

Cloud retrievals using lidar with wide field of view

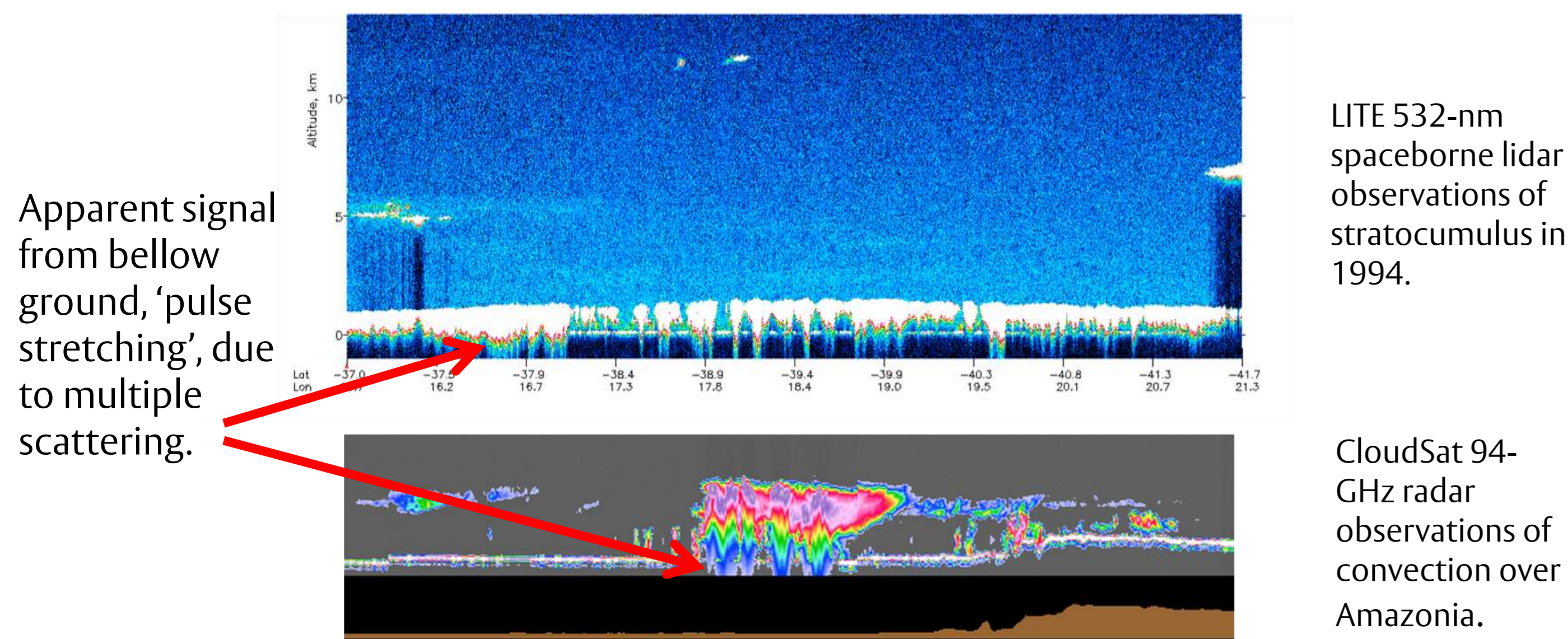
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1. Introduction

Cloud properties, particularly their extinction coefficient profile, are important in the radiation budget and hence climate.

Spaceborne lidar returns can be used to retrieve cloud extinction profiles but are affected by multiple scattering. The CloudSat radar is similarly affected in deep convection.



