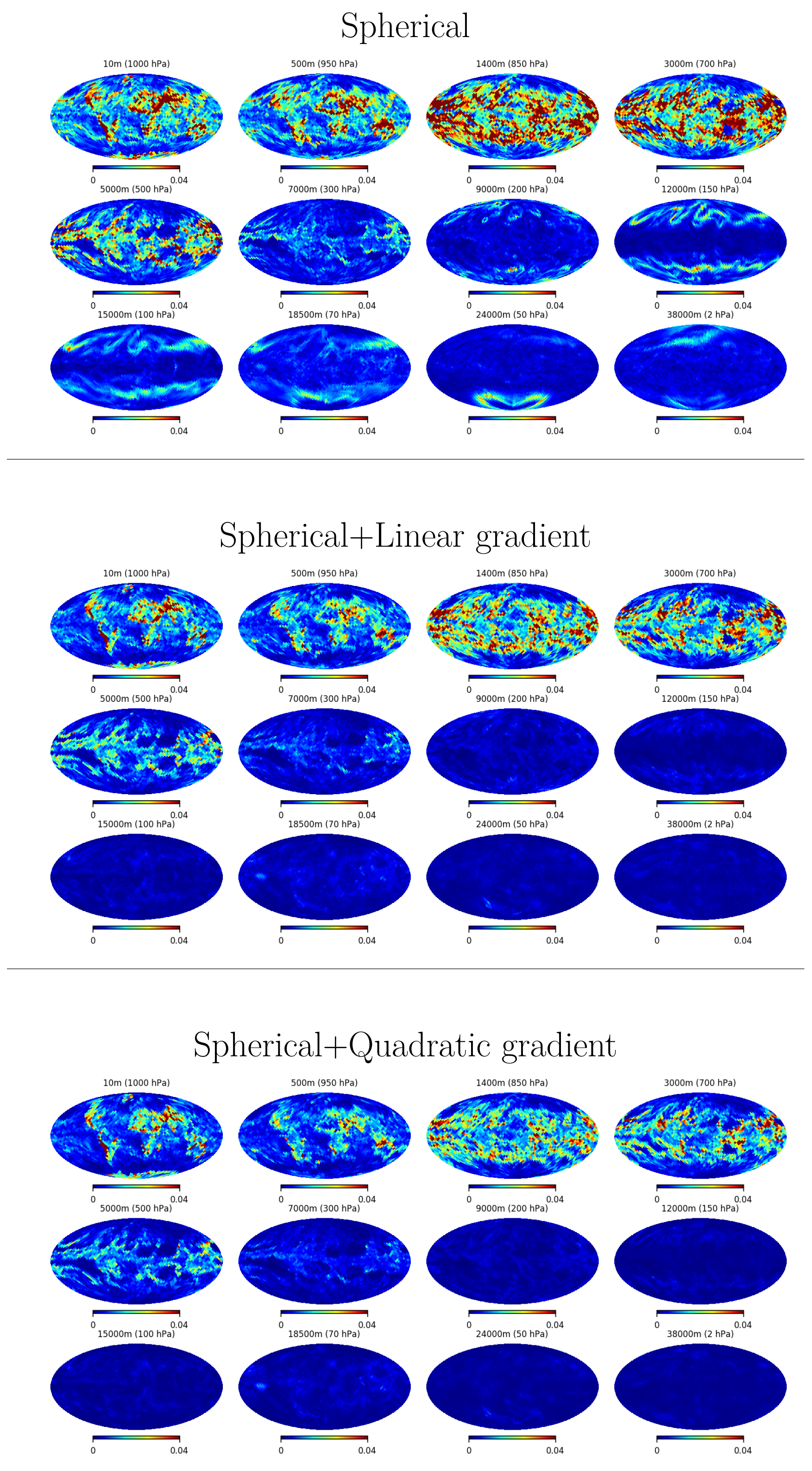

Figure 2: Fit residuals (blue is better fit) to the three spherical representations mentioned. See Figure 1.

A large fraction of the asphericity can be expressed as local tilt, particularly midlatitude fronts.

Shifting the center of the reference sphere, from osculating-to-WGS84, to atmospheric best-fit, then recomputing the retrieved profile (from phase/amplitude), a different bending profile is found. The following shows how the retrieved profile depends on the selected center.

