Using Occultation Data in Operational Meteorology

Specific Requirements, Review, Prospects

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Focus

Occultation Data

- GPS - LEO radio occultations
- (LEO - LEO radio occultations)
- (Stellar and solar occultations)

Operational Meteorology

- Weather forecasting: assimilation of occultation data
- (Verification)
- (Climate Monitoring, Reanalyses)

Contents

Requirements

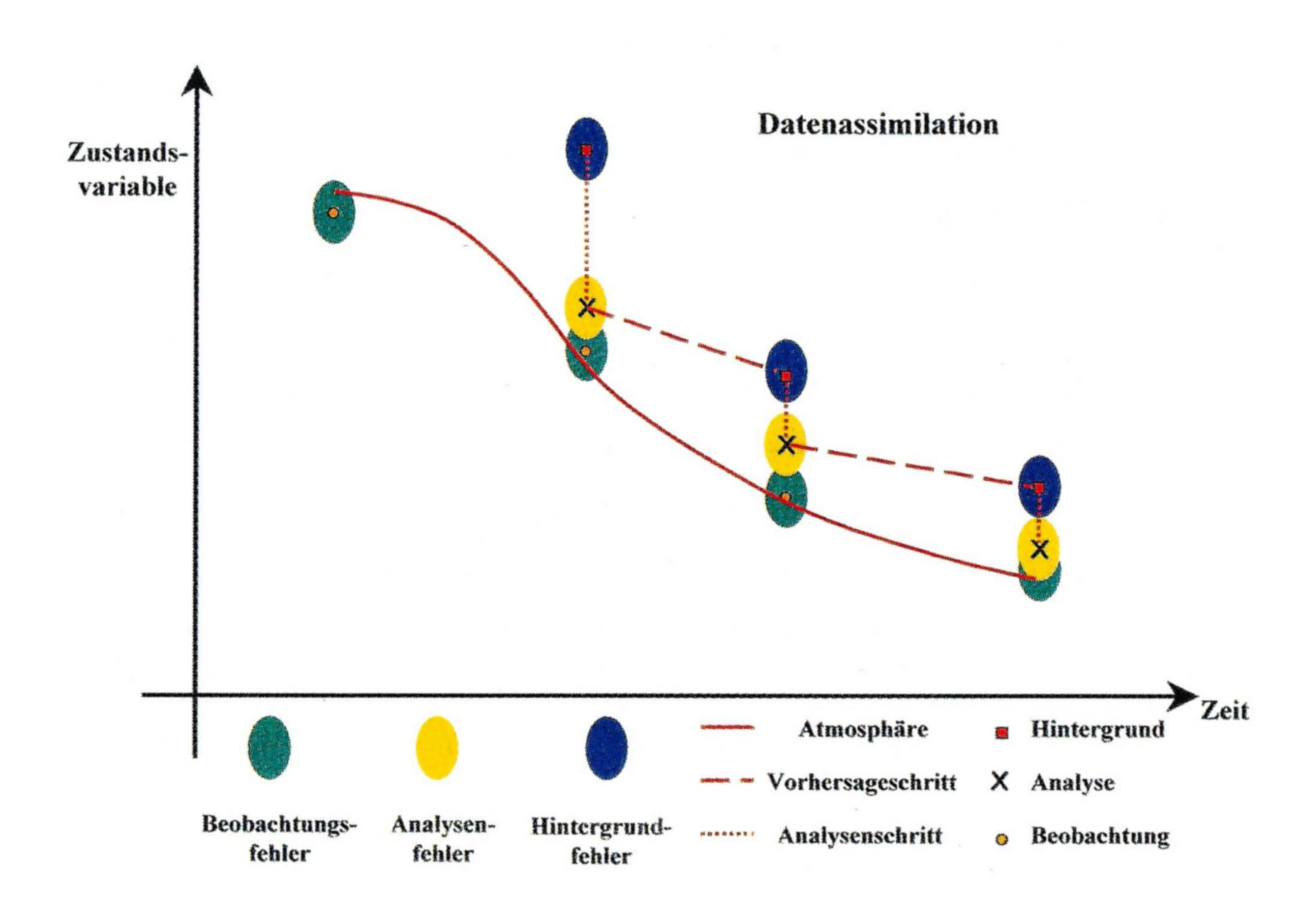
- The Data Assimilation Paradigm
- Operational Systems
- GPS Occultation Data
  - ▷ *Requirements on the Data Assimilation System*
  - ▷ *Requirements on the GPS Occultation Data (Processing)*

Review

- Observation operator (Abel inversion, Ray-tracer, ...)
  - ▷ *A Priori Error Estimates*
- Statistics
  - ▷ *A Posteriori Error Estimates*
- OSSE Studies, Data Assimilation Experiments

Prospect

The Data Assimilation Paradigm



[Wergen (2002)]

Variational Data Assimilation

Minimize the Cost Function (3DVAR)

$$J(\mathbf{x}) = \frac{1}{2}\left((\mathbf{x}-\mathbf{x}_b)\mathbf{P}_b^{-1}(\mathbf{x}-\mathbf{x}_b) + (H(\mathbf{x})-\mathbf{o})(\mathbf{F}+\mathbf{O})^{-1}(H(\mathbf{x})-\mathbf{o})\right)$$

$\mathbf{x}$	Atmospheric State Vector
$\mathbf{x}_b$	Background state (Forecast)
$\mathbf{o}$	Observation Vector
H	Observation Operator (nonlinear)
$\mathbf{P}_b$	Forecast Error Covariance Matrix
$\mathbf{O}$	Observation Error Covariance Matrix
$\mathbf{F}$	Representativeness Error

Variational Data Assimilation
Background

$$J(\mathbf{x}) = \frac{1}{2}\Big((\mathbf{x}-\mathbf{x}_b)\mathbf{P}_b^{-1}(\mathbf{x}-\mathbf{x}_b) + (H(\mathbf{x})-\mathbf{o})(\mathbf{F}+\mathbf{O})^{-1}(H(\mathbf{x})-\mathbf{o})\Big)$$

$\mathbf{x}$ **Atmospheric State Vector**
Prognostic variables on the model grid
(Temperature, Humidity, Wind Components, . . .)

$\mathbf{x}_b$ **Background state**
Forecast from the previous analysis

$\mathbf{P}_b$ **Forecast Error Covariance Matrix**
Errors of the forecast
Correlations between variables
Spacial Correlations

- size of $\mathbf{x}$: $n \approx 10^7 \dots 10^8$
- size of $\mathbf{P}_b : n^2 \approx 10^{15}$

Variational Data Assimilation
Background Error Covariances

Background covariances $\mathbf{P}_b$ account for:

- Smoothing if the observation increments (spatial correlations)
- Balance conditions (geostrophic balance)
- In addition, gravity waves are removed
  (by penalty term, digital filter, or normal mode initialization)

Operational analysis systems currently do not account for:

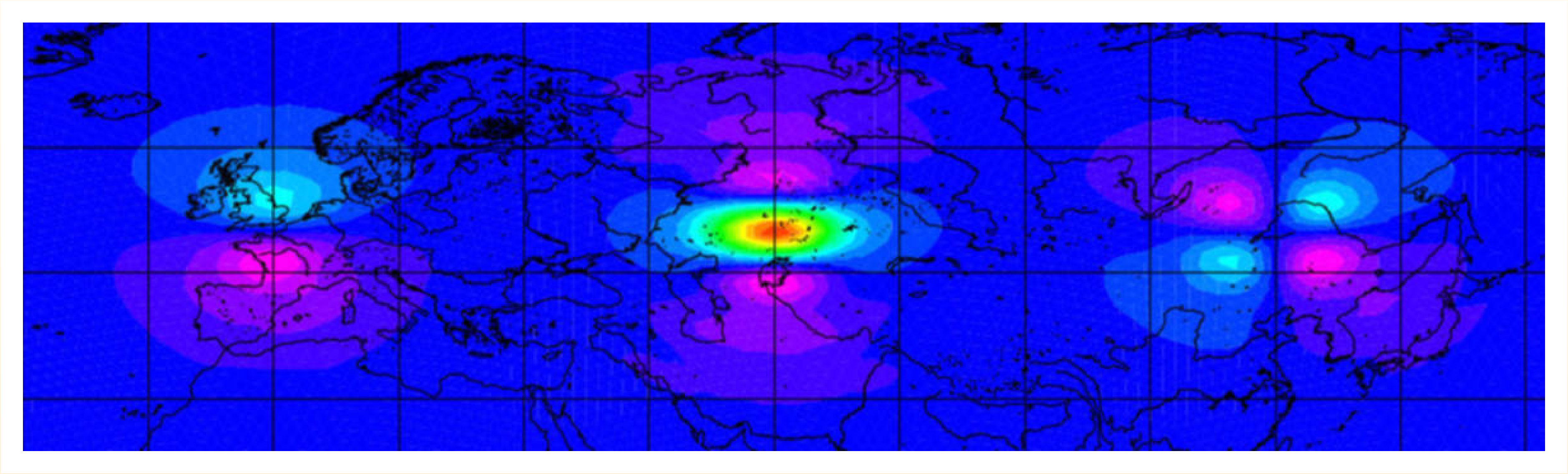
- Flow depended correlations
  (instead they are often horizontally homogeneous and isotropic)

Humidity Correlations:

- Shorter correlation length scales than temperature and wind

- Generally no correlations between humidity and temperature
- Problem: the spin-up effect
  (disturbed balance between humidity field and temperature/wind field)

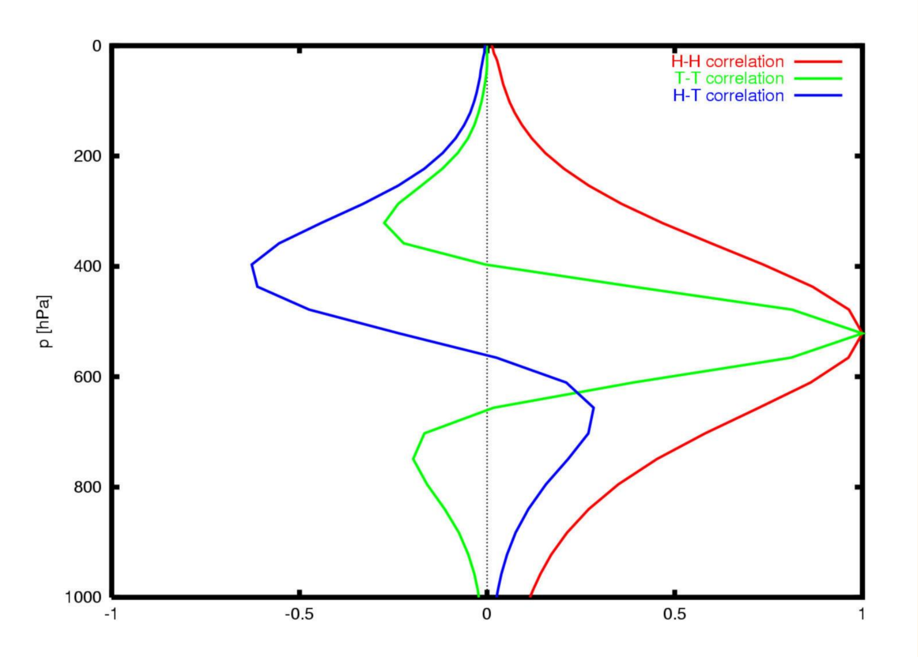
Variational Data Assimilation
Background Error Covariances