2. Lidar and multiple scattering

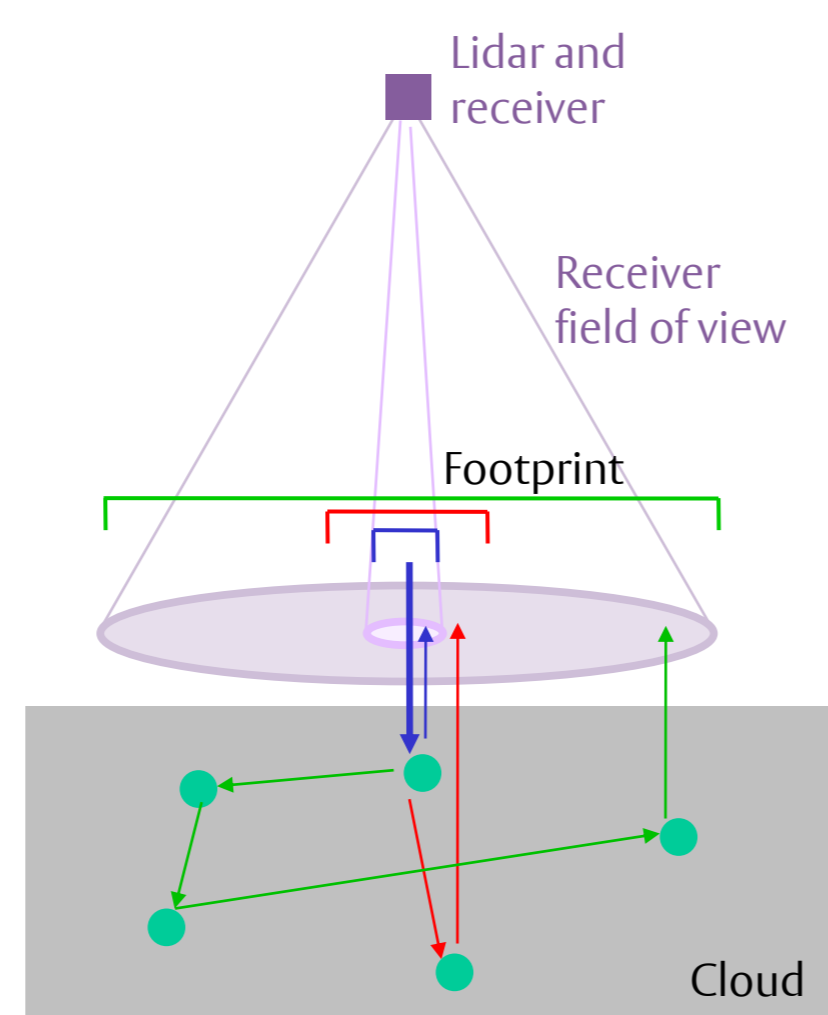
Received lidar signal has been scattered. 3 possibilities:
Received in narrow field of view = small footprint

- Single scattering;
- Quasi small angle scattering.

Received in wide field of view = large footprint

- Wide angle scattering. The extra distance travelled by the photons appears as vertical distance: 'pulse stretching'.

Hogan and Battaglia (2008) developed fast multiple and quasi-small angle scattering algorithms, suitable for a forward model.



