Improvement of auroral 3D reconstruction methods

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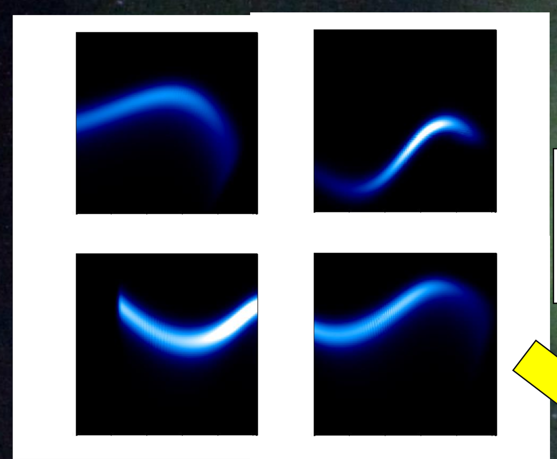
Generalized – Aurora Computed Tomography

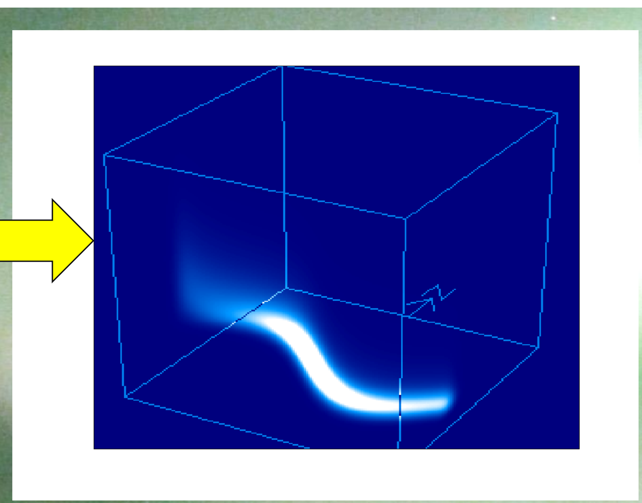
Multiple auroral images



Prior information

G-ACT is a method for reconstructing the 3D distribution of auroral emissions from multi-instrument data. [*Tanaka et al., Ann. Geophys., 29, 551-562, 2011*]

G - ACT



3D distribution of electron density measured by EISCAT radar

Bayesian inference

By using the 3D electron density data from EISCAT_3D radar for the G-ACT, the reconstruction results should be more reliable than that from the normal ACT.

Inverse analysis by the G-ACT method

model observational data

Bayes' theorem:

$$P(\mathbf{f}\mid\tilde{\mathbf{b}}) = \frac{P(\tilde{\mathbf{b}}\mid\mathbf{f})P(\mathbf{f})}{P(\tilde{\mathbf{b}})} \propto P(\tilde{\mathbf{b}}\mid\mathbf{f})P(\mathbf{f}) \quad \text{......(1)}$$

Likelihood:

$$P(\tilde{\mathbf{b}}\mid\mathbf{f}) \propto \exp\left\{-\sum_j \frac{1}{2}\left(\tilde{\mathbf{b}}_j - \mathbf{b}_j(\mathbf{f})\right)^T \mathbf{\Sigma}_j^{-1}\left(\tilde{\mathbf{b}}_j - \mathbf{b}_j(\mathbf{f})\right)\right\}$$

$$P(\mathbf{f}) \propto \exp\left(-\frac{\left\|\nabla^2\mathbf{f}\right\|^2}{2\sigma^2}\right)$$

Posterior probability:

$$P(\mathbf{f}\mid\tilde{\mathbf{b}}) \propto exp\left[-\frac{1}{2\sigma^2}\left\{\sum_j w_j^2\left(\tilde{\mathbf{b}}_j - \mathbf{b}_j(\mathbf{f})\right)^T \mathbf{\Sigma}_j^{-1}\left(\tilde{\mathbf{b}}_j - \mathbf{b}_j(\mathbf{f})\right) + \left\|\nabla^2\mathbf{f}\right\|^2\right\}\right] \quad \text{......(2)}$$

