united nations educational, scientific and cultural organization

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international centre for theoretical physics

Course on "Inverse Methods in Atmospheric Science"
1 - 12 October 2001

301/1332-13

"Remote Sounding of the Atmosphere by the Occulation Radiometer ORA: Inverse Methods and Results"

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Please note: These are preliminary notes intended for internal distribution only.

Belgian Institute
for
Space Aeronomy

Remote sounding of the atmosphere by the
Occultation Radiometer ORA:
inverse methods and results

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WANT MORE INFORMATION ? FILIP.VANHELLEMONT@OMA.BE

Presentation

The ORA experiment:
- EURECA, the occultation technique, experimental description, the mission

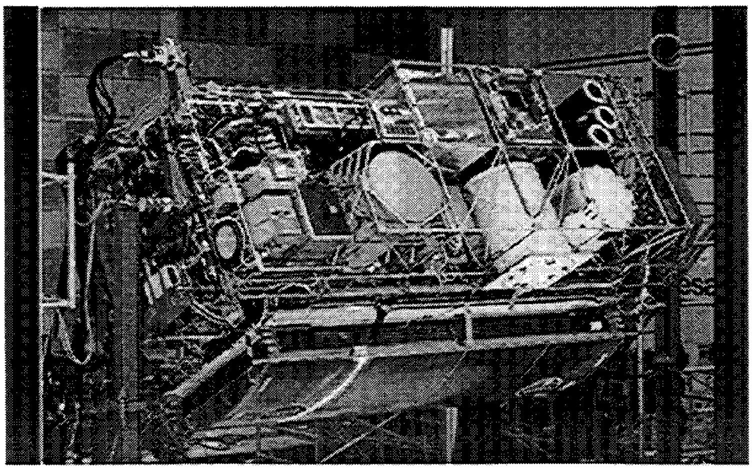
Interaction light - atmosphere
- The Sun, extinction = absorption + scattering, refraction

Data processing:
- spatial, spectral and radial inversion

ORA:
the goal

The ***Occultation Radiometer*** (ORA)
measures from an orbit around Earth:
O_3, NO_2, H_2O: concentration profiles (stratosphere)
Aerosols: particle size distribution parameters (stratosphere)
O_3 concentration profiles (mesosphere)

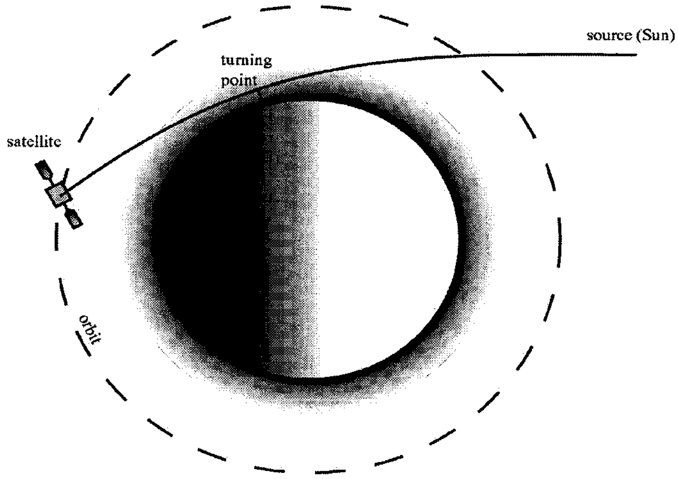
The satellite: EURECA
(European Retrievable Carrier)



•ESA - platform
•Re-launchable
•Priority: μ-gravity

ORA

The occultation technique

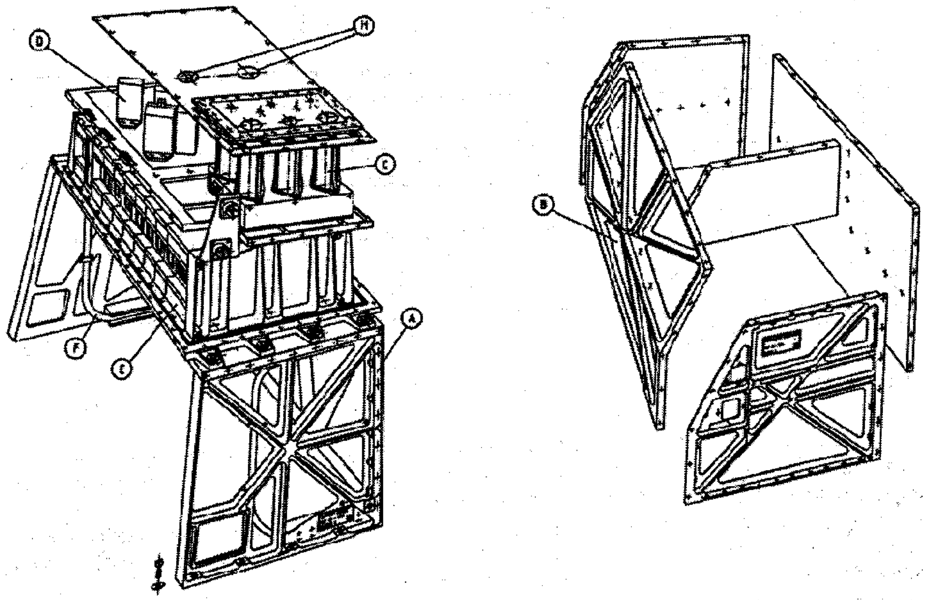


Advantages:

- •Long optical trajectories
- •Large S/N (views Sun)
- •Self-calibrating!
- •Good altitude resolution

ORA

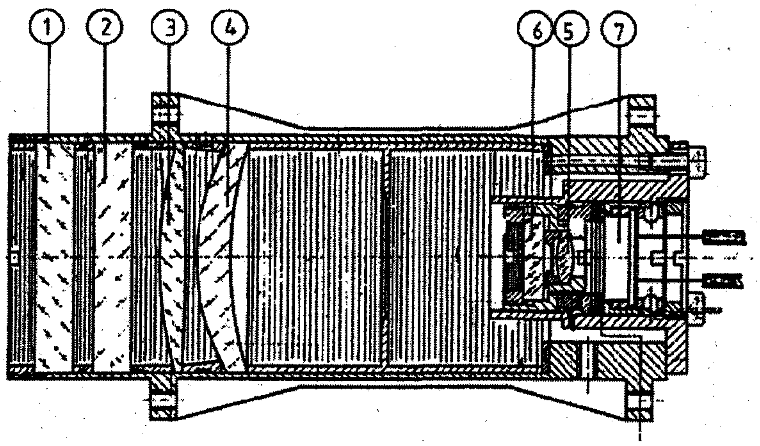
mechanical structure



ORA

8 detection channels

Spectral range: UV, visible, near infrared
259, 340, 385, 435, 442, 600, 943, 1013 nm



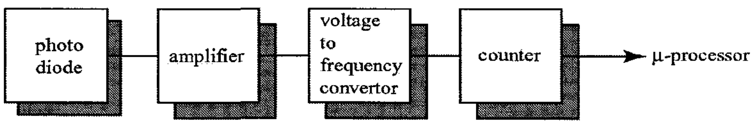
1. Window
2. Filter
3,4,5. Lenses
6. Filter
7. Photo diode

FOV: ± 2°

full solar disk at once!

ORA

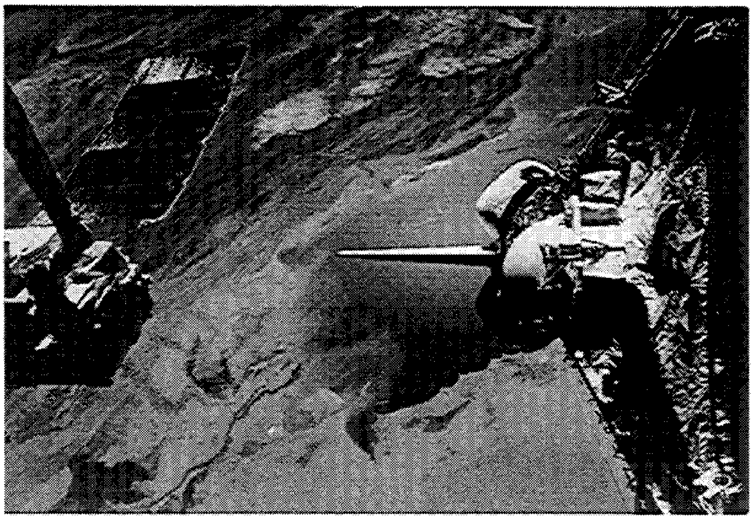
electronics



Dynamic range: 16 bit = 65536 counts

The mission

August 1992 - May 1993



Launch: 31 juli 1992, Kennedy Space Center,
Space Shuttle Atlantis

During mission: ~ 7000 occultations (sunset and sunrise)

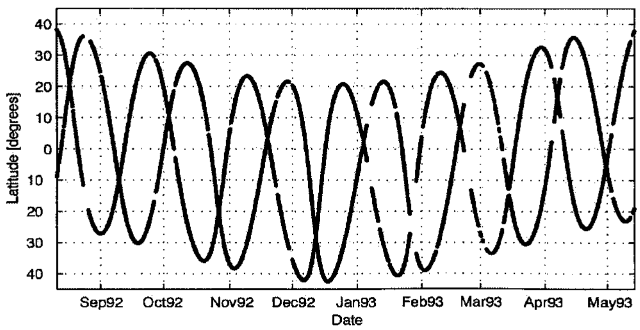
End of mission: July 1, 1993

The mission

some specifications

Orbit:
- •circular
- •altitude: 508 km
- •inclination: 28°

Satellite:
- •velocity: 7.6 km/s
- •orbital period: 95 minuten
- •30 occultations per day