3. Retrieval method

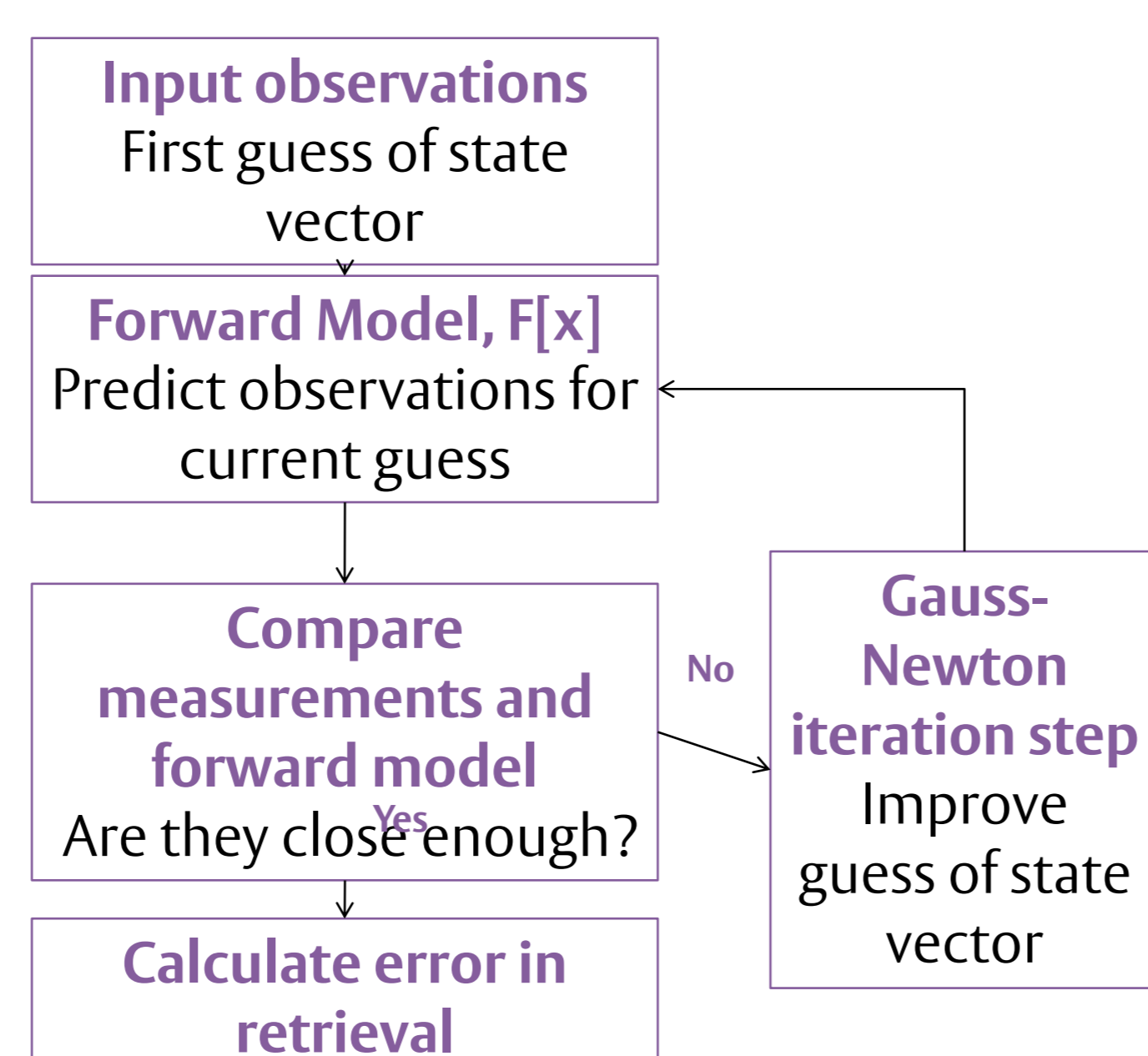
Use optimal estimation theory to solve the inverse problem.

Retrieve: state vector, x – extinction coefficient profile.

Have: observation vector, y – apparent backscatter coefficient;
Covariance matrix, R^{-1} – observation errors.

Problems: Under constrained – regions with no observations;
Instrument noise – can lead to noisy retrievals.

Additional information from:
Prior, x_a – extinction coefficient zero, assume no cloud;
Prior covariance, B^{-1} – uncertainty on prior
Smoothness constraint, T – assume a smooth profile, use Twomey-Tikhonov constraint.



$$\text{Minimise cost function: } J[x] = \frac{1}{2} (y - F[x])^T R^{-1} (y - F[x]) + \frac{1}{2} (x - x_a)^T B^{-1} (x - x_a) + \frac{1}{2} x^T T x$$