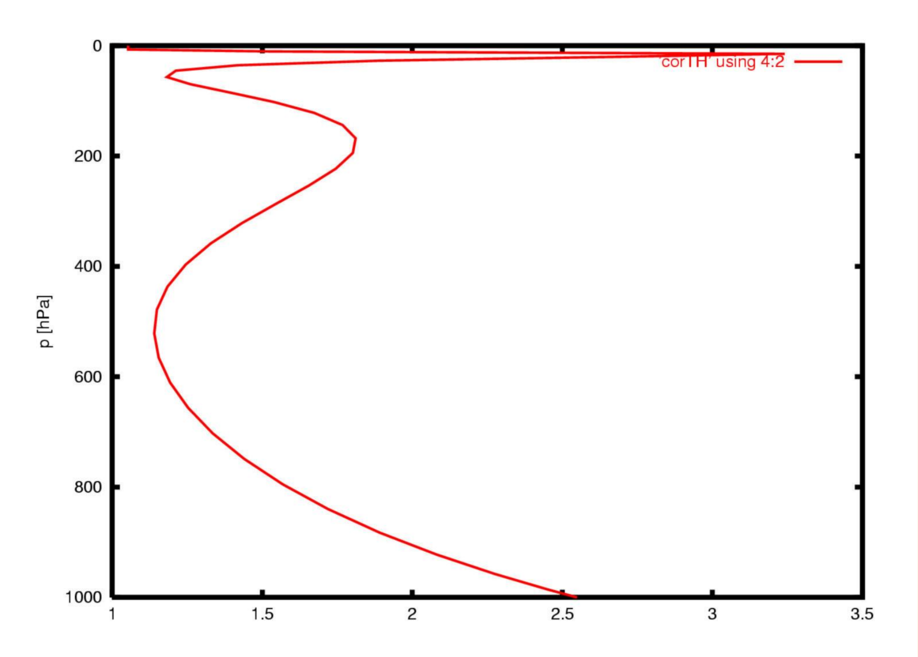
Background error Correlation of the zonal (u) wind field in model layer 15 of the DWD global model GME with single observations in 500 hPa height of temperature T and wind components u, v, respectively

Variational Data Assimilation

Background Error Covariances

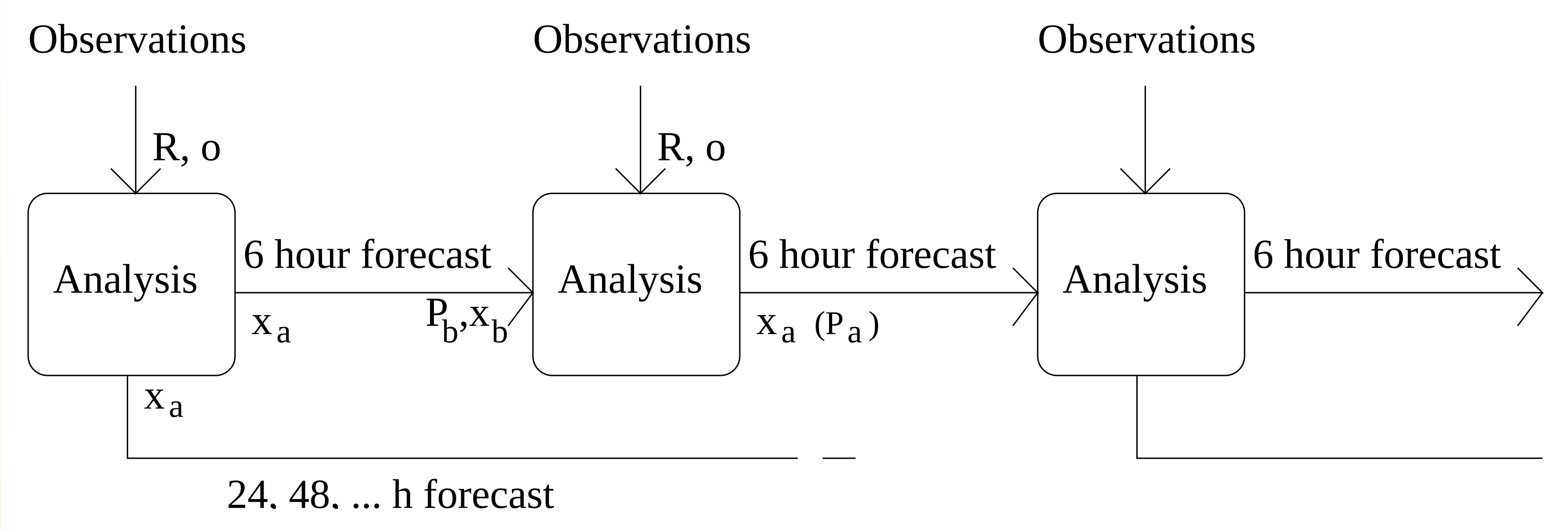


Vertical correlations (height - height), (temperature - temperature), and (height - temperature) as specified in the DWD global model GME.



Temperature Variances.

Operational Systems
Cycled Data Assimilation



Requirements:

- Cutoff time generally : 8 hours
- Cutoff time at 0,12 UTC: 2:30 hours (at DWD)
- Observations must be processed within this time, including:
  - ▷ *Orbit calculations, data processing and dissemination*
  - ▷ *Back-propagation, canonical transform (if applicable)*
  - ▷ *Quality control*
  - ▷ *Processing within DA-system (observation operator)*

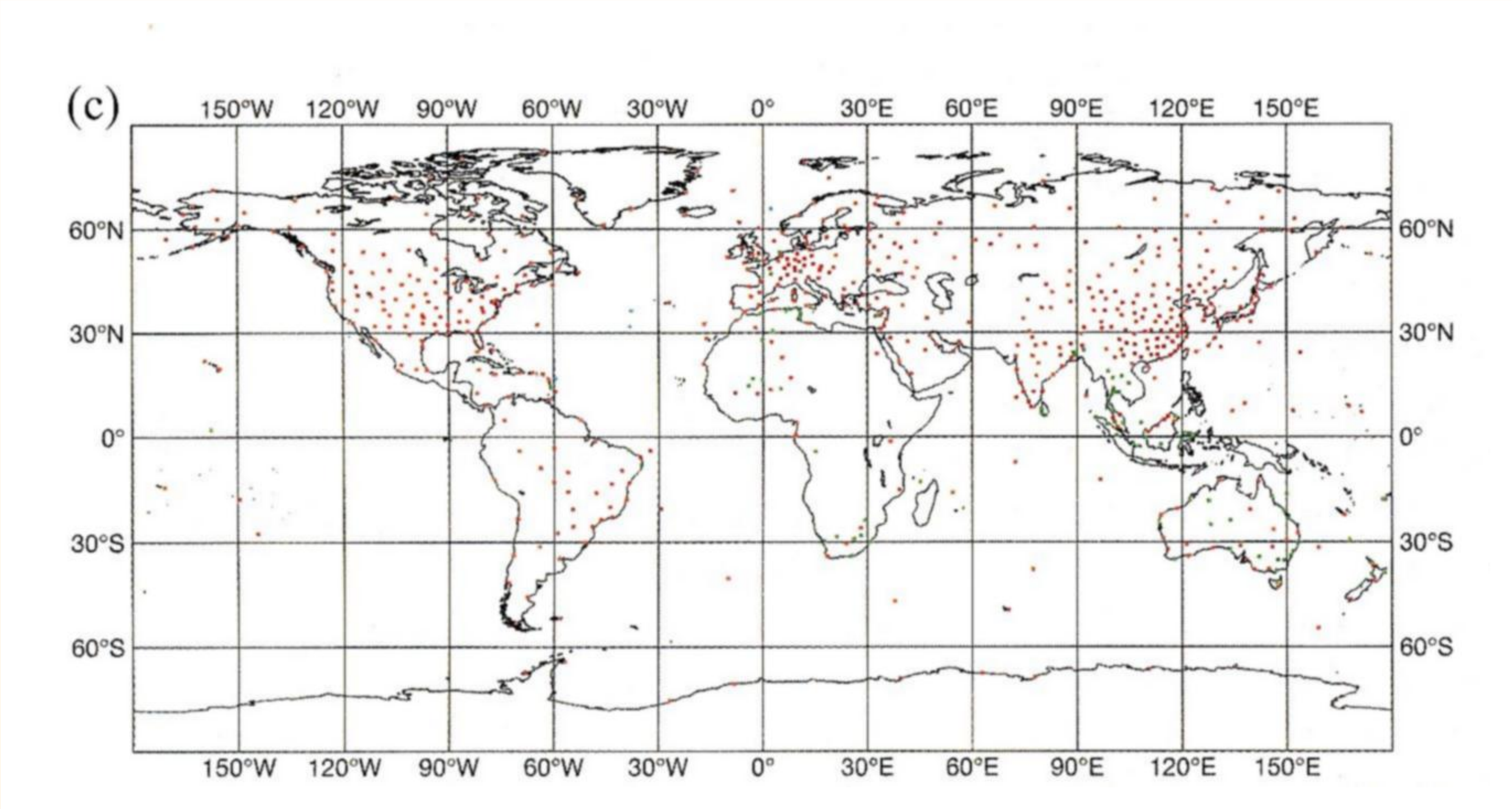
Quality Control

- Blacklisting
  Reject observations from unrelyable stations
- Check for consistency
- Check for differences forecast - observation
- Body Check
- Monitoring

- If possible, bad data should be rejected before entering the assimilation system