Occultation-latitudes:
40°S - 40°N

Interaction light - atmosphere

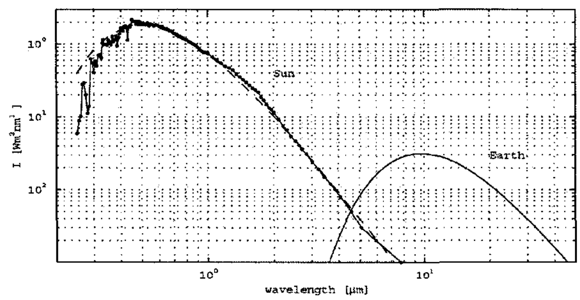
Light source: the Sun
Extinction = absorption + scattering
Refraction

Why?

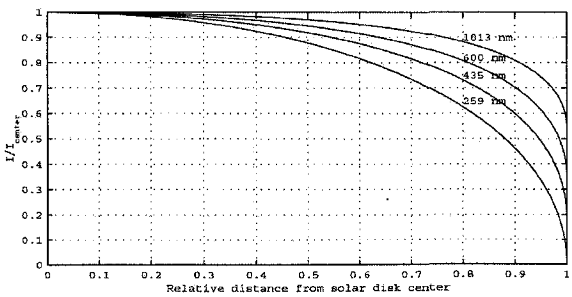
Measurement = f (unknowns)

What happens in f ?

Light source: the Sun

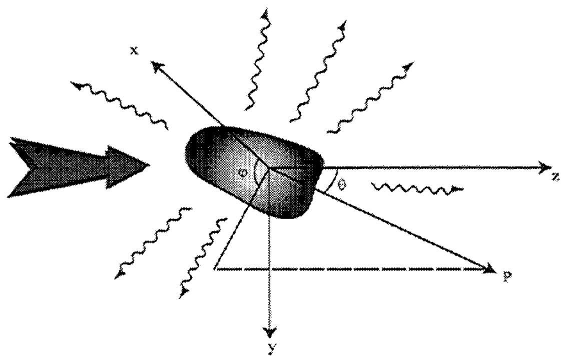


Maximum of the solar spectrum: the visible domain



Solar limb darkening: darkening towards the edge of the Sun

Extinction



Cross section

$$C_{ext} = C_{abs} + C_{sca}$$

Extinction

$$\beta_{ext} = N C_{ext}$$

Transmittance of light:

$$\tau = \exp\left(- \int_{x1}^{x2} \beta_{ext}(x) \mathrm{d}x \right)$$

Molecules:

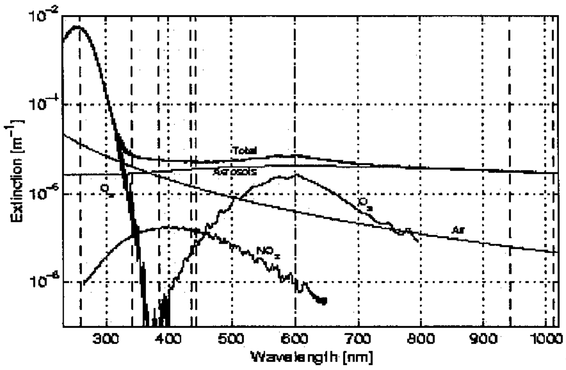
- C_{abs}: from laboratory measurements
- C_{sca}: Rayleigh law ($\sim\lambda^{-4}$)

Aerosols (spherical):

- C_{ext}: Mie theory

Extinction

The choice of channels



259 nm: mesospheric O_3

340, 385 nm: neutral density

435,442 nm: NO_2

600 nm: O_3

943 nm: H_2O

1013 nm: aerosols

Refraction

Effects:

- bending of light rays
- Flattening of the solar disk
- Refractive dilution

Refractive index is determined by P and T of the air

Data processing: Inversion

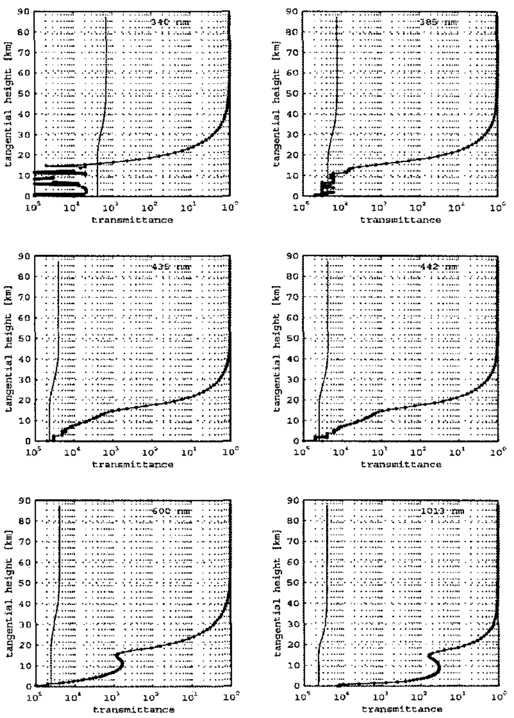
Inversion:

3 partial problems

Spatial *Inversion*		***Spectral*** *Inversion*		***Radial*** *Inversion*		
$\tau_{340}(t)$	>	$\beta_{340}(z)$		$N_{O_3}(z)$		
$\tau_{385}(t)$	>	$\beta_{385}(z)$		$N_{NO_2}(z)$		
$\tau_{435}(t)$	>	$\beta_{435}(z)$	>	$N_{air}(z)$		
$\tau_{442}(t)$	>	$\beta_{442}(z)$				
$\tau_{600}(t)$	>	$\beta_{600}(z)$		$\beta_{340,\ aero}(z)$		
$\tau_{1013}(t)$	>	$\beta_{1013}(z)$		$\beta_{385,\ aero}(z)$		
				$\beta_{435,\ aero}(z)$	>	$dN(r)/dr\ (z)$
				$\beta_{442,\ aero}(z)$		
				$\beta_{600,\ aero}(z)$		
				$\beta_{1013,\ aero}(z)$		

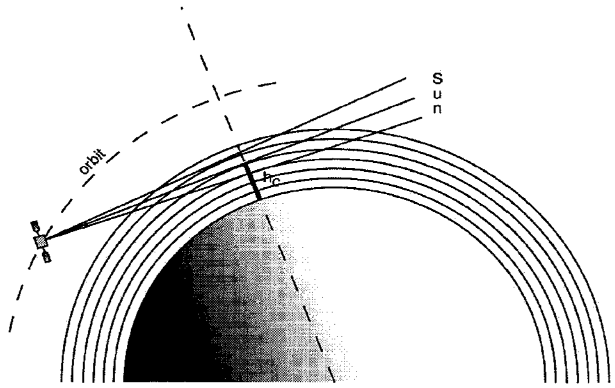
Measurements:

transmittance



Mount Pinatubo
volcanic aerosols
clearly cause a
visual effect

Spatial inversion:
exact formulation of transmittance



$$\tau = \frac{\int\limits_{\Omega}\int\limits_{\lambda} I_0(\lambda,\Omega) F_N(\lambda) \exp\left(-\int\limits_{s_{\lambda\Omega}} \beta_{ext}^{tot}(\lambda, s_{\lambda\Omega})\, ds_{\lambda\Omega} \right) d\lambda d\Omega}{\tilde{I}_{disk} \int\limits_{\Omega} d\Omega}$$

Spatial inversion:
approximations

- Refraction is independent of wavelength
- Solar limb darkening is independent of wavelength
- Discretization of solar disk in 20 discrete layers
- Expression of relation with respect to λ_c

$$\tau = \sum_{i=0}^{19} r_i g_i \exp\left(-\int\limits_{s_i} \beta_{ext}^{tot}(\lambda_c, s_i)\, ds_i \right)$$

Spatial inversion:
limited information content

Reason: wide overlap of subsequent measurements during an occultation

Consequence: solution is very unstable!

Two fundamental remedies:

- Reduction of number of unknown parameters
- Introduction of a priori (external) information

Spatial inversion: NOPE
(Natural Orthogonal Polynomial Expansion)

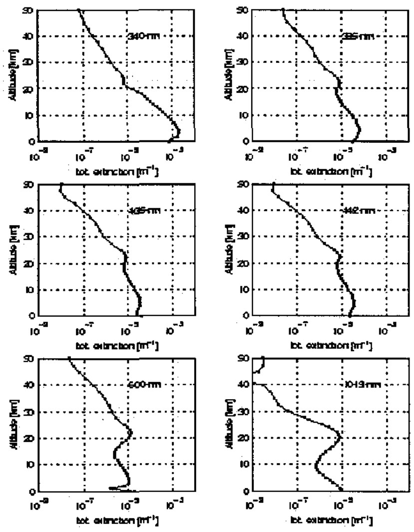
$$\beta_{\mathrm{ext}}^{\mathrm{tot}}(z) = \tilde{\beta}_{\mathrm{ext}}^{\mathrm{tot}}(z) \sum_{i=0}^{n} \alpha_i P_i(z)$$

Then: nonlinear least-squares procedure (minimization of the *Merit function*)

$$M = \left\langle \tau - \tau_{\mathrm{Model}} \middle| S_t^{-1} \middle| \tau - \tau_{\mathrm{Model}} \right\rangle$$

Spatial inversion:

results



Altitude profiles
for total extinction
at 6 wavelengths

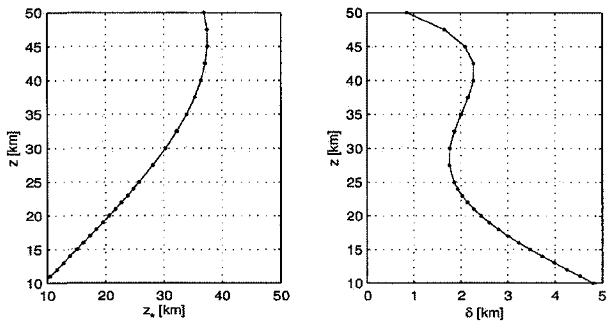
The Direct Method (DM)

Why?