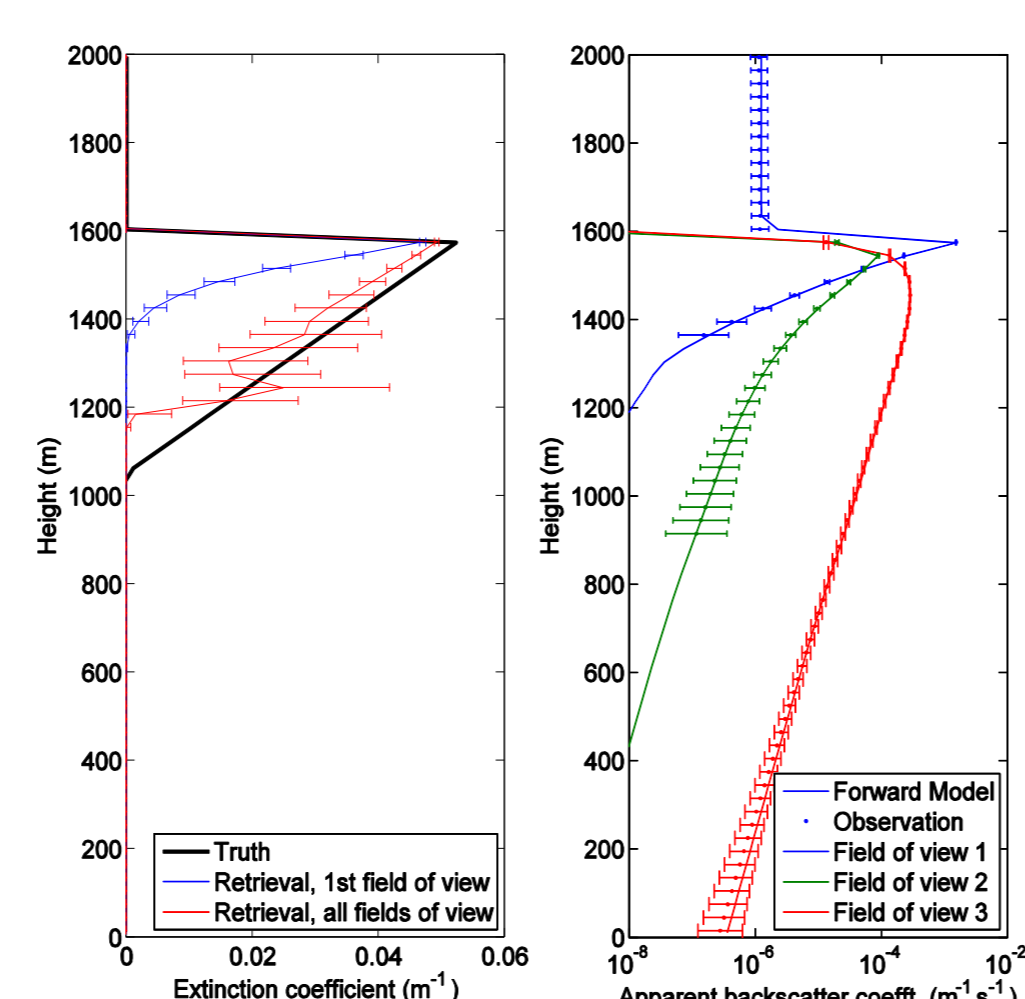
Minimise difference between observations and forward model
Minimise difference between state vector and prior
Minimise second derivative of state vector

4. Idealised cases

Study behaviour of retrieval with a simple, idealised simulation with no instrument noise. Use forward model to simulate observations for a liquid water cloud.

First simple case: triangular extinction profile. Compare:

- retrieval using only narrow field of view
- Retrieval using additional, wider, annular fields of view footprints at cloud top
- 1st (narrow) field of view: 5.4 m
- 2nd field of view: 42.9 m – 5.4 m
- 3rd field of view: 680.8 m – 42.9 m



Left: retrieved extinction profile. Right: observed and forward modelled apparent backscatter coefficient.