Operational Systems

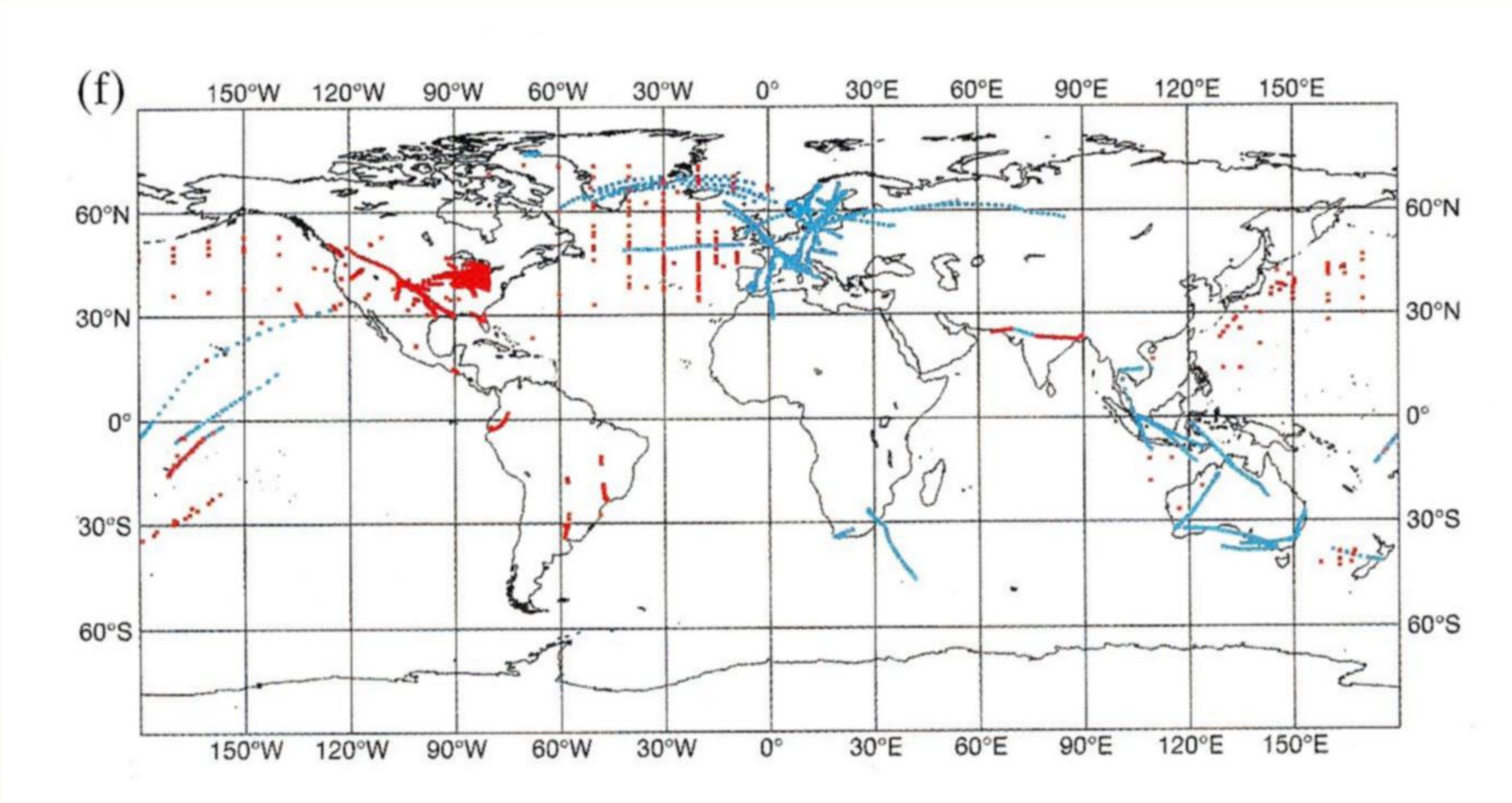
In Situ Data



Radio-soundings (TEMP,PILOT) on 2001-09-06 10:30..13:30UTC [Wergen (2002)]

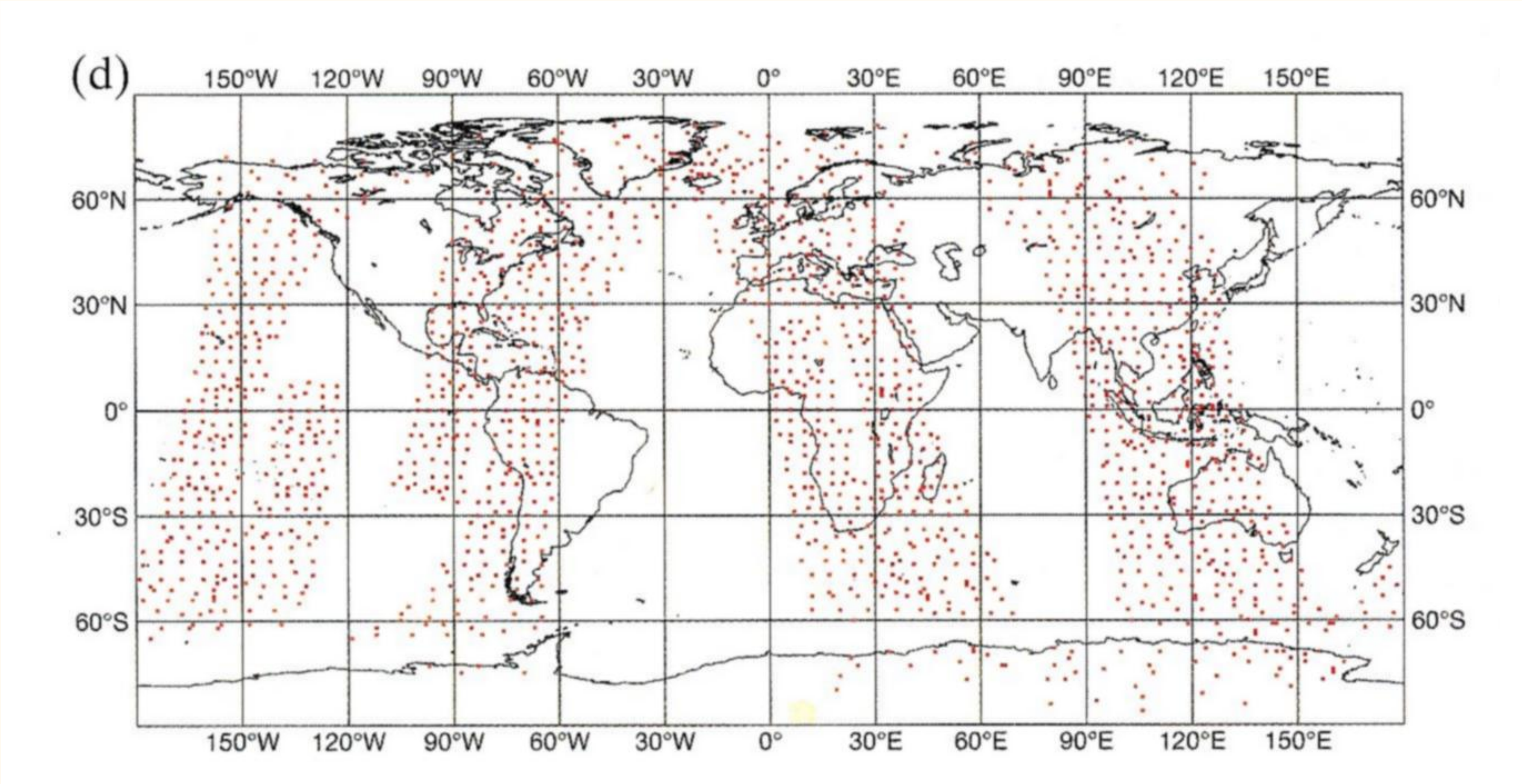
Operational Systems

In Situ Data



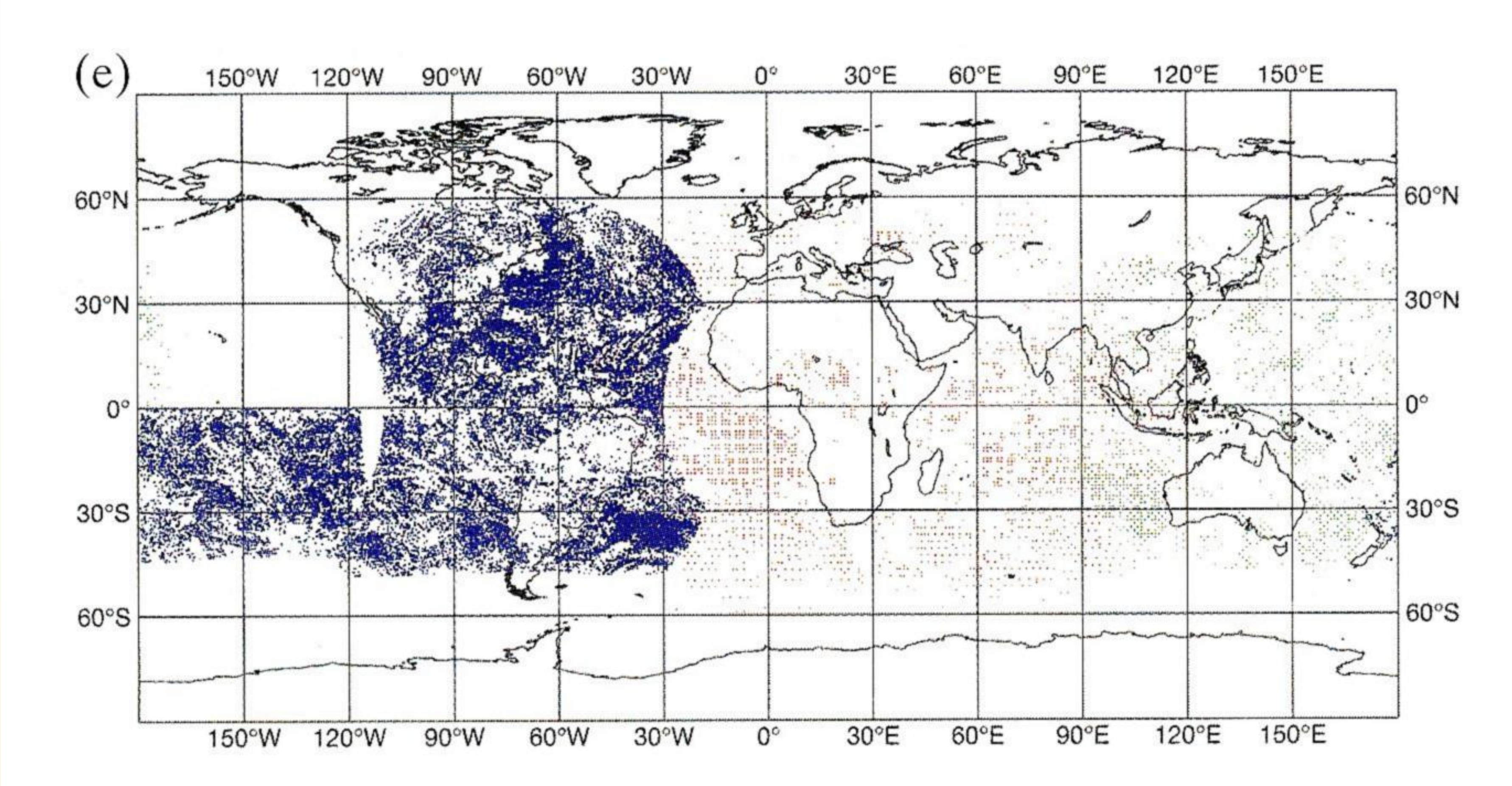
Aircraft Observations (MDAR, AIREP) on 2001-09-06 10:30..13:30UTC [Wergen (2002)]

Operational Systems
Remote Sensing Data



Polar Orbiting Satellite Soundings on 2001-09-06 10:30..13:30UTC [Wergen (2002)]

Operational Systems
Remote Sensing Data



Winds derived from geostationary Satellites on 2001-09-06 10:30..13:30UTC [Wergen (2002)]

Operational Systems
Data Density

Typical number of observations used for an assimilation window of 6 hours:

surface observations	SYNOP	7500	
	DRIBU	300-500	
upper air observations	AIREP	1100-1500	
	TEMP	100-700	*
	PILOT	50-80	
remote sensing data	SATOB	300-2000	
	CHAMP	50	

*The higher numbers of radio soundings refer to 0 and 12 UT, the lower values to 6, 18 UT.

- The density of occultation data should be comparable to TEMP data in order to have impact
- The distribution of occultation data is more homogeneous than that of TEMP data

Operational Systems
Characteristics of data

instrument	resolution (vertical)	sensitive to parameters
sounding	high (if reported)	T and q
radiances	low	T and q and others
GPS occultations	high	T and q (ambiguous)

Requirements:

- ambiguities must be resolved by the data assimilation system
  - ▷ *Background T-q correlations must be realistic*

GPS Occultation Data Availability

Past missions

- GPS/MET
- Oersted

Present missions

- CHAMP
- SAC-C
- GRACE

Future missions

- METOP
- COSMIC
- ACE+

Variational Data Assimilation
Observations

$$J(\mathbf{x}) = \frac{1}{2}\Big((\mathbf{x}-\mathbf{x}_b)\mathbf{P}_b^{-1}(\mathbf{x}-\mathbf{x}_b) + (H(\mathbf{x})-\mathbf{o})(\mathbf{F}+\mathbf{O})^{-1}(H(\mathbf{x})-\mathbf{o})\Big)$$

$\mathbf{o}$ Observations

Original observations are path delays.