DM gives extra correction at altitudes where the measured signal contains only a small amount of information ($\tau \sim 0$ or 1)

Method: statistical connection $$\beta_{\text{ext}}^{\text{tot}}(z) = G_{z,h}\left(\tau_{\text{NOPE}}(h)\right)$$

Interesting extra result: spatial resolution of ORA ~ 2 km!



Spectral inversion

separation of the different constituents

$$\begin{bmatrix} C_{340}^{air} & C_{340}^{O_3} & C_{340}^{NO_2} & 1 & 0 & 0 & 0 & 0 & 0 \\ C_{385}^{air} & C_{385}^{O_3} & C_{385}^{NO_2} & 0 & 1 & 0 & 0 & 0 & 0 \\ C_{435}^{air} & C_{435}^{O_3} & C_{435}^{NO_2} & 0 & 0 & 1 & 0 & 0 & 0 \\ C_{442}^{air} & C_{442}^{O_3} & C_{442}^{NO_2} & 0 & 0 & 0 & 1 & 0 & 0 \\ C_{600}^{air} & C_{600}^{O_3} & C_{600}^{NO_2} & 0 & 0 & 0 & 0 & 1 & 0 \\ C_{1013}^{air} & C_{1013}^{O_3} & C_{1013}^{NO_2} & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} N^{air} \\ N^{O_3} \\ N^{NO_2} \\ \beta_{340}^{aero} \\ \beta_{385}^{aero} \\ \beta_{435}^{aero} \\ \beta_{442}^{aero} \\ \beta_{600}^{aero} \\ \beta_{1013}^{aero} \end{bmatrix} = \begin{bmatrix} \beta_{340}^{tot} \\ \beta_{385}^{tot} \\ \beta_{435}^{tot} \\ \beta_{442}^{tot} \\ \beta_{600}^{tot} \\ \beta_{1013}^{tot} \end{bmatrix}$$

Pre-assumption: aerosol spectrum = polynomial of 2nd degree

$$\beta_j^{aero} = c_0 + c_1(\lambda_j - \lambda_{1013}) + c_2(\lambda_j - \lambda_{1013})^2$$

Spectral inversion:

A global approach: altitude smoothing

- At each altitude zi: $\mathbf{A_i x_i = y_i}$
- Stack all matrices in one big matrix

$$\begin{pmatrix} \mathbf{A_1} & 0 & \cdots & 0 \\ 0 & \mathbf{A_2} & 0 & 0 \\ \vdots & 0 & \ddots & \vdots \\ 0 & 0 & \cdots & \mathbf{A_n} \end{pmatrix} \cdot \begin{pmatrix} \mathbf{x_1} \\ \mathbf{x_2} \\ \vdots \\ \mathbf{x_n} \end{pmatrix} = \begin{pmatrix} \mathbf{y_1} \\ \mathbf{y_2} \\ \vdots \\ \mathbf{y_n} \end{pmatrix}$$

- Construct 'a priori' covariance matrix with off-diagonal elements

$$\sigma^2(z_1, z_2) = \sigma(z_1)\sigma(z_2)\exp\left\{-\left(\frac{z_1 - z_2}{L}\right)^2\right\}$$

Spectral inversion:

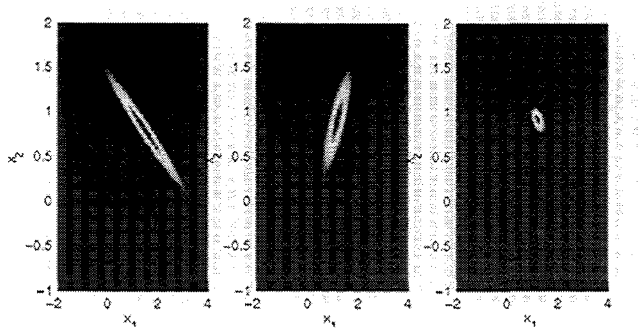
a Bayesian method (1)