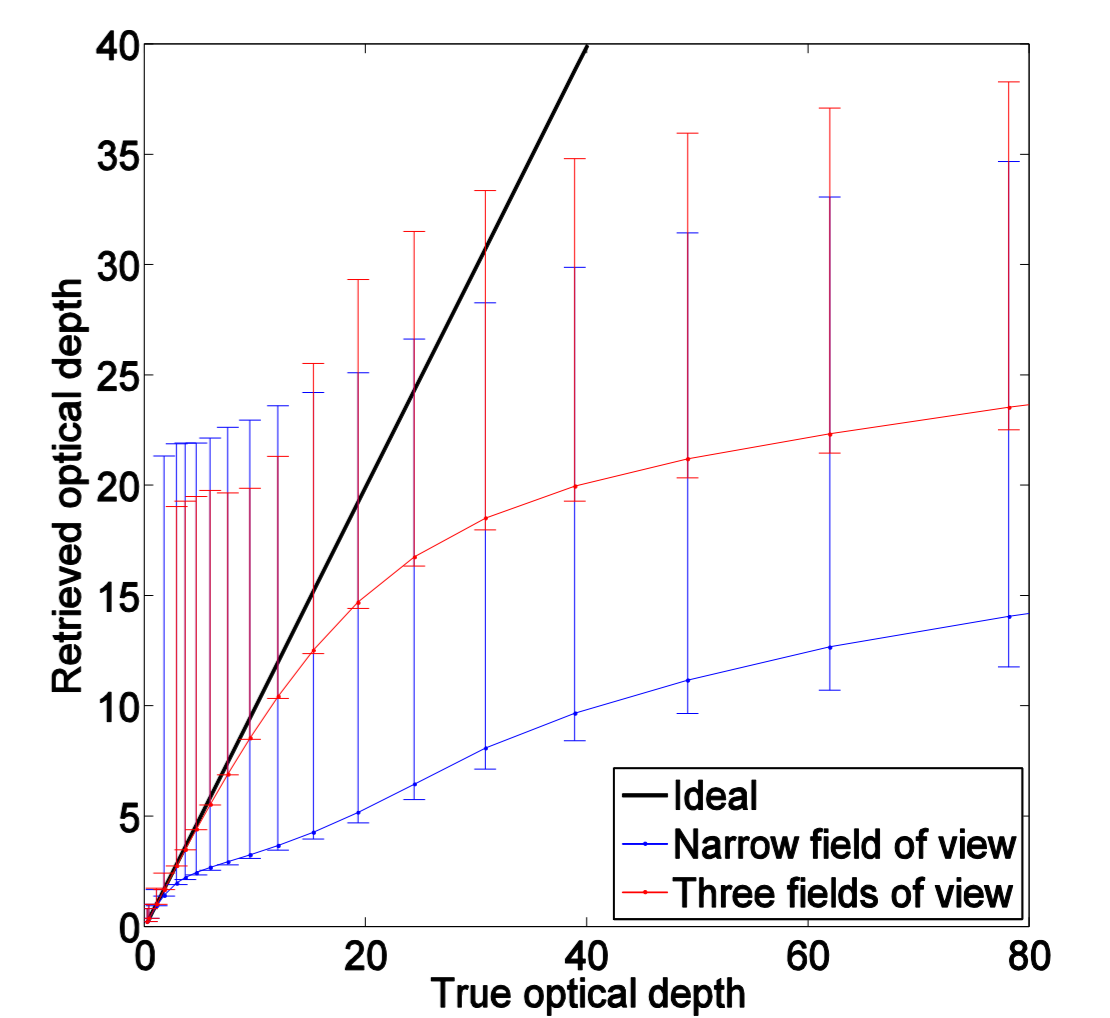
4.1 Retrieving optical depth

Perform retrieval of triangular extinction coefficient profile for a range of optical depths:

- Using only one narrow field of view;
- Using three fields of view.

Up to an optical depth of 9, optical depth is retrieved with a bias of less than 10% when three fields of view used.

Using only a narrow field of view, optical depth is retrieved up to 0.5 optical depths. Attenuation of the signal leads to uncertainty in the maximum extent of the cloud hence the negative error on the optical depth is smaller than the positive error. The magnitude of the positive error is partly determined by the uncertainty on the prior.

