Characterization of line-of-sight effects in gravity waves as observed in the stratosphere, mesosphere and thermosphere-ionosphere

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Ray tracing & imaging

The ray tracing concept
Ray tracing, in computer vision, is the solution of the system of equations that results of the intersection of the line-of-sight (LOS) of the camera (observer) with a given ellipse. We can represent the Earth as a sphere, or more realistically with a WGS84 ellipsoid. The camera will be the imaging instrument, be it a spectrometer, a CCD or even GPS. So the use of ray tracing is suitable for any kind of LOS integration imaging.

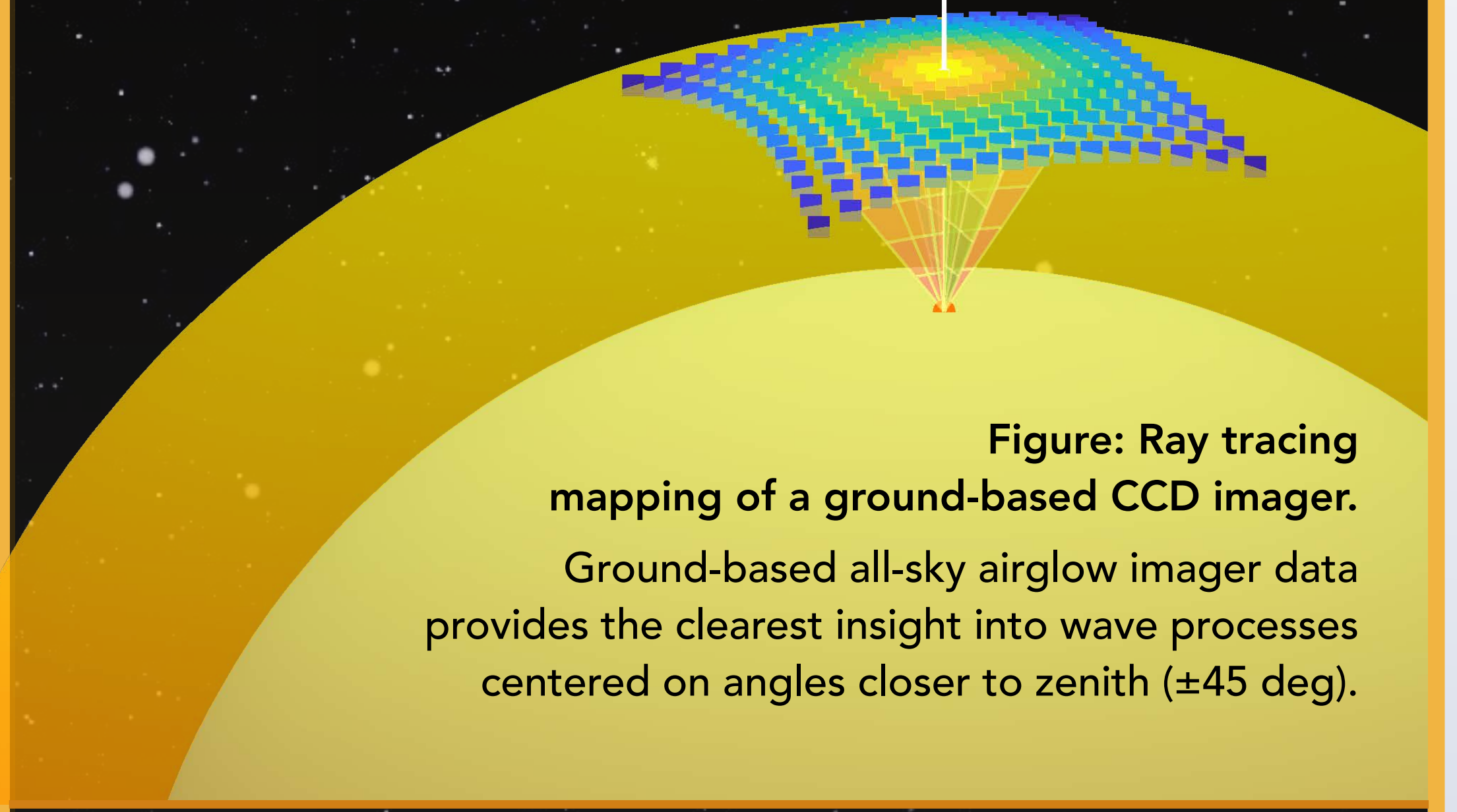
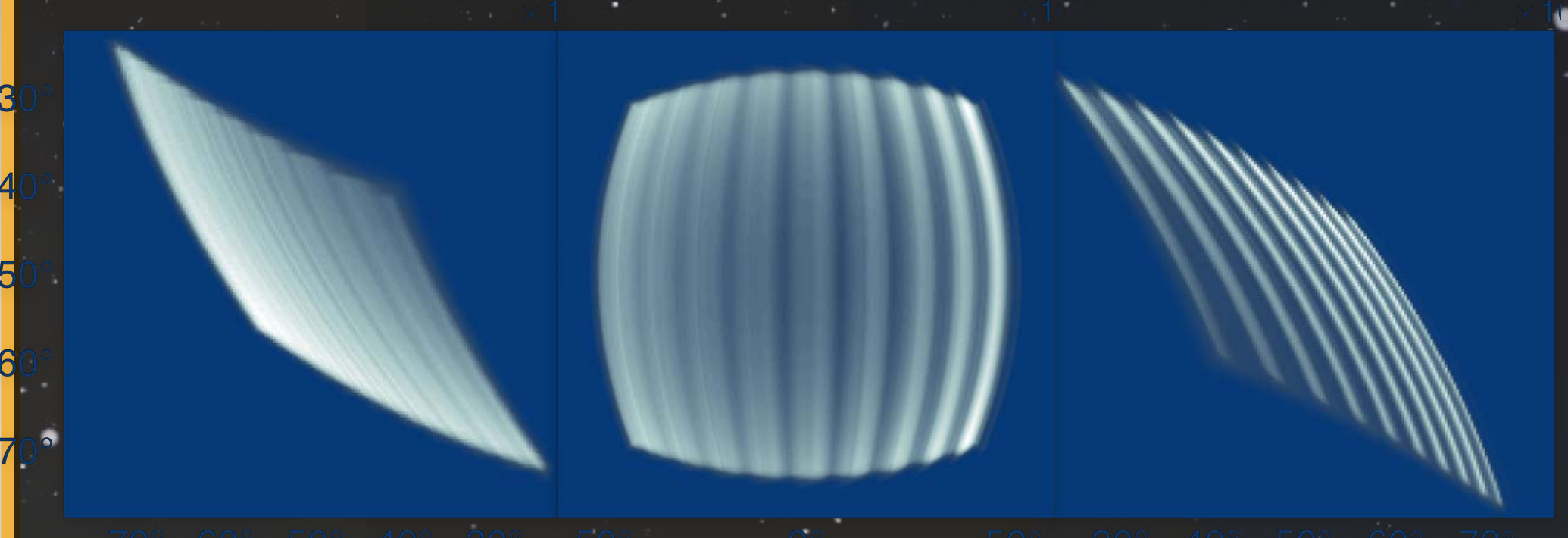