Derived observations may be:

- bending angles
- refractivity profiles
- Temperature/Humidity profiles

H Observation operator

Derives the model equivalent to $\mathbf{o}$ from the model state $\mathbf{x}$

May be:

- Refractivity (T, q)
- Forward Abel integration
- Ray Tracer

$\mathbf{F}$ Forward modeling error of H

$\mathbf{O}$ Observational error

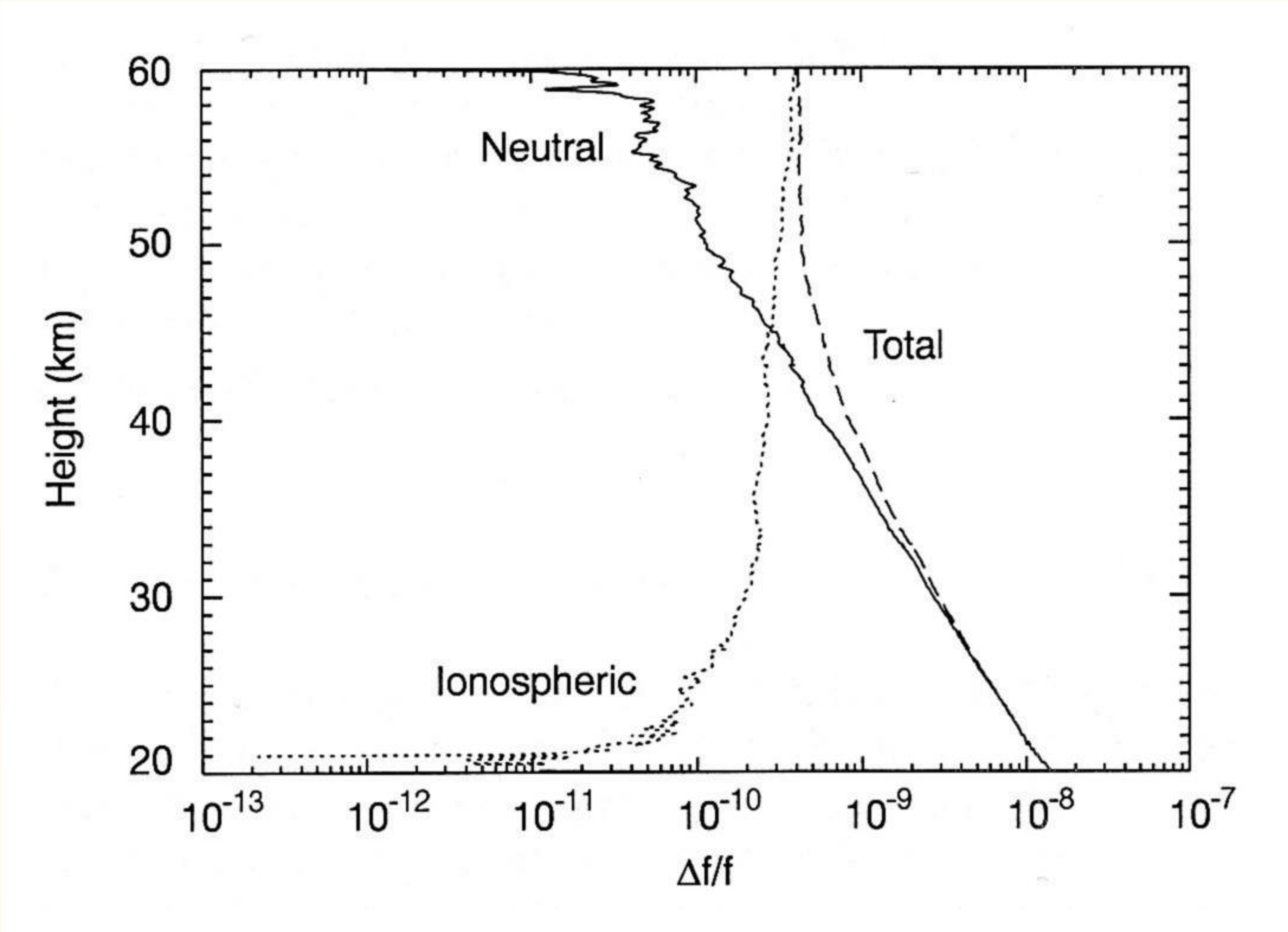
Observations o

- Raw data
  - ▷ *Path Delay*
- Differentiation
  - ▷ *Bending Angle*
- Back-propagation
- Canonical Transform
  - ▷ *Bending Angle*
- Abel Inversion (statistical optimization required)
  - ▷ *Refractivity Profile*
- 1DVAR
  - ▷ *Temperature and Humidity Profiles*

Observation Operators H

- *Bending Angle*
  - *Ray Tracer*
- *Refractivity Profile*
  - $N(t, q)$
- *Temperature and Humidity Profiles*
  - *Interpolation*

Observation Error Estimation
Ionospheric Correction



Doppler shift as function of height [Hocke(1997),AG]

Observation Error Estimation
Ionospheric Correction

Ionospheric Correction:

- Linear correction of phase delays:

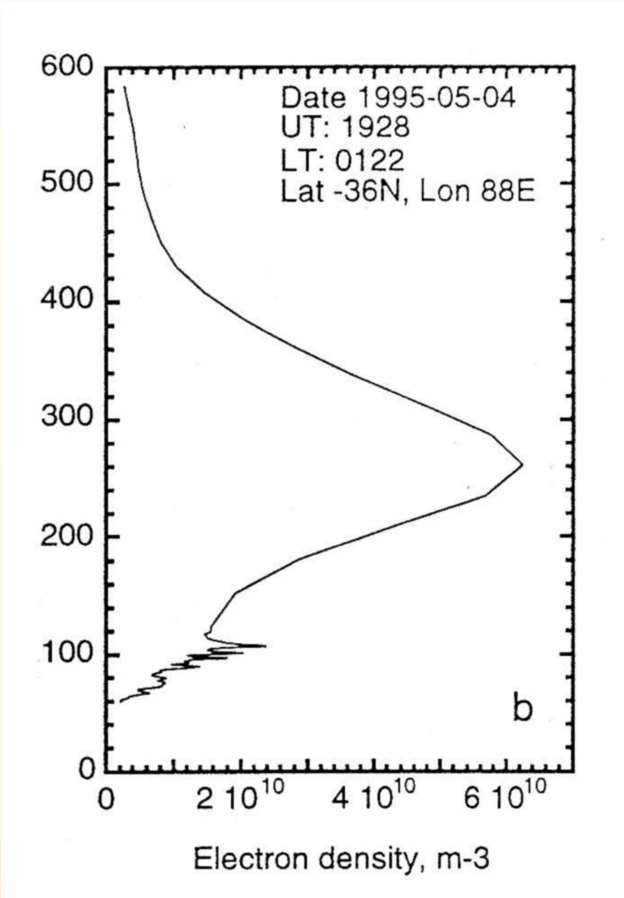
$$L_c(t) = \frac{f_1^2 L_1(t) - f_2^2 L_2(t)}{f_1^2 - f_2^2}$$

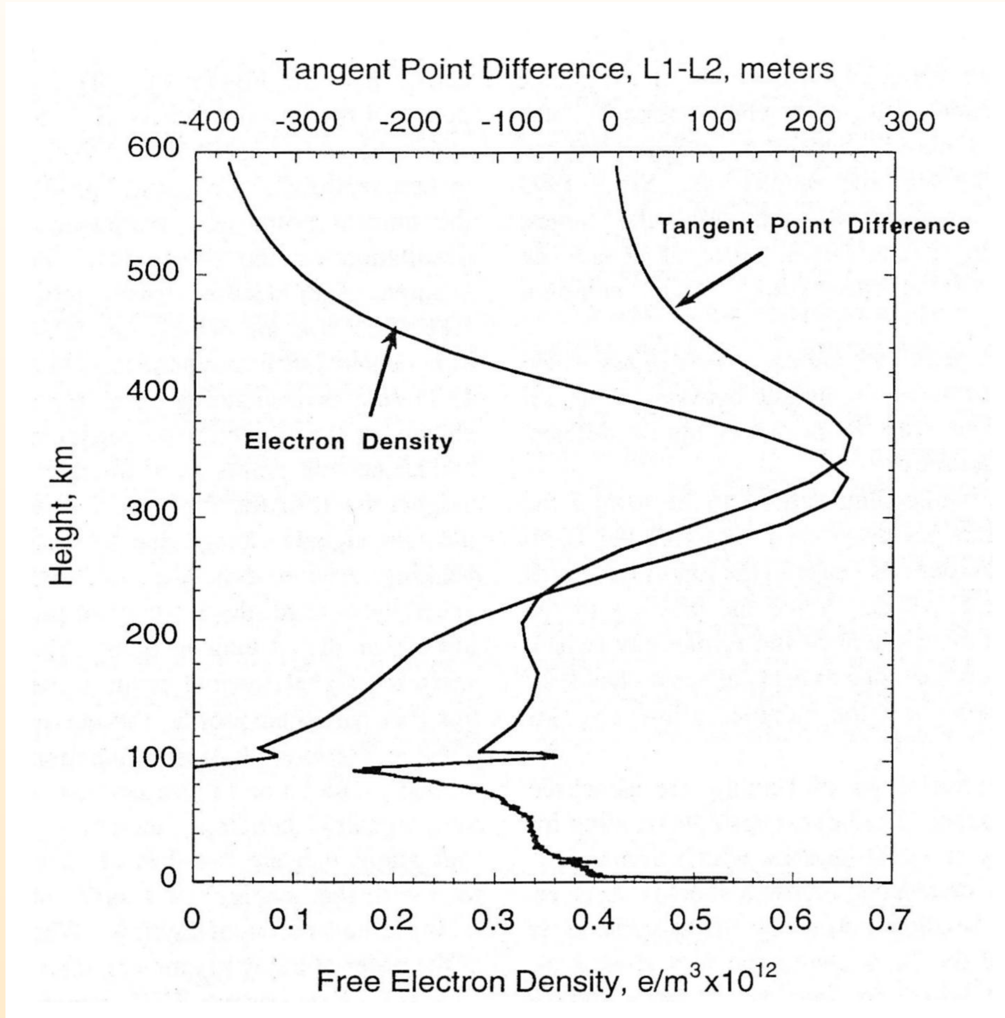
- Linear correction of bending angles:

$$\alpha(a) = \frac{f_1^2 \alpha_1(a) - f_2^2 \alpha_2(a)}{f_1^2 - f_2^2}$$

The latter procedure better accounts for the separation of L_1 and L_2 paths. The residual remains as error source for the neutral atmosphere retrieval.