- Measurement y and unknown x are characterized by normal distributions
- Inverse problem: y=K.x (linear)
- Using Bayes theorem: the solution x is the one for which:

$$\langle \mathbf{y}-\mathbf{Kx}|\mathbf{S}_\mathbf{y}^{-1}|\mathbf{y}-\mathbf{Kx}\rangle + \langle \mathbf{x}-\mathbf{x}_\mathbf{a}|\mathbf{S}_\mathbf{a}^{-1}|\mathbf{x}-\mathbf{x}_\mathbf{a}\rangle = \text{minimum}$$

$$\tilde{\mathbf{x}} = \mathbf{x}_\mathbf{a} + \left(\mathbf{K}^\mathbf{T}\mathbf{S}_\mathbf{y}^{-1}\mathbf{K}+\mathbf{S}_\mathbf{a}^{-1}\right)^{-1}\mathbf{K}^\mathbf{T}\mathbf{S}_\mathbf{y}^{-1}\left(\mathbf{y}-\mathbf{Kx}_\mathbf{a}\right)$$

$$\mathbf{S}_\mathbf{x}^{-1} = \mathbf{K}^\mathbf{T}\mathbf{S}_\mathbf{y}^{-1}\mathbf{K}+\mathbf{S}_\mathbf{a}^{-1}$$



Spectral inversion:

a Bayesian method (2)

True nature: $\begin{pmatrix}3\\4\end{pmatrix} = \begin{pmatrix}1 & 2\\1 & 3\end{pmatrix}\cdot\begin{pmatrix}x_1\\x_2\end{pmatrix}$ $\quad \mathbf{x} = \begin{pmatrix}1\\1\end{pmatrix}$

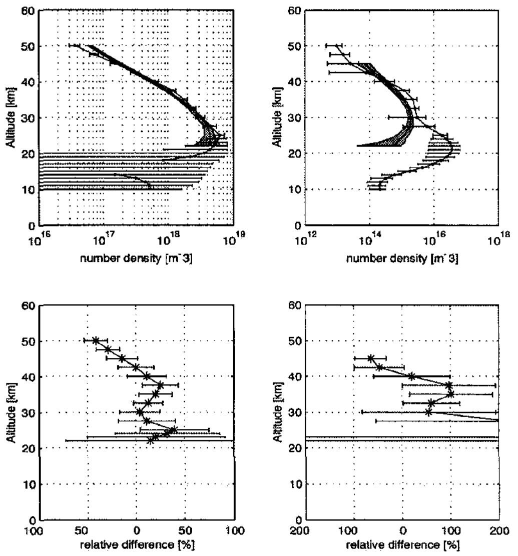
Measurement: $\mathbf{y} = \begin{pmatrix}3.1\\3.9\end{pmatrix}$ $\quad \mathbf{S}_\mathbf{y} = \begin{pmatrix}0.04 & 0\\0 & 0.09\end{pmatrix}$ $\quad \mathbf{x} = \begin{pmatrix}1.5\\0.8\end{pmatrix}$

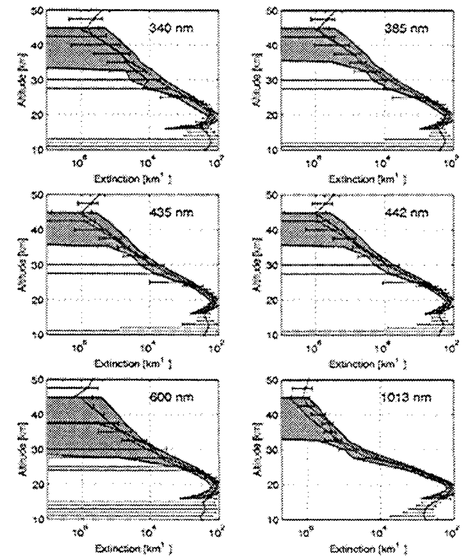
A priori: $\mathbf{x}_\mathbf{a} = \begin{pmatrix}1.2\\0.9\end{pmatrix}$ $\quad \mathbf{S}_\mathbf{a} = \begin{pmatrix}0.09 & 0.072\\0.072 & 0.09\end{pmatrix}$

Solution: $\tilde{\mathbf{x}} = \begin{pmatrix}1.22\\0.92\end{pmatrix}$ $\quad \tilde{\mathbf{S}}_\mathbf{x} = \begin{pmatrix}0.0192 & -0.0049\\-0.0049 & 0.0056\end{pmatrix}$

Spectral inversion:

Results + comparison with SAGE II





Aerosols

Radial inversion + some results

Radial inversion:

formalism + assumptions

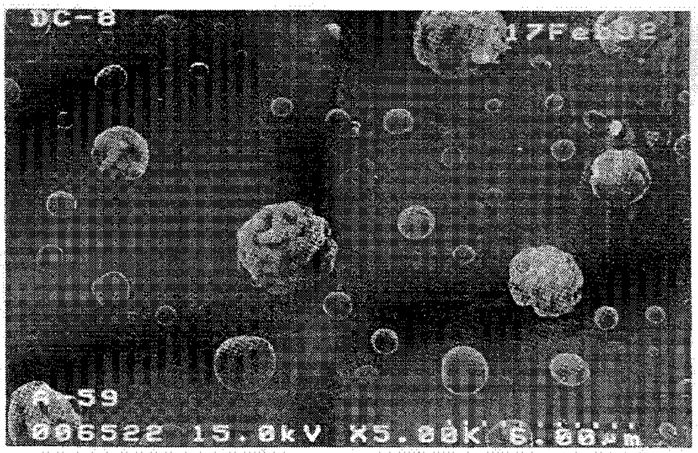


Figure 3. Plane view of stratospheric H_2SO_4/H_2O droplets and sulfuric-acid-coated volcanic ash particles collected on February 17, 1992, near (53°N; 67°W) at 10.7 km msl.