Figure: Ray tracing mapping of a ground-based CCD imager. Ground-based all-sky airglow imager data provides the clearest insight into wave processes centered on angles closer to zenith (±45 deg).

Space-borne observations
Imagers onboard moving platforms may capture different LOS across the airglow layer (viewing wave features from different angles as they pass) that can be chosen to better image features that are sensitive to LOS effects.

Figure: Ray tracing mapping of spaceborne, track-aligned CCD imagers.

Off-zenith imaging
Airglow observations made at steep viewing angles lead to scale filtering effects. The integration of the emission rates represents loss of information regarding the structure of the airglow layer as it effectively "flattens" it. The use of simulated airglow structures enables direct comparisons to the structures present within the emitting layers.

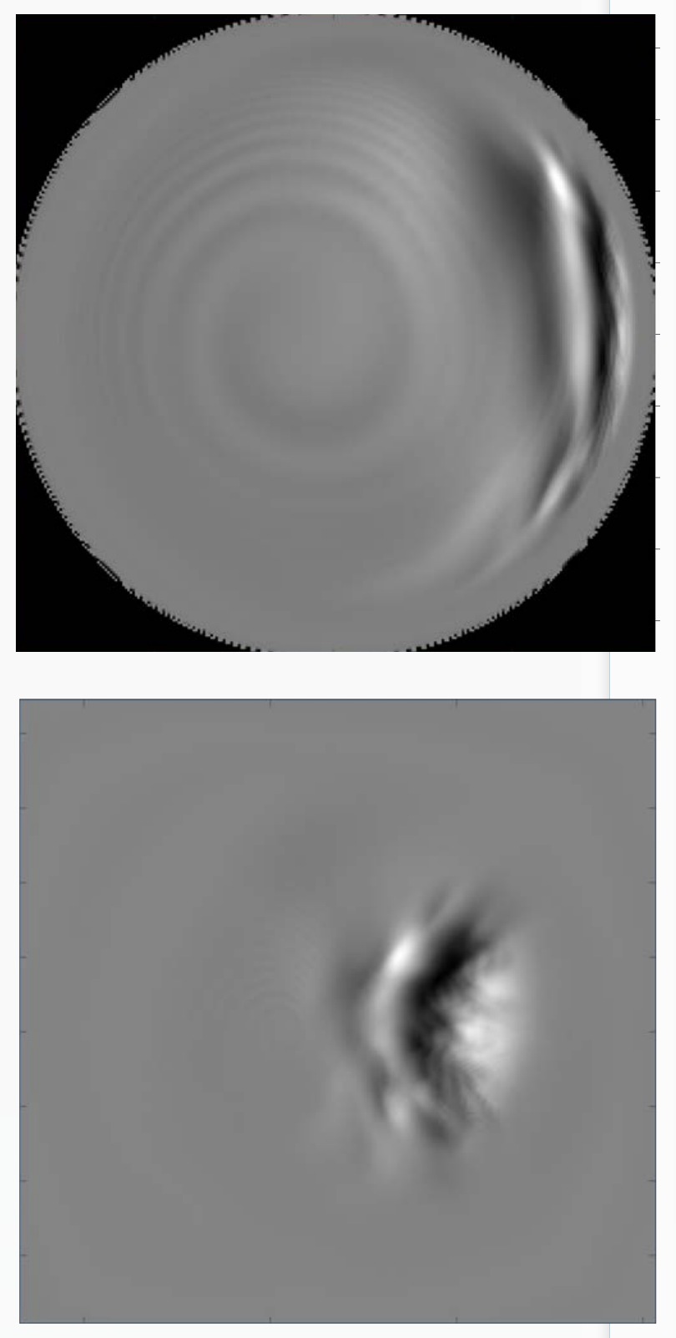


Background and motivation: detectability challenges
Gravity waves (GWs) have significant impact in the upper layers of the atmosphere and are major drivers of its circulation [e.g., Fritts and Alexander, RG, 41, 2003], such as convectively generated GWs that can have sufficiently large vertical wavelengths and large horizontal phase speeds and which are often observed to be radially propagating [e.g., Taylor and Hapgood, PSS, 36(10), 1988; Yue et al., JGR, 114, 2009; Nishioka et al., GRL, 40, 2013]. Further, we now have considerable evidence for the capability of multi-sensor studies to connect measurements at different layers of the atmosphere to obtain GW parameters at multiple altitudes for particular events [e.g., Yue et al., JGR, 118, 2013; Akiya et al., GRL, 41, 2014; Azeem et al., GRL, 42, 2015]. GWs observations are, however, susceptible to line-of-sight (LOS) effects when imaged through deep layers of the atmosphere. It has been suggested these LOS effects introduce biases to the measured GW parameters for upward propagating waves [*Hines and Tarasick*, PSS, 1987; *Hickey et al.*, JGR, 2010]. However, these biases may provide enough intensity enhancements to allow for the detection of certain phenomena that otherwise would be beneath the sensibility threshold of imaging instruments.

Background and motivation: detectability challenges
We have developed a modeling framework for synthetic imaging through perturbed layers, using the output of the compressible atmospheric dynamics model "MAGIC" and the self-consistent multi-fluid ionosphere model "GEMINI" [*Zettergren and Snively*, JGR, 120, 2015]. Simulations are constructed with physically-constrained convective sources of GWs at midlatitude. Outputs include species and electron densities, and emission rates for multiple airglow layers (OH, oxygen), which allow us to simulate different imaged measurements:

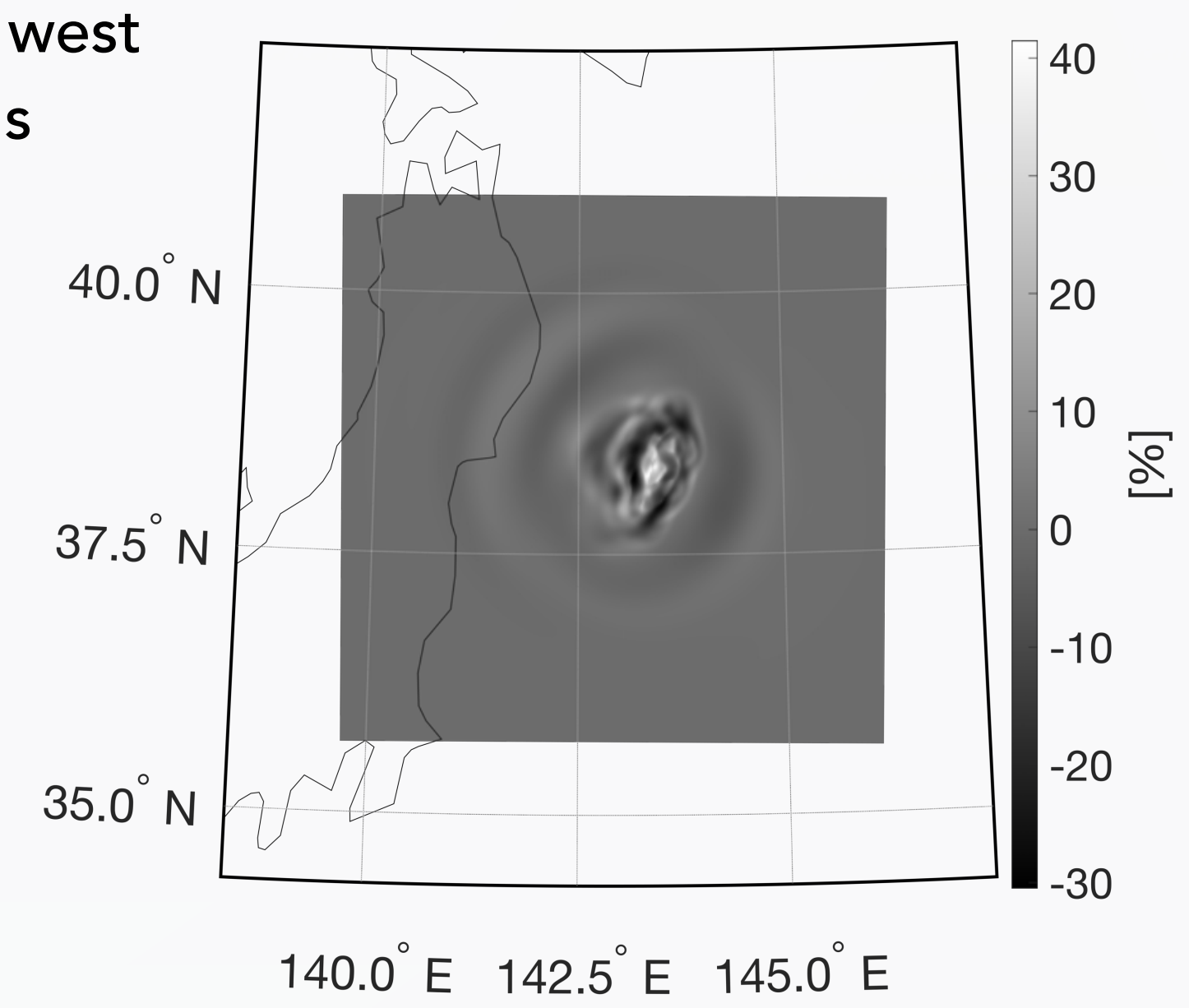
- stratospheric CO_2 radiance (~35 km peak), measured by the AIRS IR spectrometer [*Aumann et al.*, IEEE, 41, 2003],
- mesospheric OH(3,1) band emissions (~87 km peak), observed from ground or space,
- and the OI 630 nm (~250 km peak) emission, observed by ground-based all-sky imagers such as MANGO [*Bhatt and Kendall*, AGU FM, 2017] (not shown here).

Using these "observables", we investigate and characterize LOS effects through multiple layers, and demonstrate constraints placed on real observations, towards enabling rigorous model-data comparisons.



Case study: near-epicenter mesospheric airglow perturbations for a hypothetical nighttime earthquake analog to 2011 Tohoku [Inchin et al., 2019]:
Surface displacements, calculated in a forward seismic waves propagation simulation based on kinematic slip model with SPECFEM3D-Globe, are used to drive 3D MAGIC at ground level. These waves create detectable fluctuations in the mesospheric airglow and may be detectable by imagers. Shown to the left are the simulated imagers off the coast of Japan for the AWs in OH airglow at a fixed time (epicenter @ ~50 km west from the shore). The OH intensity perturbations are quite large at ±40% and showcase significant filtering of scales when compared to the vertical (column) integration of the 3D data (image on the right), important for interpretation.