Observation Error Estimation
Ionospheric Correction





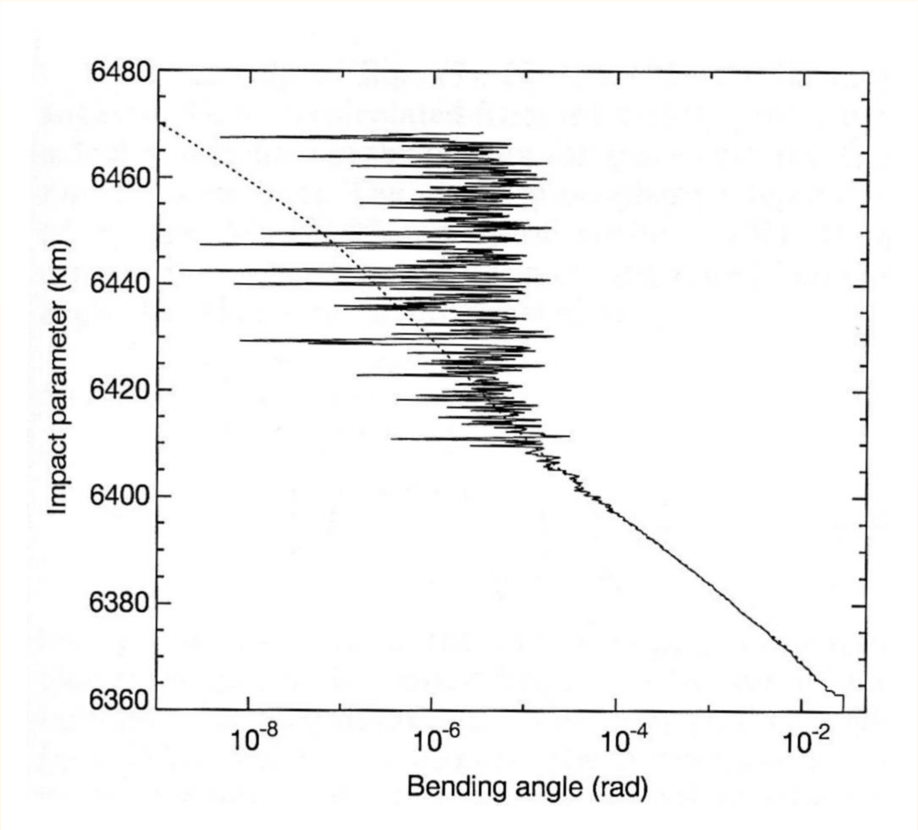
[Hajj+Romans(1998),RS]

Observation Error Estimation
Statistical Optimization

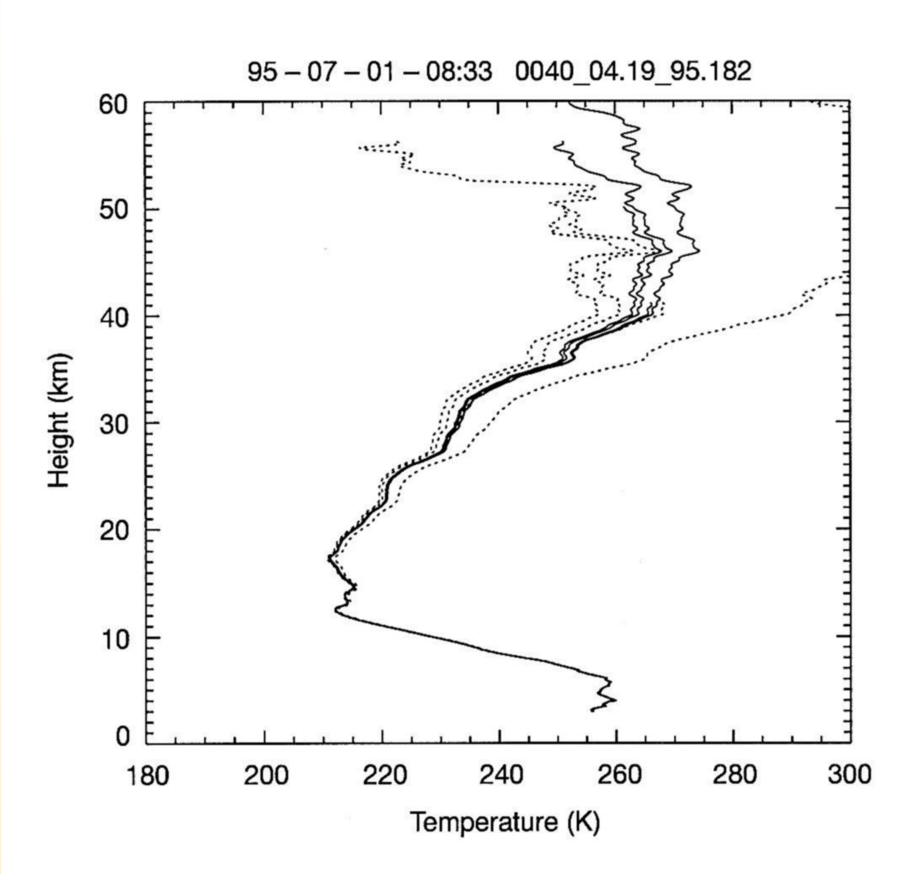
At heights beyond 50 km the relative error of the measured bending angle is $> 100\%$.

- In order to evaluate the Abelian inversion integral, bending angles derived from a statistical model of the neutral atmosphere must be used.
- The same applies if a ray tracer is used as the observation operator
- The transition from measured to climatological bending angles may be based on the statistics of the deviations between climatology and observations.
- Application of this Statistical Optimization basically introduces a bias.

Observation Error Estimation
Statistical Optimization

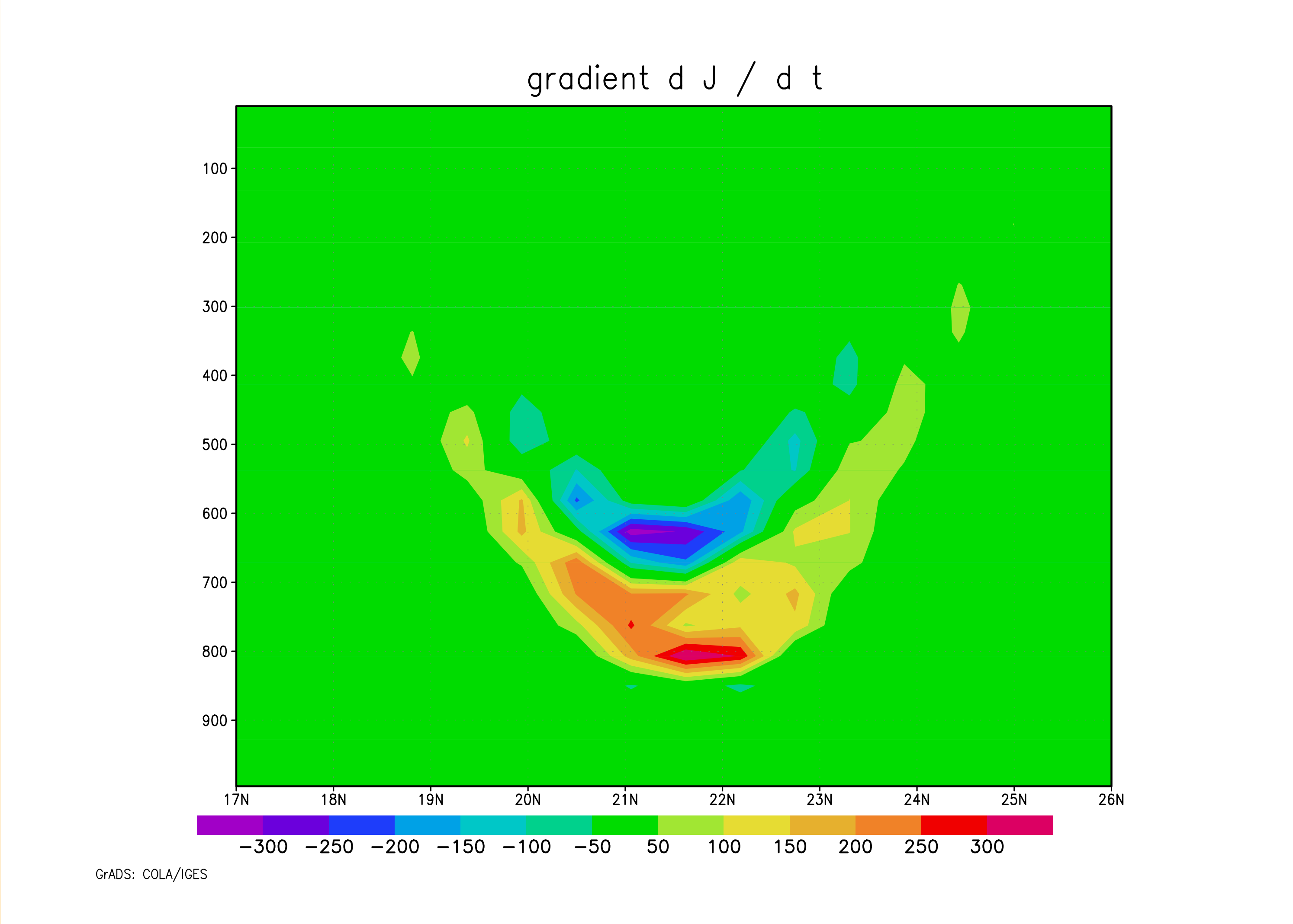


Bending angle of the neutral atmosphere, from GPS/MET (solid line) and from a climatological model (dotted line) [Hocke(1997),AG]



Effect of different initialization heights of the Abelian integral inversion on the temperature profile, with (solid lines) and without (dotted lines) statistical optimization.

Observation Error Analysis
Horizontal Gradients



Gradient of the cost function with respect to the atmospheric temperature for a ray-tracer observation operator

Observation Error Analysis
Horizontal Gradients

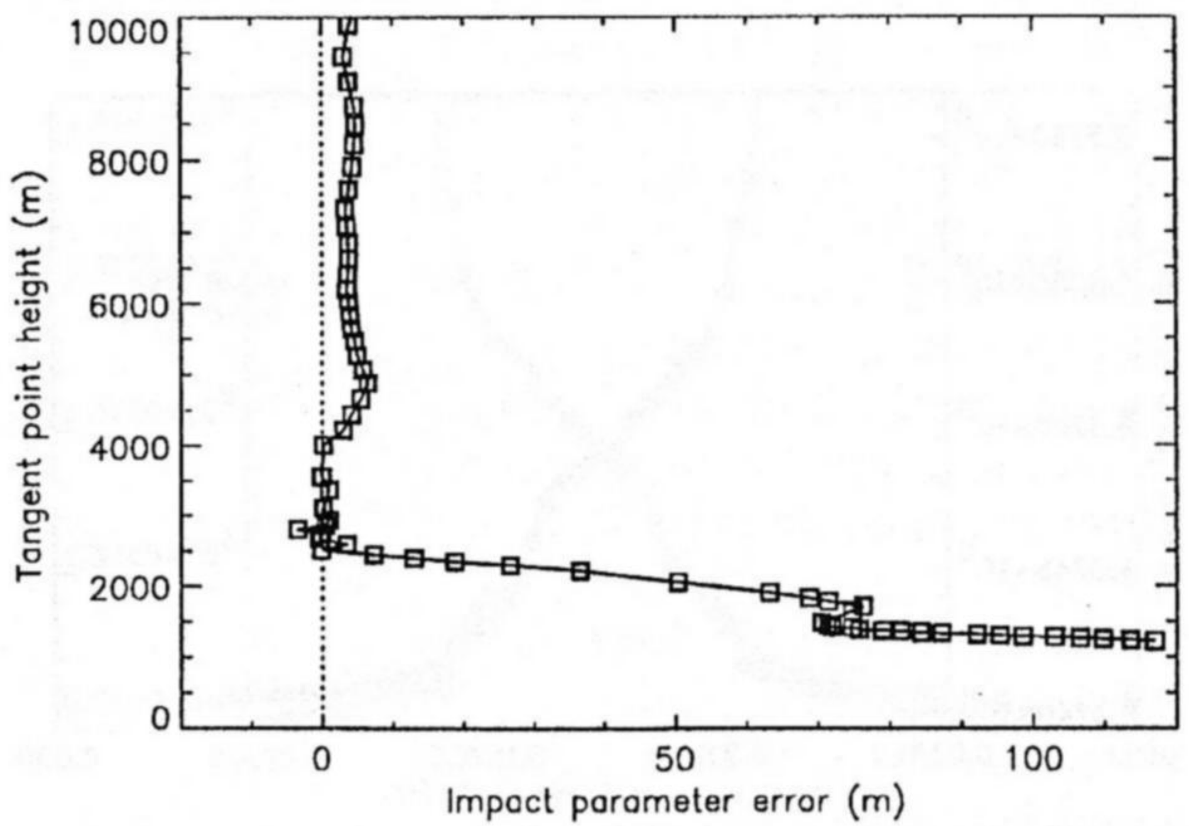


Figure 5. The error in the derived impact parameter value as a result of along-track gradients.

