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**School on "Exploring the Atmosphere by Remote Sensing Techniques"**
**18 October - 5 November 1999**

**1151-21**

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# "Infrared Methods & Techniques for Atmospheric Science"

Lecture 1: Representative Space Experiments

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**Paris**
**France**

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

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# Infrared methods and techniques for atmospheric science

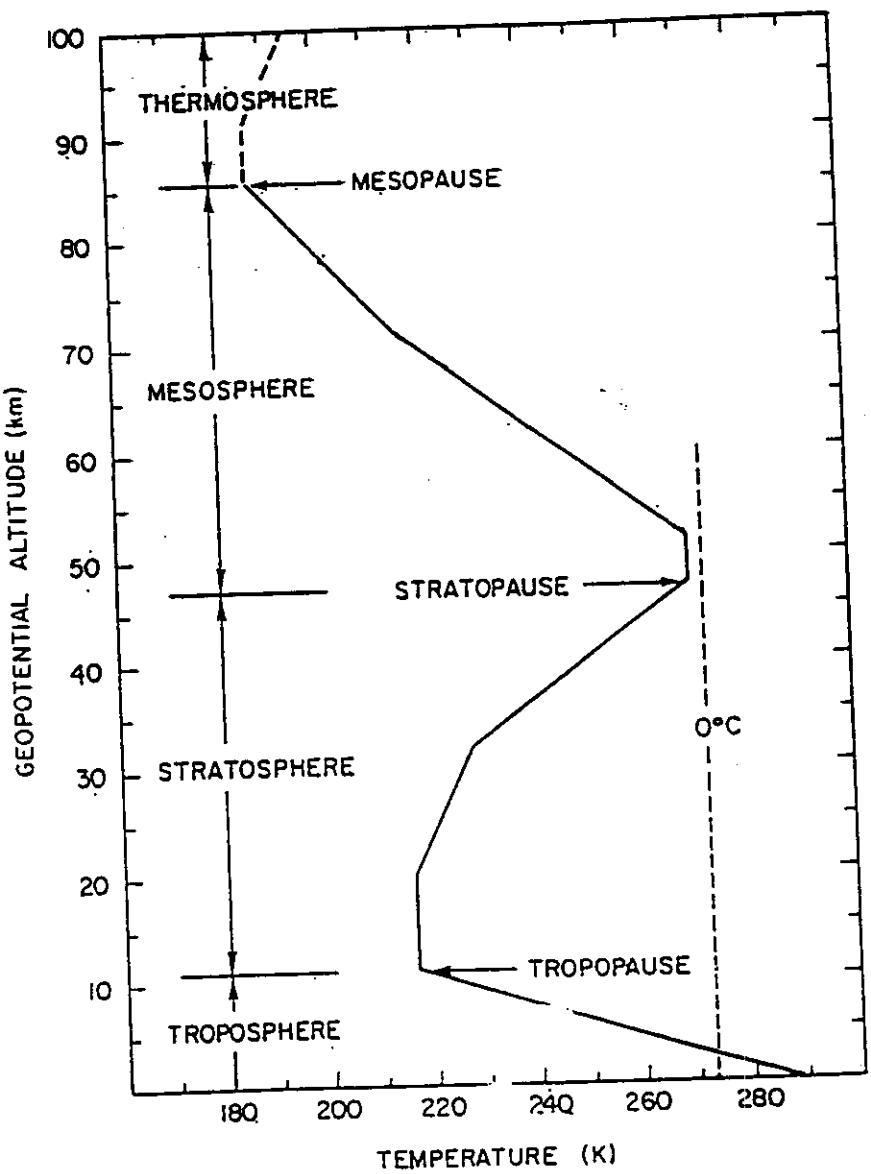
1st lecture



1st lecture: representative space experiments

2nd lecture: radiative transfer, molecular spectra, tropospheric sounding

Seminar: LPMA balloon experiment




Temperature-height profile for U.S. Standard Atmosphere 0-86 km.

# Atmospheric trace species

***Permanent gases:***

**$N_2$ (78 %), $O_2$ (21 %), Ar (1 %), Ne, He, Kr, Xe**

***Variable gases:***

| | | |
|---|---|---|
| **$H_2O$** | 0-7 % = 0 – 70000 ppmv<br>~ 5 ppmv | troposphere<br>stratosphere |
| **$CO_2$** | 360 ppmv | season, trend |
| **$O_3$** | 8 ppmv | stratosphere |
| **$N_2O$** | 310 ppbv | mixing ratio |
| **$CH_4$** | 1.7 ppmv | $\chi_i = \frac{N_i}{N}$ |
| **CO** | ~ 110 ppbv | |
| **NO** | | 1 % = 10000 ppmv |
| **$NO_2$** | 1 ppbv – 1 pptv | 1 ppmv = $10^{-6}$ |
| **$HNO_3$** | | 1 ppbv = $10^{-9}$ |
| **CFC** | ~ 100 pptv | 1 pptv = $10^{-12}$ |