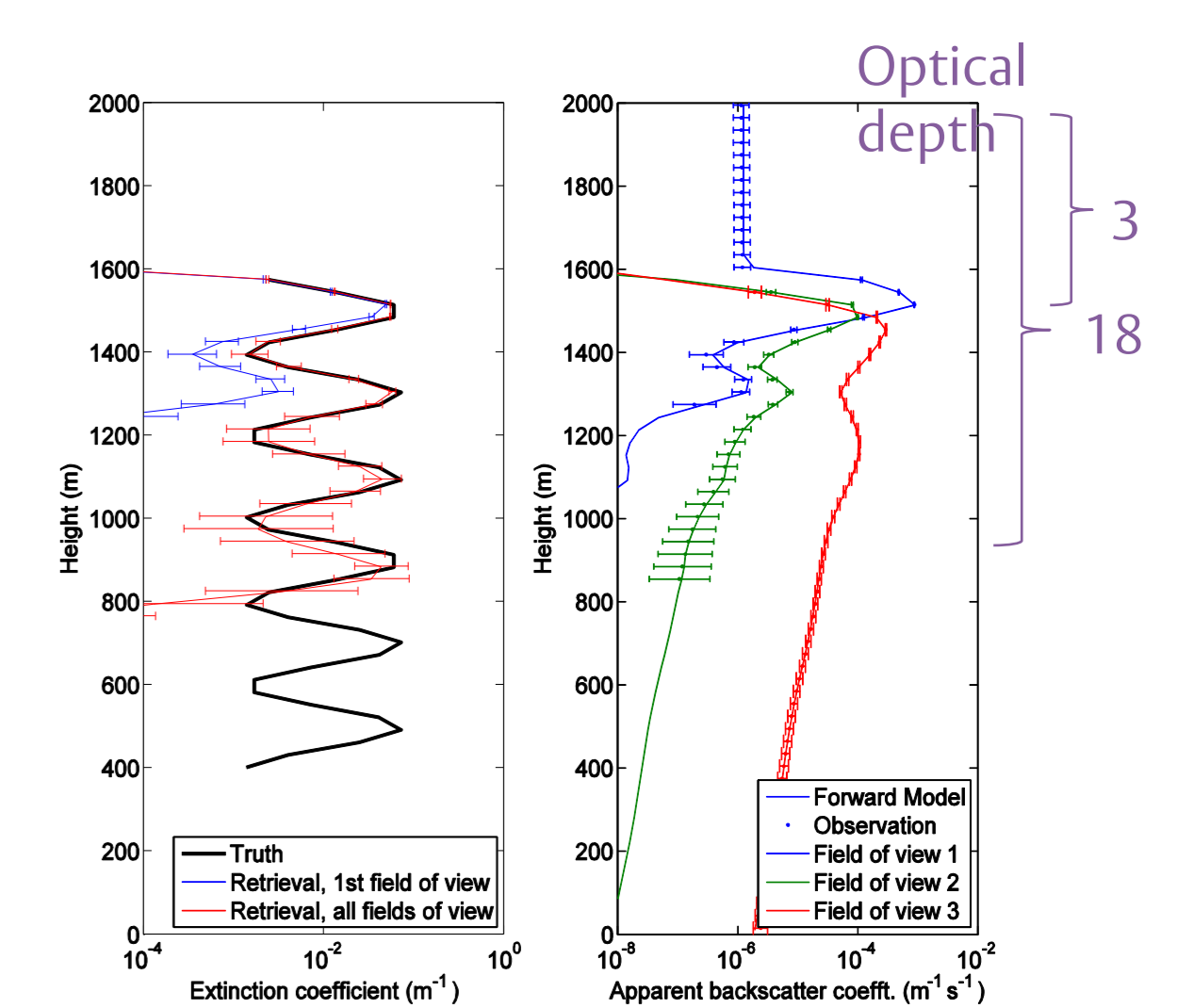


4.2. Observing structure

How does the retrieval perform for a cloud with more, vertical structure? Simulate a liquid water cloud with a sinusoidal extinction profile.