Ray tracer in mesoscale model forecast,
12km by 12 km grid

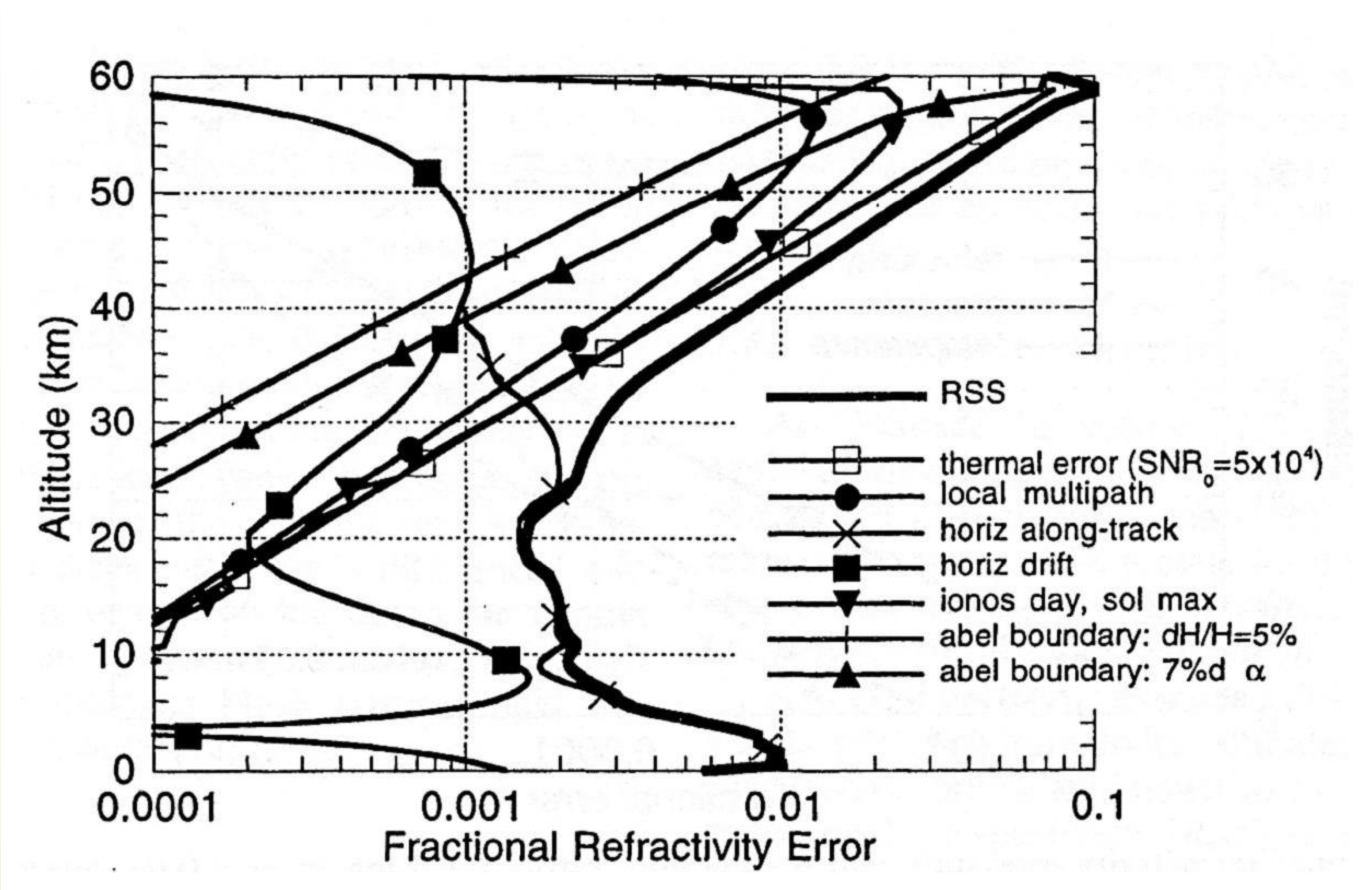
impact parameter error up to 100m

effective bending angle error of 10%

typically 3% error near the surface

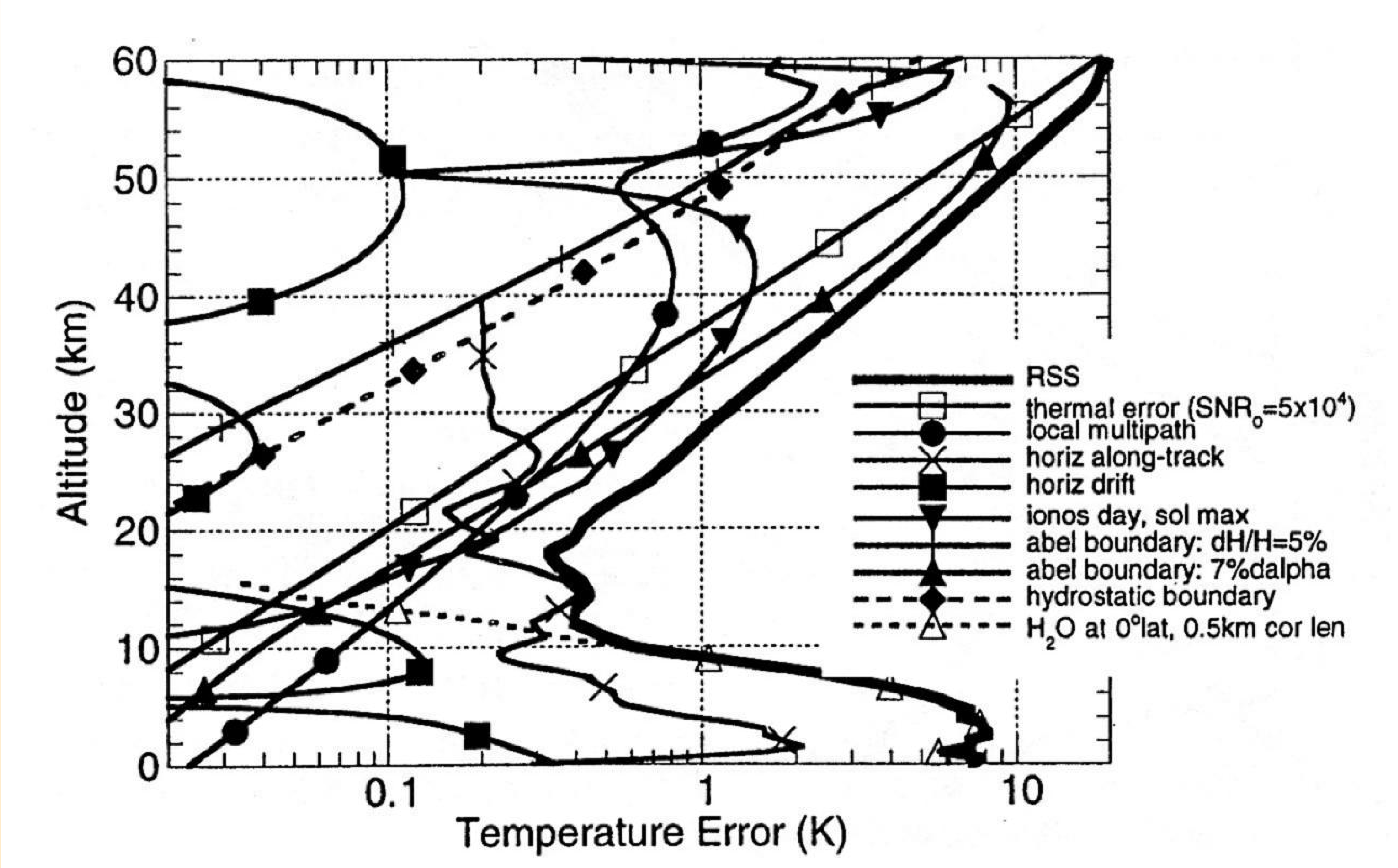
[Healy(2001),JGR-A]

Observation Error Estimation



Kursinski+al(1997),JGR-A

Observation Error Estimation



Kursinski+al(1997),JGR-A

1-Dimensional Variational Retrieval
Rationale

$$J(\mathbf{x}) = \frac{1}{2}\Big((\mathbf{x}-\mathbf{x}_b)\mathbf{P}_b^{-1}(\mathbf{x}-\mathbf{x}_b) + (H(\mathbf{x})-\mathbf{o})(\mathbf{F}+\mathbf{O})^{-1}(H(\mathbf{x})-\mathbf{o})\Big)$$

Approach:

- Perform analysis for 1 occultation
- Account for estimated observational errors
- Account for assumed background errors

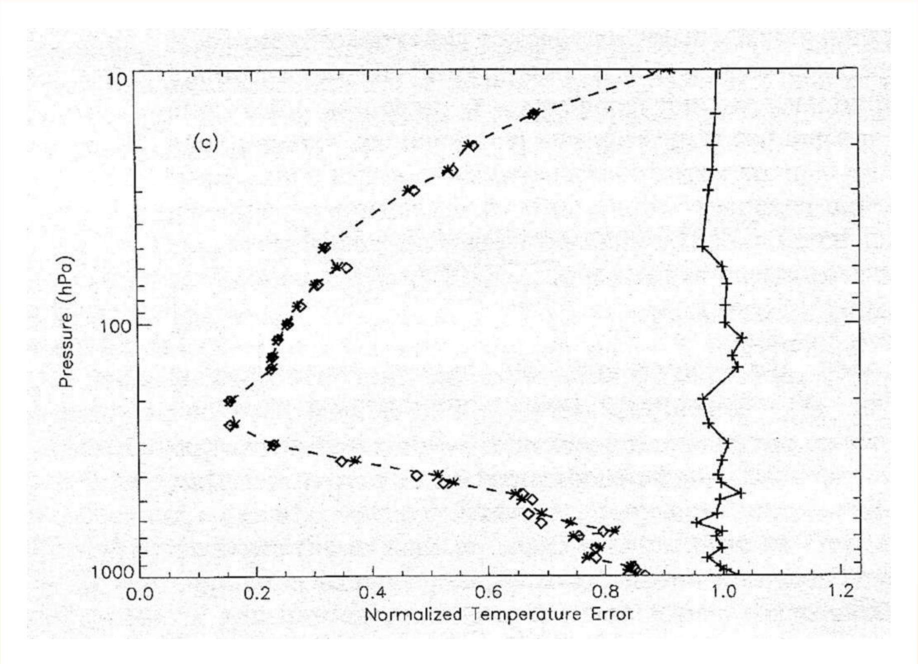
Study:

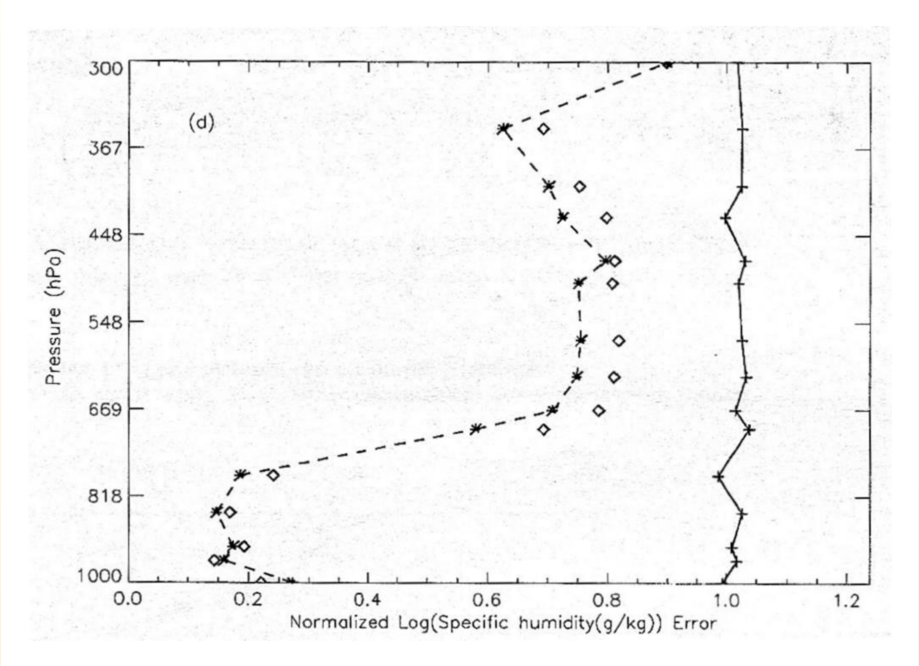
- Information content of the data
- Solution of the 'water vapor ambiguity'

Application:

- Derive T, q profiles

1-Dimensional Variational Retrieval





Normalized retrieved temperature and humidity errors for a tropical profile [Healy+Eyre(2000),QJRMS] (double twin experiment)

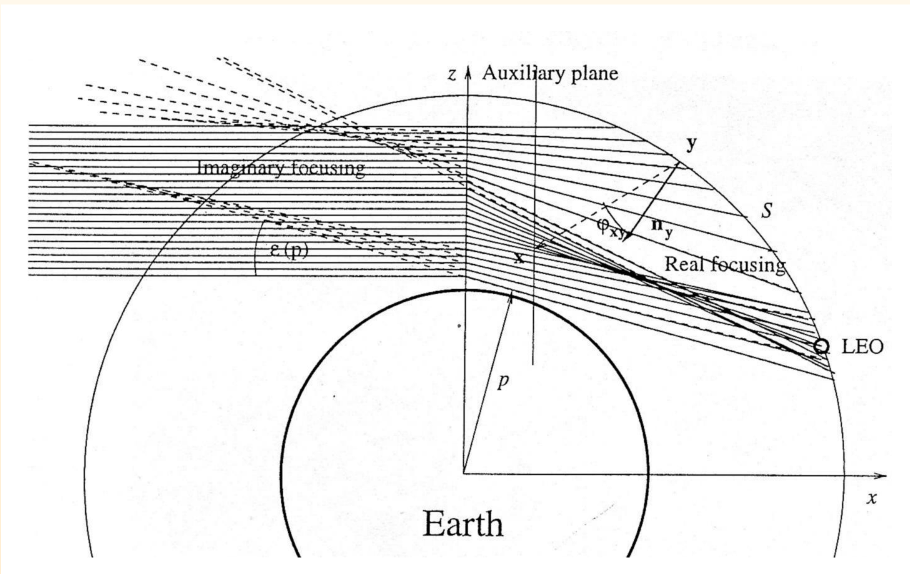
Observation Error Estimation

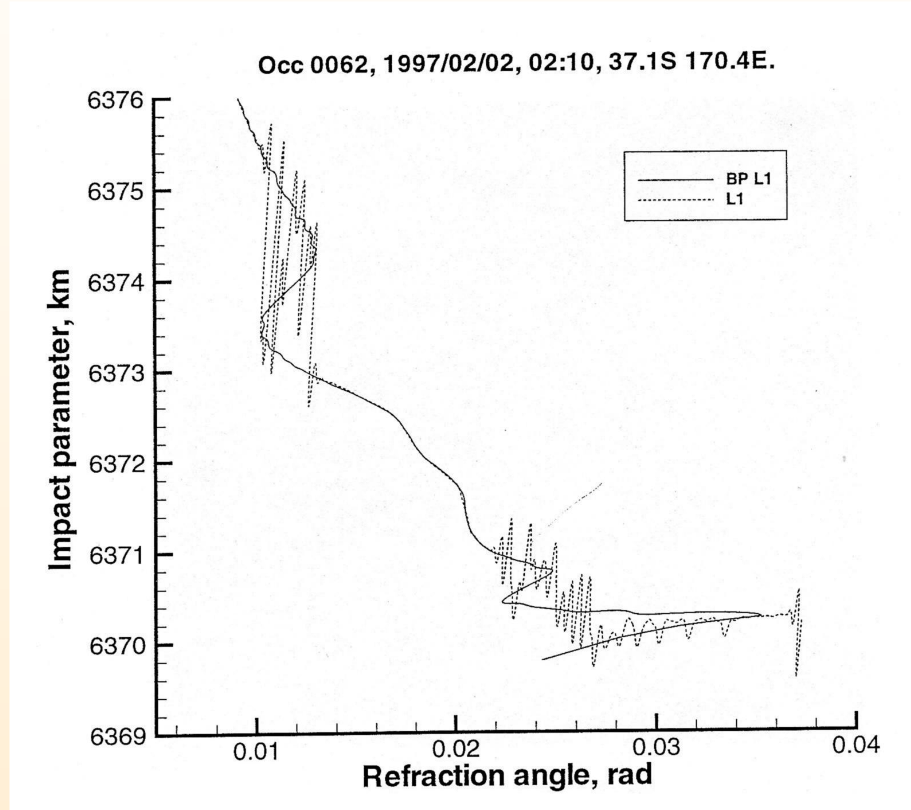
Multi-path

Bending angles and Doppler phase shifts are uniquely related to each other only if rays are reaching from the receiver from exactly one direction.

- This prerequisite is not fulfilled under multi-path conditions.
- Multi-path conditions occur in areas of strong refractivity gradients, mainly stemming from humid layers in the lower troposphere.
- In order to overcome multi-path problems the back-propagation method is applied.
- Back-propagation also allows to achieve a higher vertical resolution, with $\bigtriangledown z$ smaller than the Fresnel radius.

Back-propagation



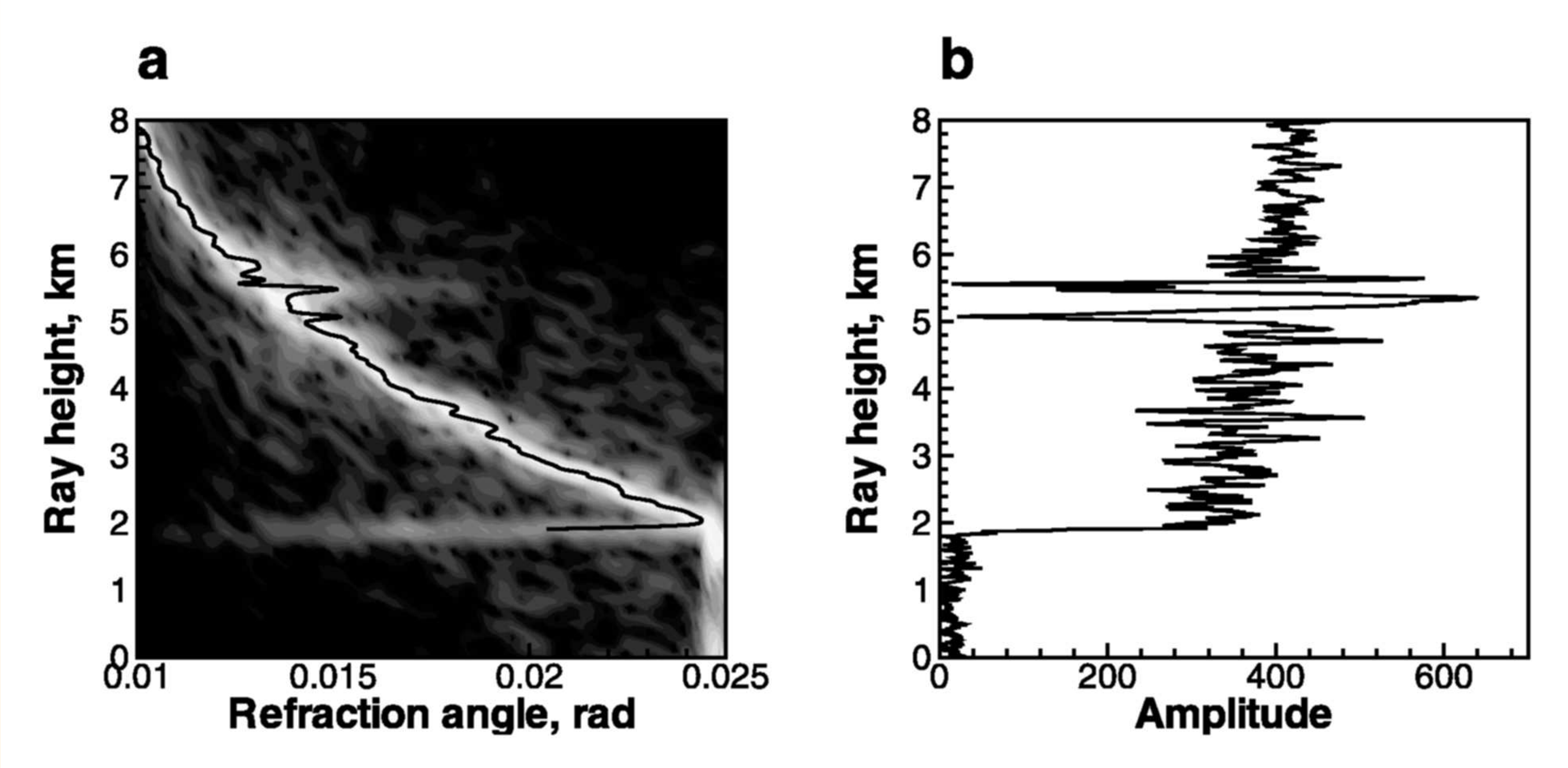


Multi-path propagation geometry, Refraction angle computed from L1 artificial phase with and without back-propagation [Gorbunov(2000),RS]