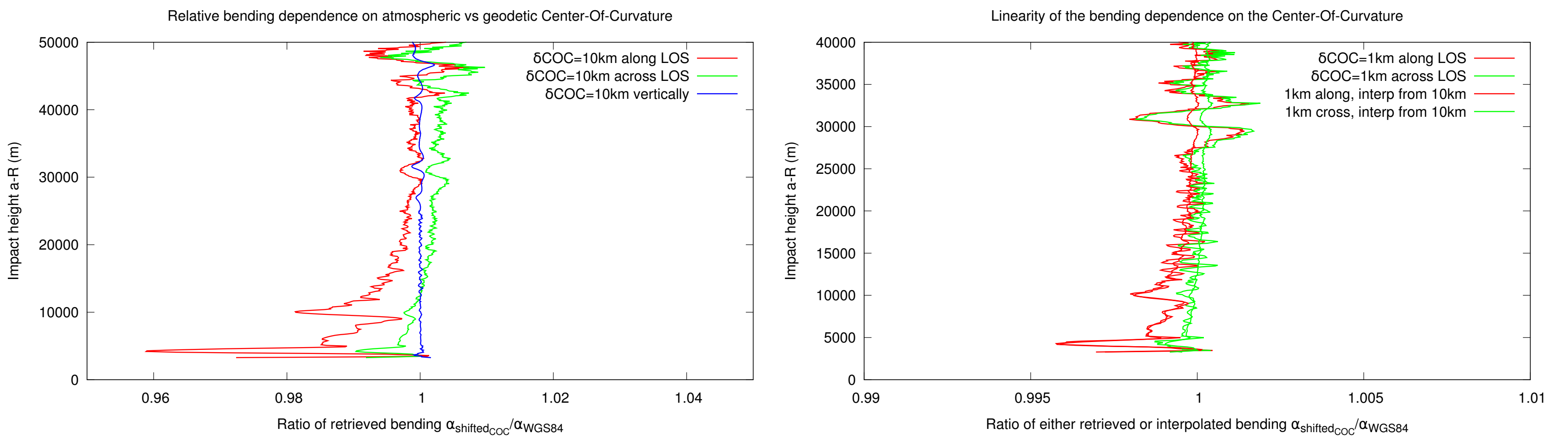

Figure 3: Bending profiles calculated shifting the reference sphere from osculating to a nearby sphere, of similar center, and radius to match. The left plot shows the ratio of bending (when the center is shifted), to the reference bending, osculating sphere). Several shifts are tested, along , across, and vertically, each producing a bending profile. The right pannel tests the linearity of this space of solutions with respect to the shift.

These profiles are found to vary close to **linearly** for normal shifts of the center of curvature. The atmospheric states may thus affect optimal data processing. But the substantial linearity implies that the space of possible impacts is not huge. From the user point of view, a shifted center of curvature leads to a shift in the Tangent Point (wrt WGS84 osculating).