Narrow field of view only: only first peak retrieved, down to an optical depth of 3.

Three fields of view: sensitive to four profile peaks, down to an optical depth of 18.

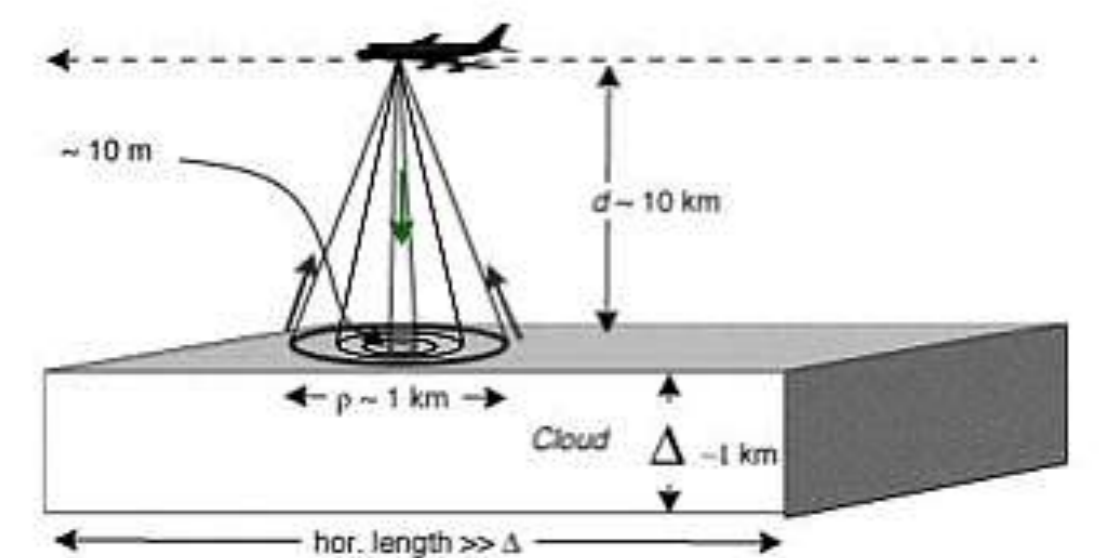


5. How does the method perform on real data?

5.1 The THOR experiment

Thickness From Offbeam Returns

- Airborne, 540 nm lidar.
- Receiver has 7 annular fields of view plus additional, segmented field of view.
- When flown at 10 km:
 - narrowest field of view ~10m footprint at ground;
 - widest field of view ~1km footprint at ground.