$\mathbf{f}$: differential directional number flux of electrons
j : type of data
$\tilde{\mathbf{b}}$: observational data (auroral images, electron density)
σ^2 : variance of $\nabla^2\mathbf{f}$
w_j : weighting factors for each data
$\mathbf{\Sigma}_j^{-1}$: inverse covariance matrix

$$\varphi(\mathbf{f};w_j) = \sum_j w_j^2\left(\tilde{\mathbf{b}}_j - \mathbf{b}_j(\mathbf{f})\right)^T \mathbf{\Sigma}_j^{-1}\left(\tilde{\mathbf{b}}_j - \mathbf{b}_j(\mathbf{f})\right) + \left\|\nabla^2\mathbf{f}\right\|^2$$

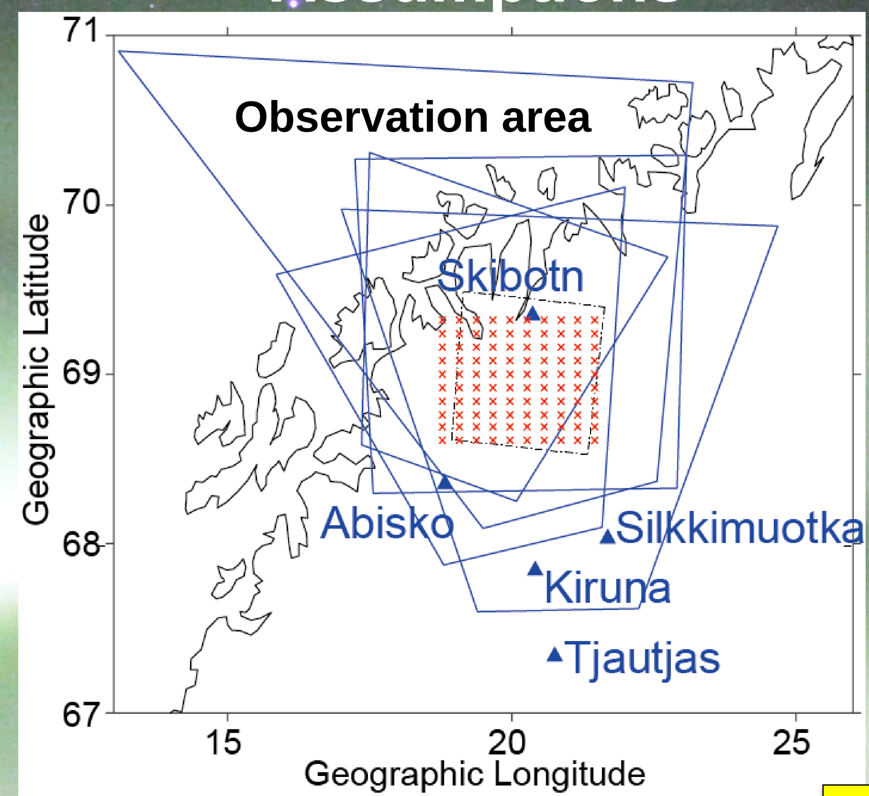
$$= w_1^{\,2}\mathbf{\Sigma}_{i,1}^{-1}\left\|c_i\tilde{\mathbf{g}}_i - \mathbf{P}_{i,1}\mathbf{M}_1\mathbf{f}\right\|^2 + w_2^{\,2}\mathbf{\Sigma}_2^{-1}\left\|\tilde{\mathbf{n}}_{\mathbf{e}}^{\,2} - \mathbf{P}_2\mathbf{M}_2\mathbf{f}\right\|^2 + \left\|\nabla^2\mathbf{f}\right\|^2 \quad \text{......(3)}$$