Canonical Transform

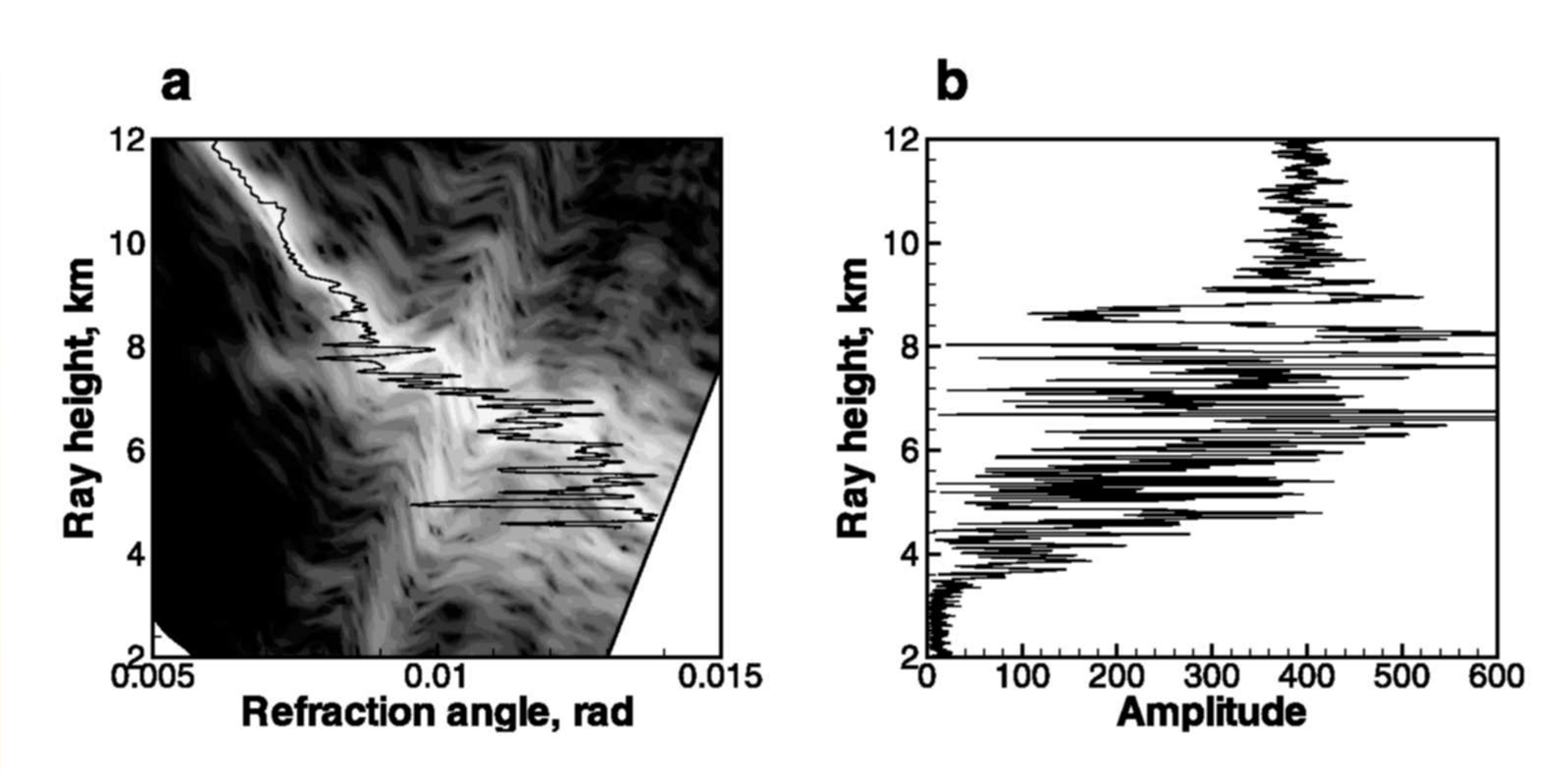
- Back-propagation does not necessarily lead to a unique relationship $\alpha(a)$.
- This is achieved by the Canonical Transform method.
- Both Back-propagation and Canonical Transform method rely on the fact that observation can be interpreted as Amplitude and phase.
- Rigorous assessment of the errors of the methods is difficult.
- Back-propagation and Radio-Optics Method allow a (subjective) assessment of data quality.

Assessment of data quality



(a) Local spacial spectra and refraction angle and (b) CT amplitude of a good data set reaching the ground [Gorbunov(2002),JGR]

Assessment of data quality



(a) Local spacial spectra and refraction angle and (b) CT amplitude of a bad data set [Gorbunov(2002),JGR]

A Posterior Error Estimation
Statistical Comparisons

2 ROCKEN ET AL.: ANALYSIS AND VALIDATION OF GPS/MET DATA

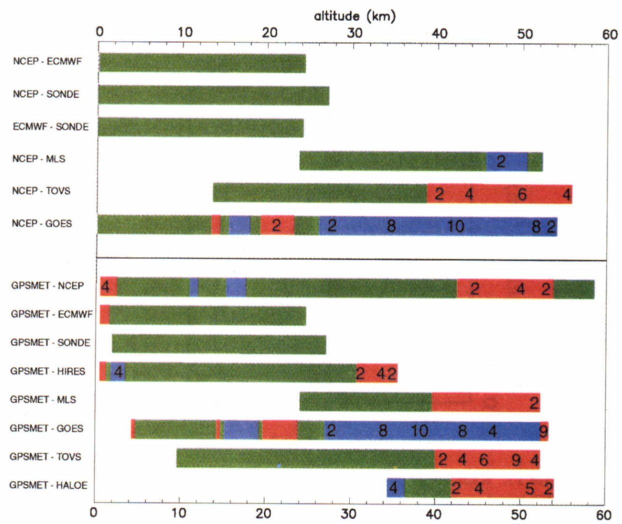


Plate 20. Summary of temperature comparison statistics. The upper six bars compare correlative temperatures, and the lower eight bars compare GPS/MET dry temperature to correlative dry temperatures. The data sources compared are labeled on the left. Colored bars indicate altitude intervals of the comparisons. Regions where average temperatures agree within ±1°C are indicated in green, positive differences greater than 1°C are in red, and negative differences less than -1°C are in blue. The magnitude of temperature differences (°C) is labeled where it occurs.

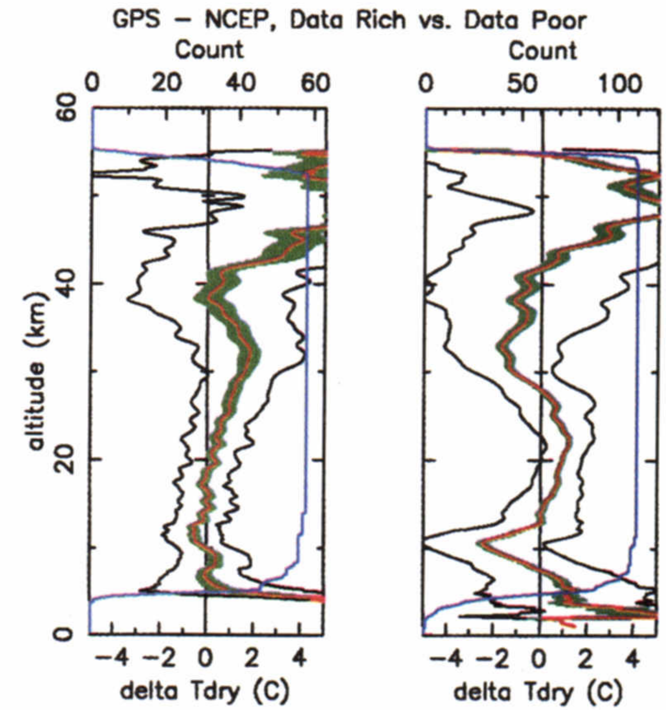


Plate 22. GPS/MET minus NCEP dry temperature profiles for data rich (left panel) and data poor (right panel) regions.

Comparison of GPS/MET derived dry temperatures with various data sources and NCEP analyses [Rocken+al(1997),JGR]

Summary: Observation Error Estimation

- specify errors as accurate as possible
  - ▷ *account for individual condittions (e.g. ionospheric activity)*
  - ▷ *specify correlations*

- Identify bad data

- Automatically, in real time

Summary: Specific Requirements

Requirements from Operational Data Assimilation

- Real Time Processing
- Estimation of observational errors
- Estimation of observational errors correlations
- Identification of bad data

Requirements for the data assimilation system

- Fast Observation Operators
- Handling of ambiguities
- Handling of nonlocal observations

OSSE and Data Assimilation Experiments

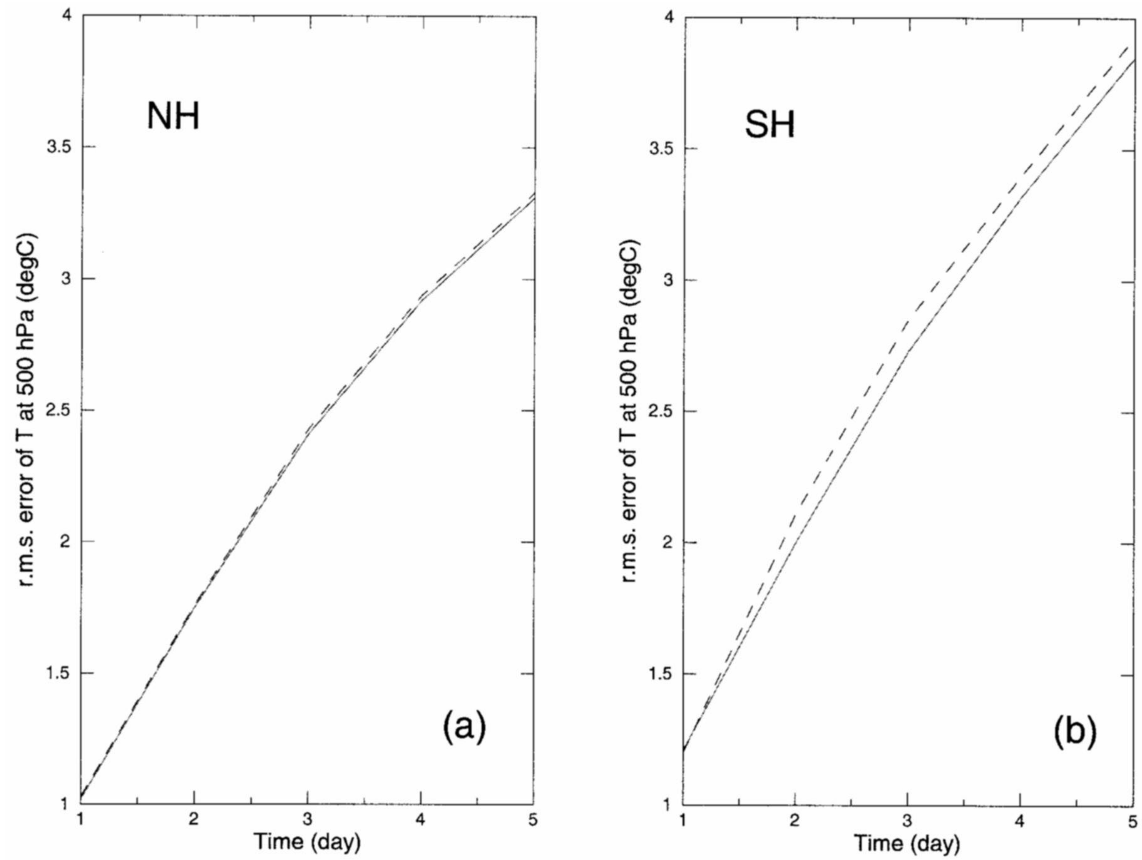


Figure 15. RMS errors for the 1- to 5-day forecasts from NOGPS and BOTH experiments for (a) Northern Hemisphere and (b) Southern Hemisphere. Results are averaged over 10–20 forecasts (20 June–30 June 1995).

RMS error for 1 - 5 days forecasts from assimilation experiments (20 June - 30 June 1995) with with (solid) and without (striped) assimilation of GPS/MET RO for northern (NH) and southern (SH) hemisphere.[Liu+al(2001),JGR]

Prospects

- In view of the upcoming GPS occultation missions, operational assimilation of GPS radio occultations is promising

- still problems with the moist atmosphere