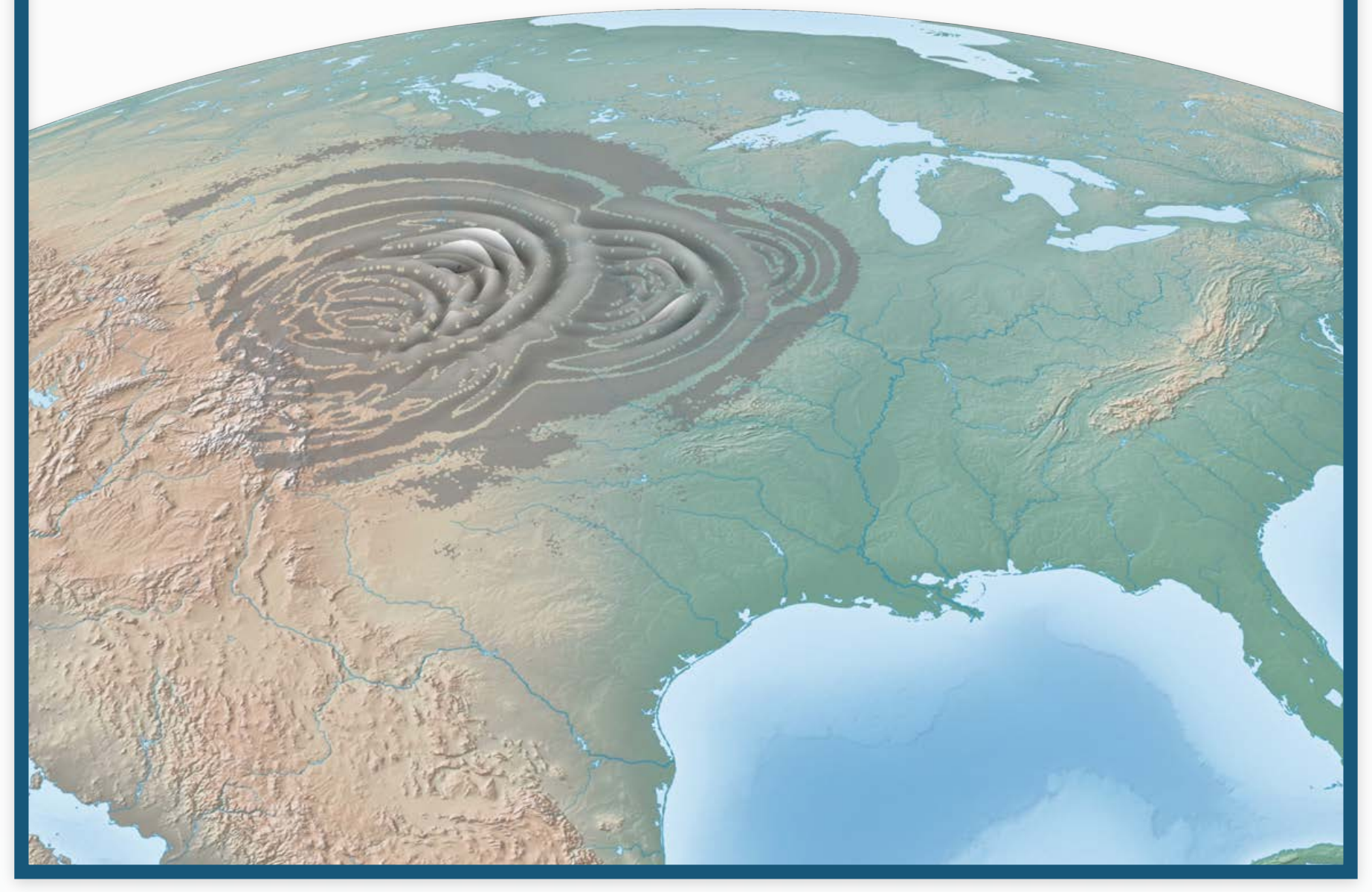
(left, top) Simulated CCD image of OH VER. (left, bottom) Unwarped CCD image.