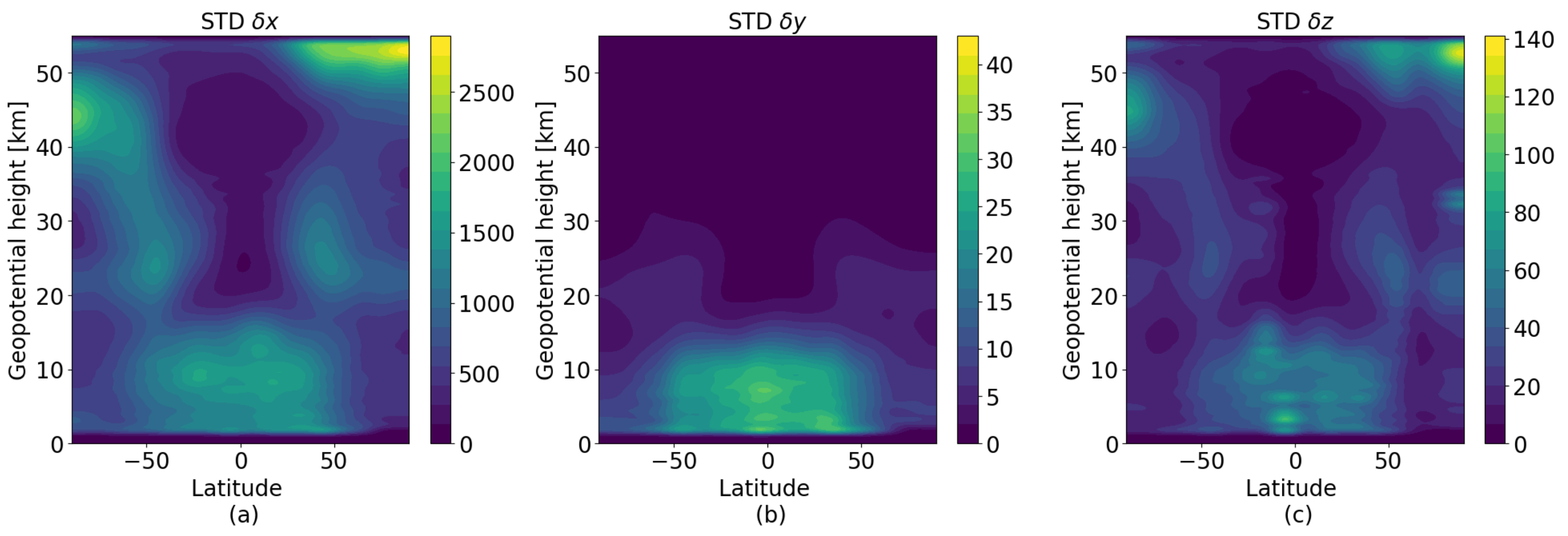

Figure 4: Statistics of Tangent Point shift (Nov 1st-7th, 2016) associated to the choice of a best-fit sphere (to the NWP refractivity), instead of the osculating (to the local ellipsoid). Shown are STD of displacements along the line of sight (x), horizontally across (y), and vertically (z) of COSMIC profiles.

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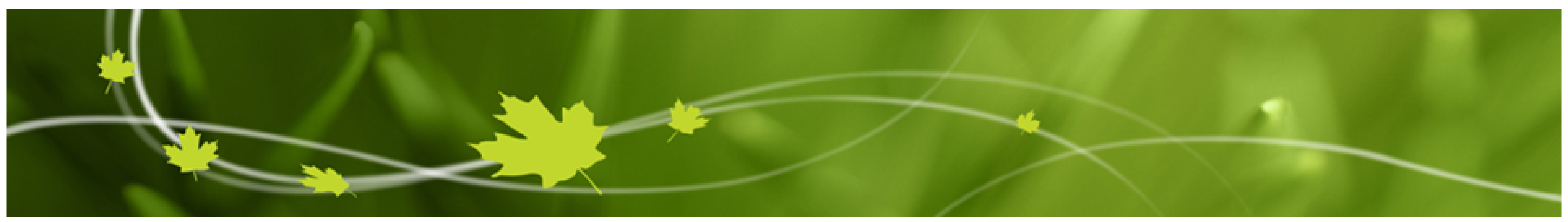

Conclusion and Outlook

A large fraction of the horizontal structure of refractivity, which departs from the classical "spherical symmetry" (WGS84 osculating), is still close to spherical shells, but with respect to another center. This suggests exploring the use of tools that require spherical symmetry, and whose accuracy would normally be limited by it, beyond their normal applicability, if the center of curvature and radius are allowed to float, and chosen to best-fit the atmosphere.
Notable atmospheric features that lead to departures from optical sphericity are midlatitude rossby waves, polar vortices, and the low tropical troposphere. The first two are well representable with a sphere (non-osculating). The low tropical troposphere, however, is very irregular. Compared to the reference situation of a perfectly spherical atmosphere, concentric to the local ellipsoid, the ensemble of these possible simple shapes is more complex but moderately small, sufficiently to be summarily explored exhaustively. It can be described as the ensemble of centers of curvature (COC), **normally at less than about 10 km** from the osculating COC.
We have explored reducing COSMIC phase/amplitude data (with EUMETSAT's ROPP Wave Optics algorithm), with respect to both the standard osculating COC, and several arbitrarily chosen COC's aroound it. The resulting bending profiles vary with the chosen COC, but a large part of this variation is linear.
For NWP purposes, a full description of all possible retrieved profiles, given all possible asphericities, unknown at the stage of phase/amplitude processing, would be too complex. The space of all variations is too large. Instead, if a small subset of this space is identified as more relevant, it may be calculated and described preemptively. In this sense, the dependence of the retrieved profile upon the chosen COC is sufficiently simple and can be described (without actual knowledge of best-fit COC's). Yet, this subspace accounts for a large fraction of the asphericity.

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