Inverse problem:

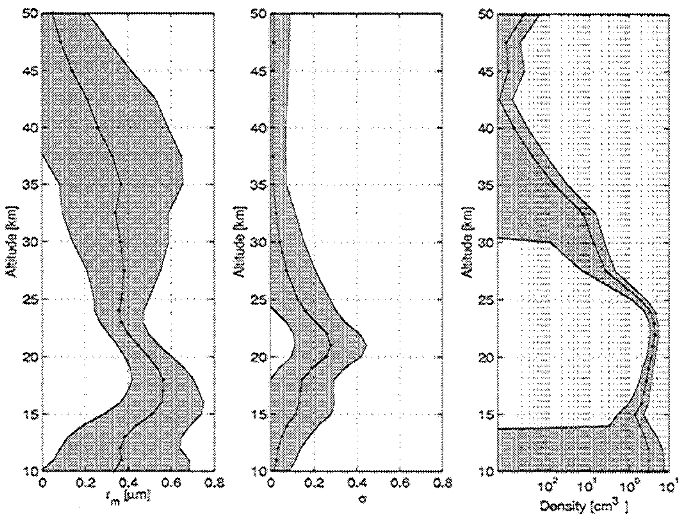
$$\beta_{\text{ext}}^{\text{aero}}(\lambda) = \int_0^\infty C_{\text{ext}}(\lambda, r) \frac{dN(r)}{dr}\, dr$$

Assumptions:

- H_2SO_4-H_2O (65-80 %)
- n = 1.43 + i 0.0 (no absorption)
- $C_{ext}(\lambda,r)$: Mie theory
- Particle size distribution:
  lognormal function
  3 parameters: N, r_m en σ

Radial inversion:

resulting profiles

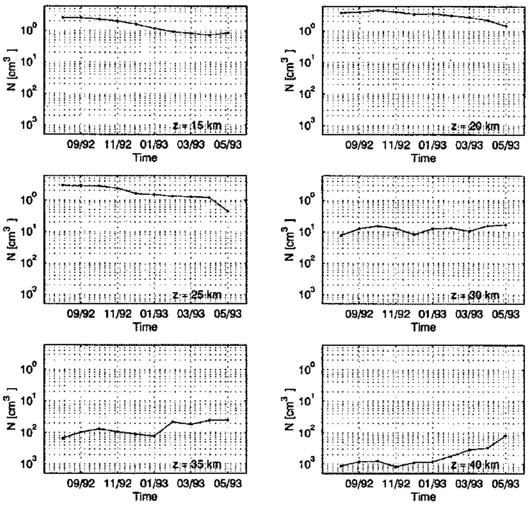


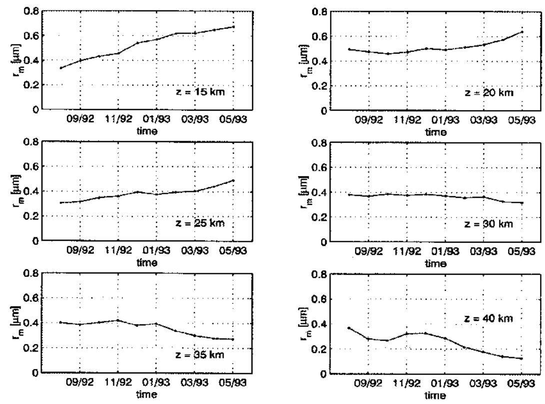
Typical values in the lower stratospheric layers (~23 km):

N = 4 particles cm^{-3}
r_m= 0.5 µm
σ = 0.2

Aerosols

Evolution in time (1)