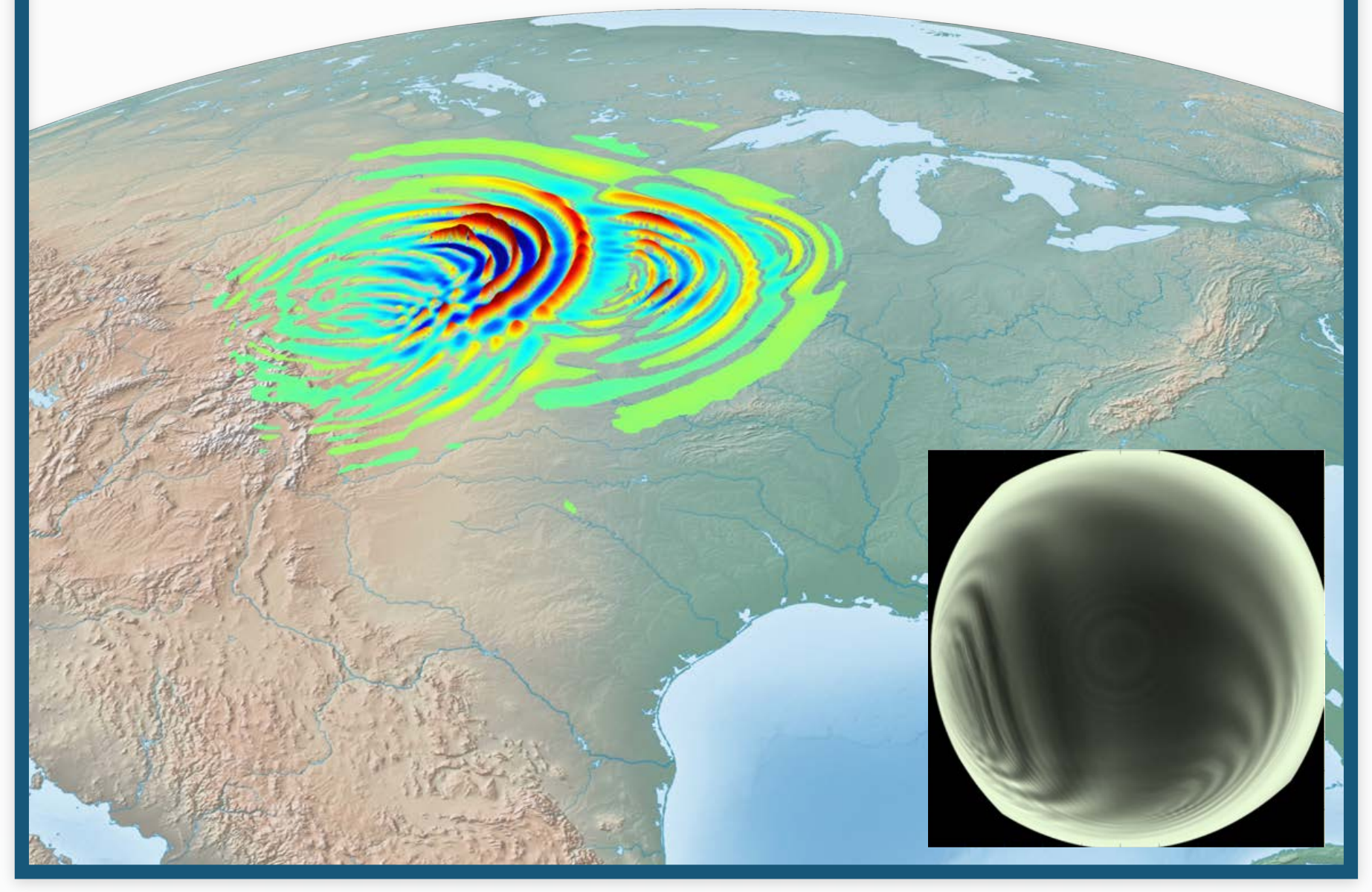
(right) Vertical integration of OH VER perturbations due to offshore earthquake. Synthetic images show significant scale filtering.

Case study: a convective thunderstorm over Iowa [Heale et al., 2019]:
The gravity wave source for this MAGIC simulation is latent heating rates associated with a thunderstorm complex using precipitation rate data from NOAA's Doppler weather radar network, NEXRAD, and using the latent heating profile algorithm by [Stephen et al., AMS, 2016]. Here shown are CO_2 radiances in units of brightness-weighted-temperature using weighting profiles as in [Hoffmann et al. JGR, 2010]. As the concentric gravity waves propagate upwards we can see evidence of breaking and possibly secondary gravity wave generation. Making this simulations available for comparison with data is possible by simulating AIRS (for CO_2 radiances) or a space-borne imager (for OH airglow imaging).