Auroral images Electron density

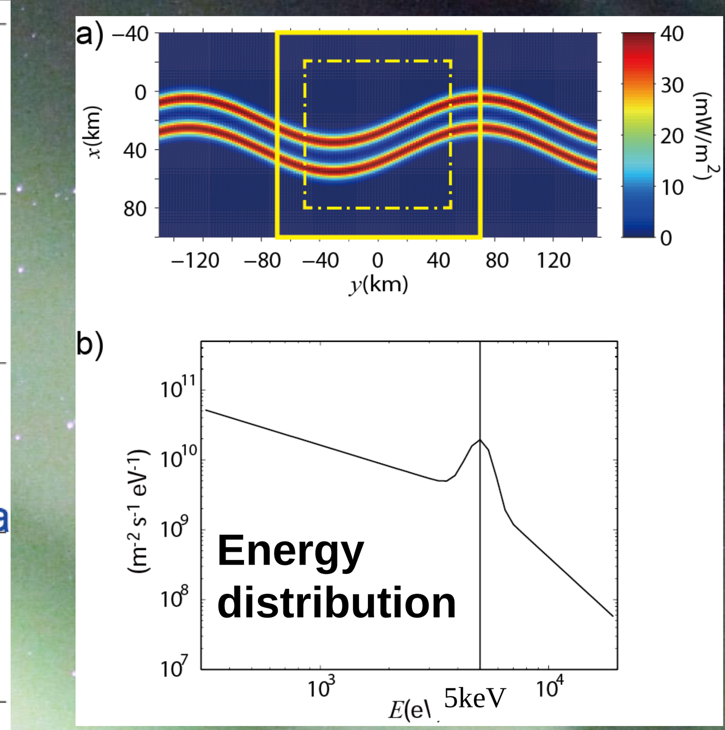
Hyper-parameters

An example of G-ACT by simulation
(Tanaka et al., 2024)