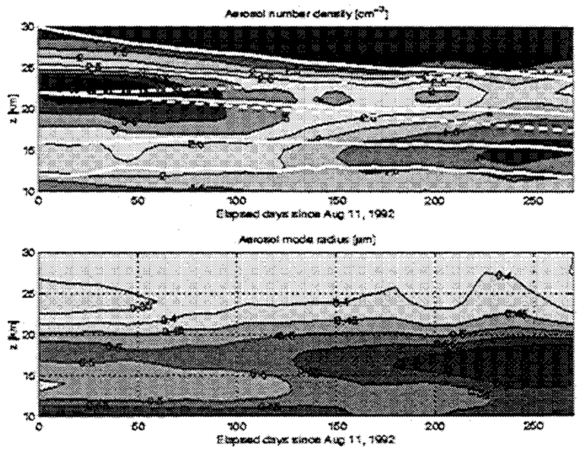
z < 30 km: N decreases,
r_m increases

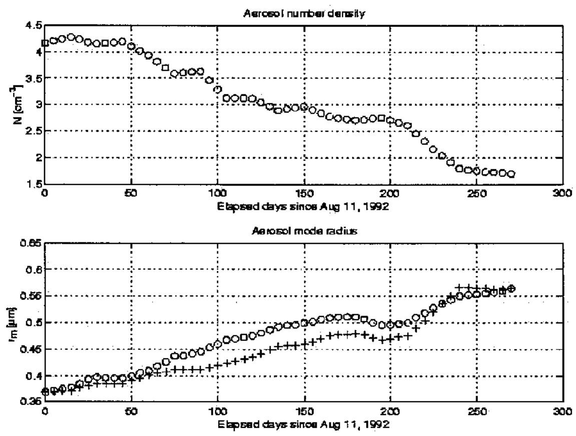
z > 30 km: N increases,
r_m decreases

Aerosols:

Evolution in time (2)

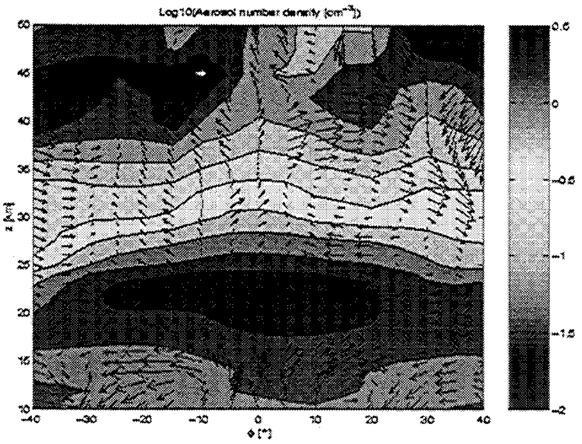
During coagulation, the total aerosol volume has to be constant

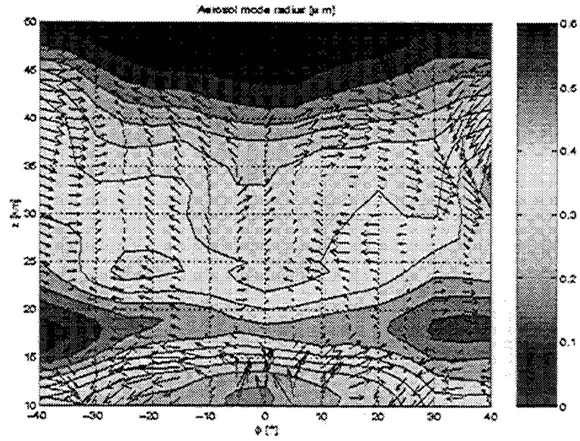




Aerosols:

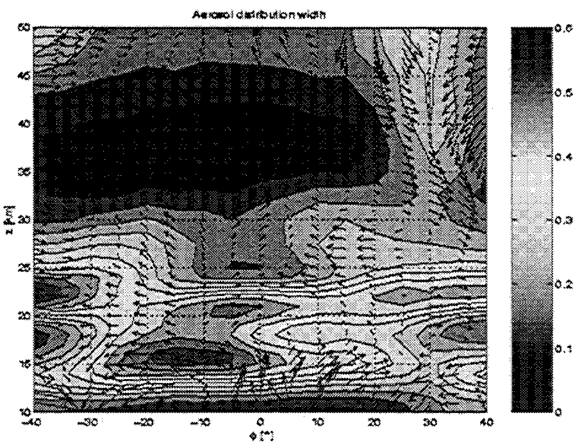
Variation in latitude (1)

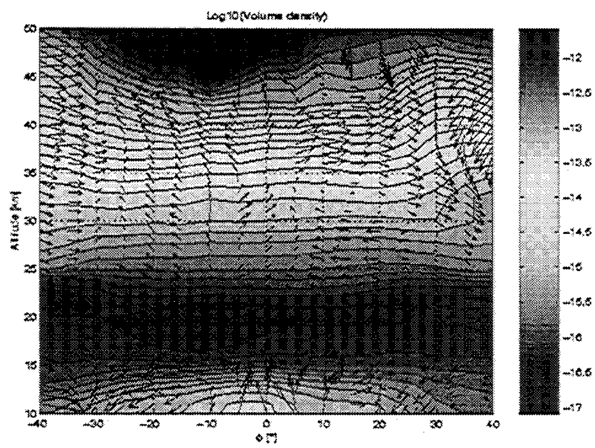




Aerosols

Variation in latitude (2)





Conclusion

• Although a low-cost instrument with a wide FOV implies complex inverse methods, satisfactory results can be obtained.

• The used inverse methods (NOPE, Bayesian method) have been proven to be effective