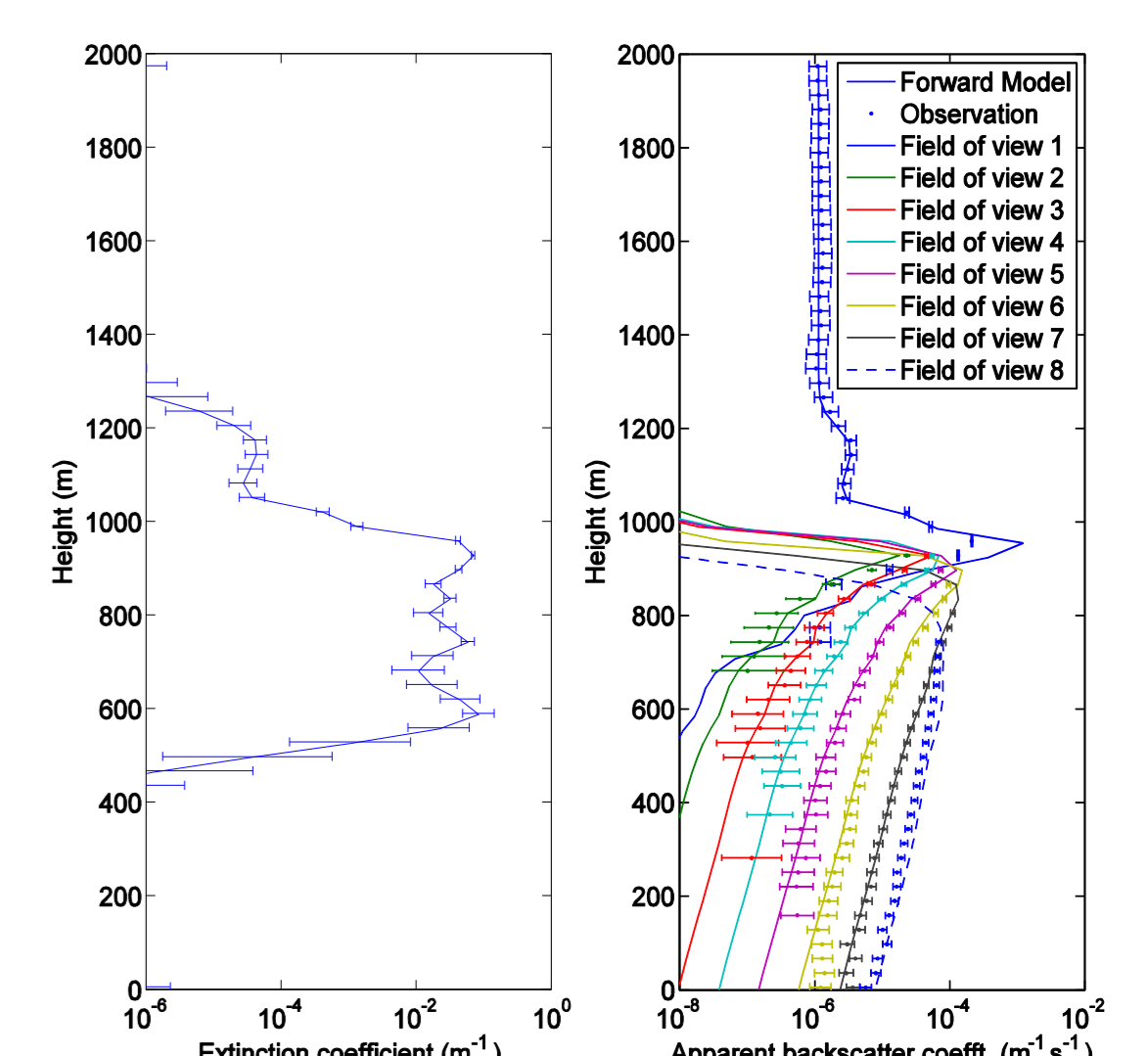


5.2 Retrieval using THOR data

THOR cloud observation of liquid water cloud from March 2002 validation campaign over Oklahoma.

Eight fields of view are forward modelled (right) to retrieve a profile of extinction coefficient (left).

An optical depth of 15.5 ± 1.2 is retrieved.



6. Conclusions

For the first time, a variational retrieval scheme including a description of multiple scattering has been applied to observations from lidar specially equipped with a multiple field of view receiver. Not only can the retrieval deal with the problematic effects of multiple scattering but additional information about optical depth and vertical cloud structure is available by including wide fields of view. This has applications to both spaceborne lidar and radar.

Further work will consider alternative prior and smoothness constraints as well as developing the retrieval for ice clouds and aerosol.

References

1. Hogan, R. J., 'Fast lidar and radar multiple-scattering models. Part 1: small-angle scattering using the photon variance-covariance method.', *J. Atmos. Sci.*, 65, pp. 3621-3635 (2008)
2. Hogan, R. J., Battaglia, A., 'Fast lidar and radar multiple-scattering models. Part 2: wide-angle scattering using the time dependent two-stream approximation.', *J. Atmos. Sci.*, 65, pp. 3636-3651 (2008)
3. Cahalan, R. F., M. McGill, J. Kolasinaski, T. Varnai, and K. Yetzer, 'THOR-Cloud thickness from offbeam lidar returns', *J. Atmos. Oceanic Technol.*, 22, pp. 605-627 (2005)