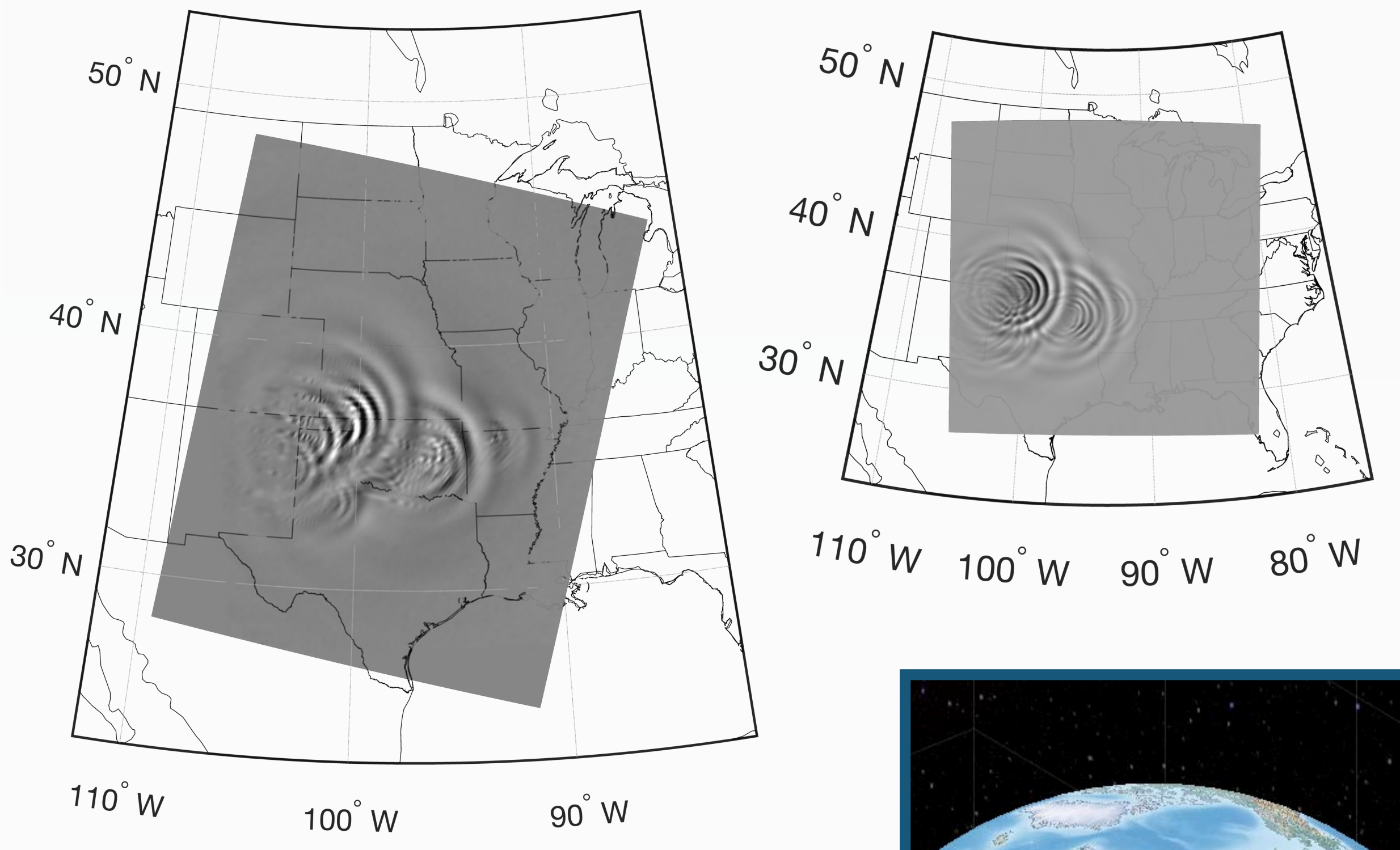
CO_2 radiance (BWT) due to a convective thunderstorm over Iowa. Data shows two clear concentric gravity waves propagating upwards through the troposphere. Peak radiance @~36 km.



OH VER perturbations over Iowa due to a convective thunderstorm. The OH airglow is modeled with a 2 km resolution and is seen by ground-based 512×512 CCD synthetic imager.