Assumptions

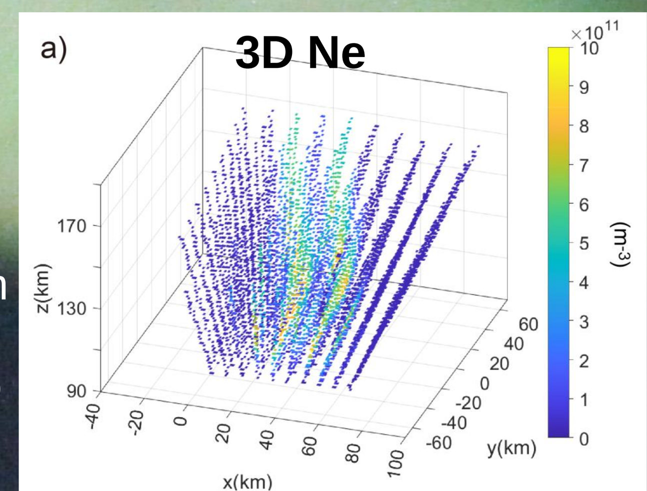


Auroral shape

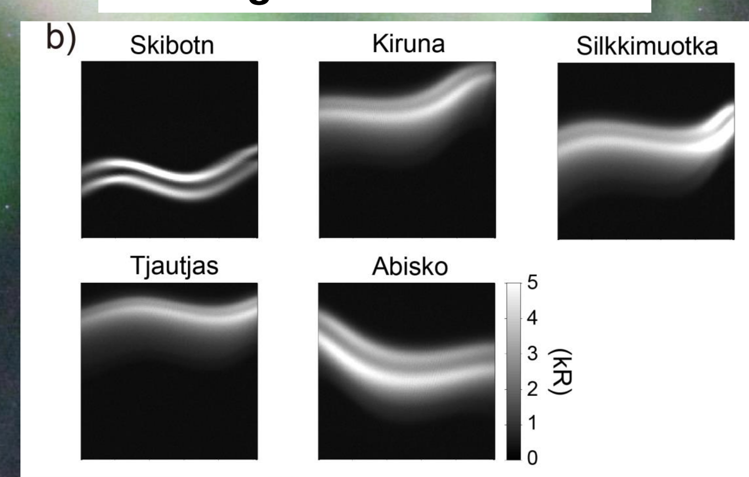


Simulated data

10x10 beam scan by EISCAT_3D



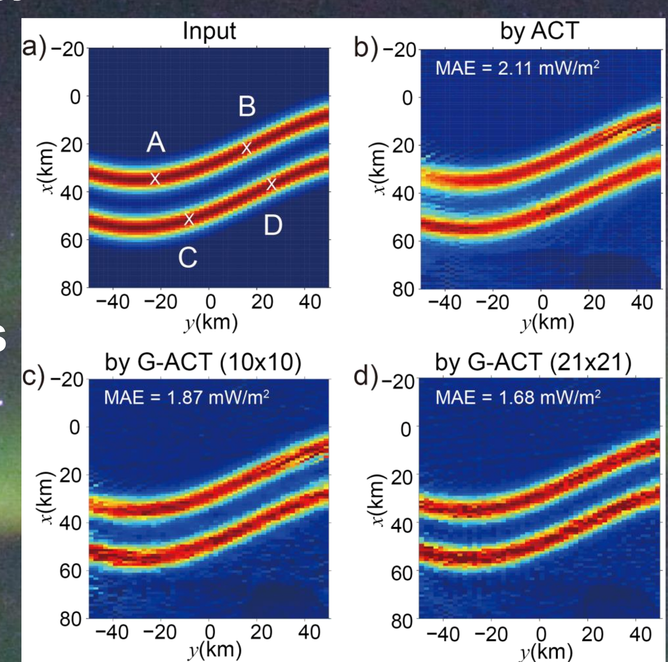
Images from 5 sites



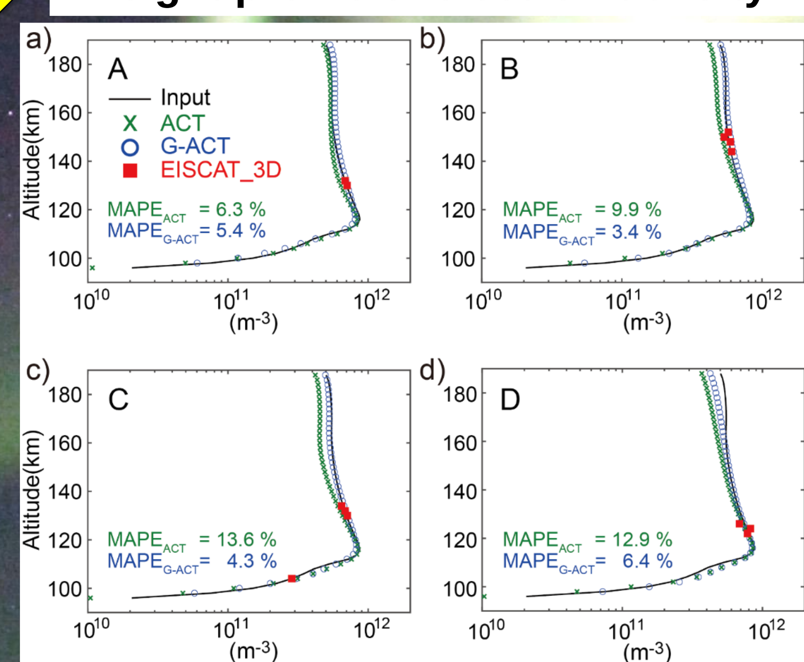
Total energy flux (Q_0)

Reconstruction

From 5 images + 3D Ne

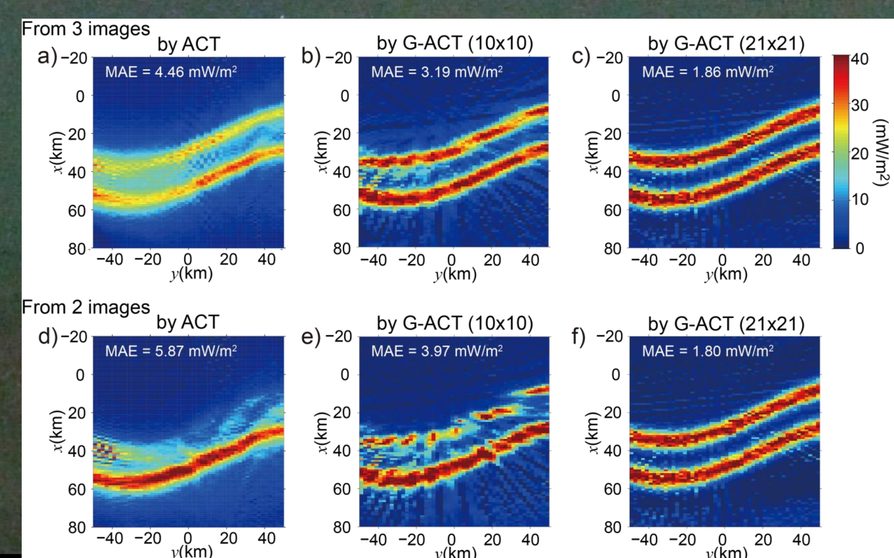


Height profile of electron density



From 3 images (S, K, T) + 3D Ne

From 2 images (S, K) + 3D Ne



Improvement of analysis methods

Issues : It takes time to process the data and solve the inverse problem, in particular, for the hyper-parameters.