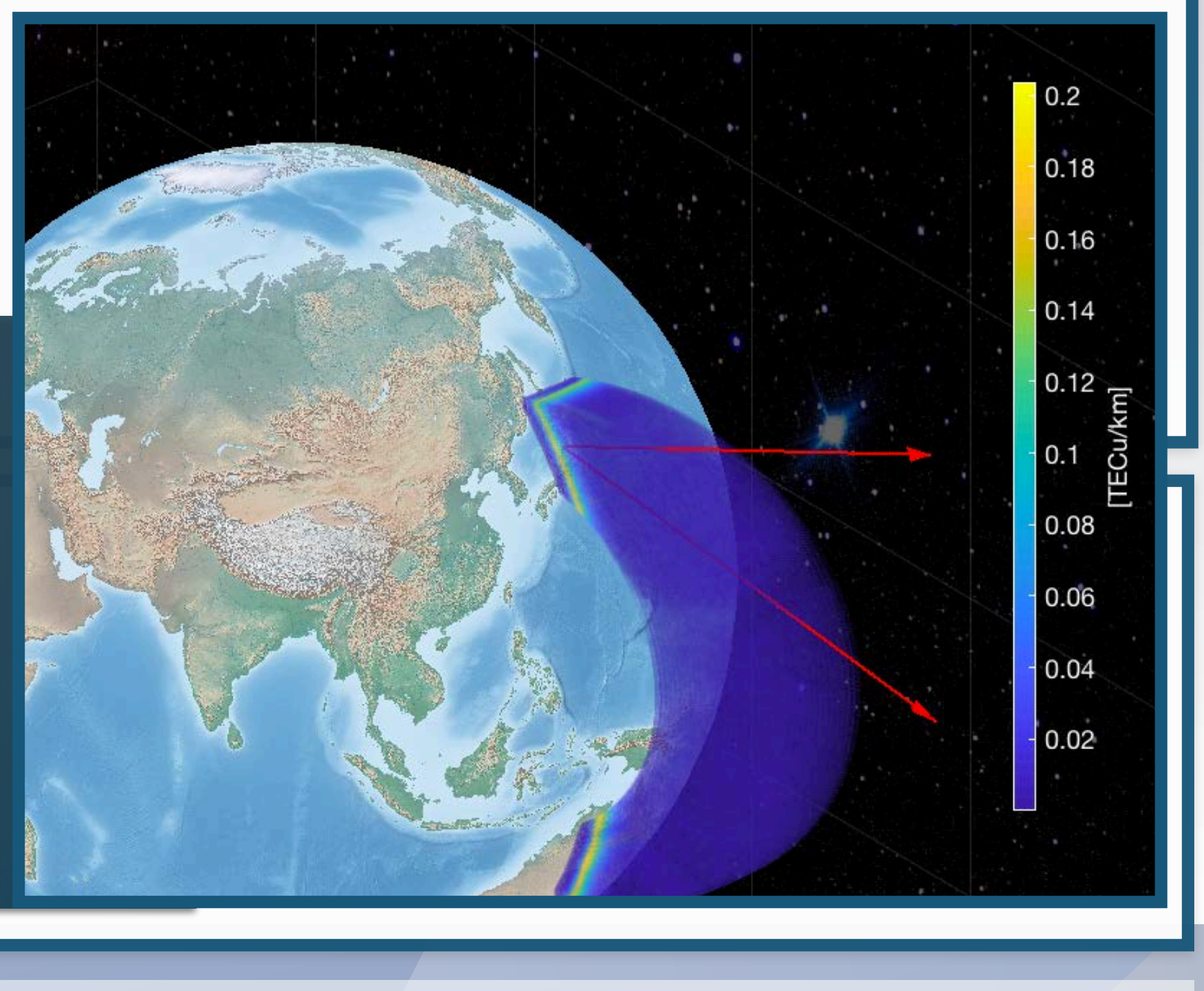


Shown below are the satellite swaths for the simulated AIRS imaging. The instrument parameters are: ±48.95° FOV, 725 km mean altitude, 2.67 s integration, 7.5 km/s mean velocity with the plot being nadir slabs. On the right is the vertical (column) integration of the 3D data. There are two clear concentric sources over Oklahoma however, due to LOS enhancements, smaller sources are more prominent in the simulated satellite swath data.



(left) Simulated satellite swaths of CO2 radiance imaging. (right) Column integration of data. The observed GWs sources are clear and they are due to a thunderstorm system.

The GEMINI Connection:
Our simulation capabilities extend to TEC integrations by adapting GEMINI's domain and specifying GPS receiver-satellite pairs. Acoustic or gravity waves that propagate through the thermosphere are detectable in TEC, and will exhibit significant LOS effects due to the observing geometry.



Concluding remarks
Our synthetic imaging framework allows us to diagnose the observability challenges associated with large-scale GWs and understand the effects of imaging obliquely through dense layers throughout the atmosphere. We have shown two examples of significant LOS effects: filtering of scales, relevant to wave-breaking, and wave feature enhancement due to oblique imaging.

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