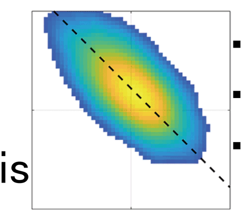
Simulation

Modelled data

Various observation conditions

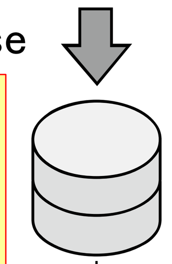
- Auroral shape and position
- Number of cameras
- Wave length
- S/N ratio

3D Analysis



- Results
- Hyper-parameters
- Errors

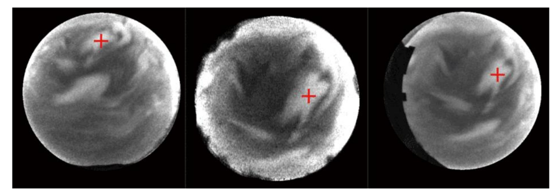
Database



Solution(1): The hyper-parameters, which are most time-consuming to determine, are pre-calculated under some typical conditions using model simulations and are compiled into a database to automatically determine the appropriate hyper-parameters for the observed data.

Observation

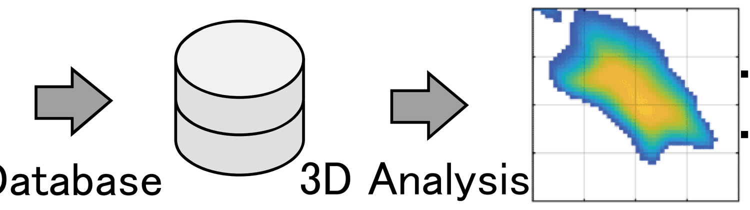
Hyper-parameters Errors



Observed adata

Database

3D Analysis

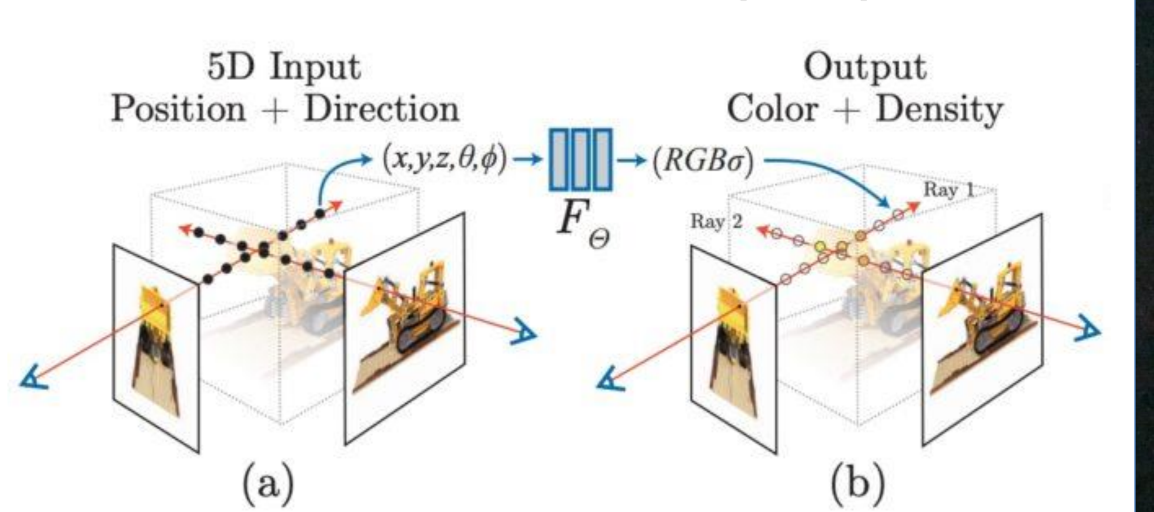


- Results
- Error evaluation

Solution(2): Use the state-of-the-art 3D reconstruction and visualization techniques based on AI, e.g., Neural Radiance Field (NeRF) or 3D Gaussian Splatting (3DGS).

- NeRF is a method based on deep learning for reconstructing a 3D representation of a scene from 2D images.
- We have started to develop the 3D reconstruction and visualization methods based on AI in collaboration with NII.

Neural Radiance Field (NeRF)



Summary

- To enhance the efficiency of 3D analysis, we are developing new procedures in which hyperparameters and errors are precomputed under typical conditions using model simulations and compiled into a database.
- We are also trying to develop AI-based 3D reconstruction and visualization methods in collaboration with NII. These methods can quickly and accurately reconstruct and visualize 3D scenes and have already been applied to various research fields,.