## US standard atmosphere 1976
## Molar mass and mixing ratio of dry air at sea level

| *Species* $i$ | *Molar mass* $M_i$ *g/mol of kg/kmol* | *Mixing ratio* $\chi_i$ |
|---|---|---|
| $N_2$ | 28.0134 | 0.78084 |
| $O_2$ | 31.9988 | 0.209476 |
| Ar | 39.948 | 0.00934 |
| $CO_2$ | 44.00995 | 0.000314 |
| Ne | 20.183 | 0.00001818 |
| He | 4.0026 | 0.00000524 |
| Kr | 83.80 | 0.00000114 |
| Xe | 131.30 | 0.000000087 |
| $CH_4$ | 16.04303 | 0.000002 |
| $H_2$ | 2.01594 | 0.0000005 |

$$M_0 = \frac{\Sigma \chi_i M_i}{\Sigma \chi_i} = 28.9644 \text{ g mol}^{-1}$$

$M_0 \approx$ cst from sea level up to ~ 80 km

M decreasing above 80 km (photodissociation of $O_2$)

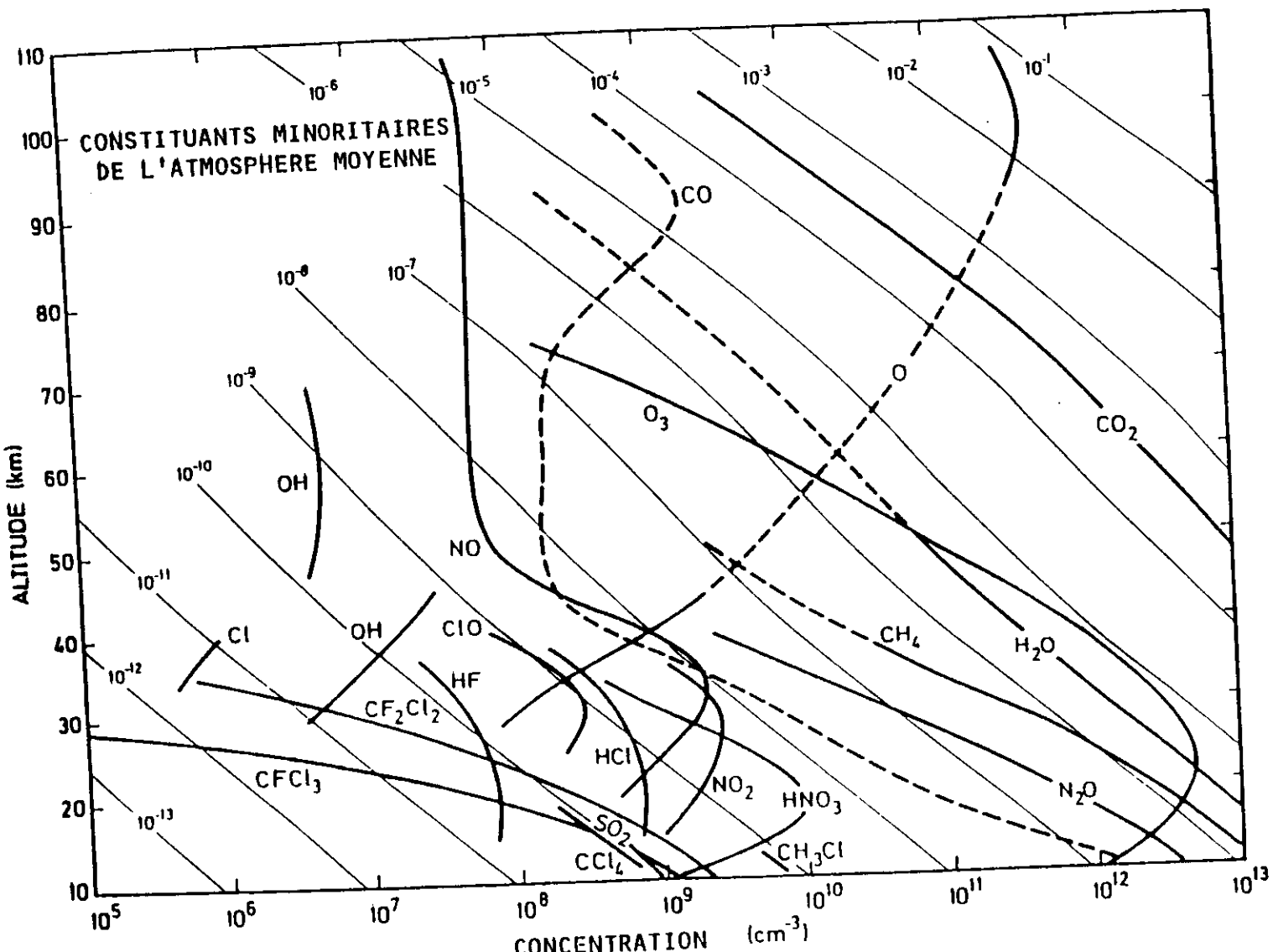



**Fig. 3.-** Quelques mesures de constituants minoritaires dans l'homosphère. Les courbes en trait fin correspondent à des rapports de mélange constants (Ackerman, 1979).

# Which spectral region ?

Mid-infrared is widely used :

- strong spectral features
- high resolution available

} → high sensitivity

- large intervals covered → multi-species

But not universal :

Micro-wave : ClO , $O_3$ , $H_2O$, $O_2$ , ....

Far-infrared : OH , $HO_2$ , HOCl , HBr

Visible : $NO_3$ , $NO_2$ , $O_3$

UV : OClO , $SO_2$ , $O_3$ , BrO ..

## Spectral variables

| | | | | |
|---|---|---|---|---|
| $\nu$ | frequency | Hz | MW | |
| $\lambda$ | wavelength | μm | IR | nm, Å UV-visible |
| $\tilde{\nu}$ | wavenumber | $cm^{-1}$ | IR | |

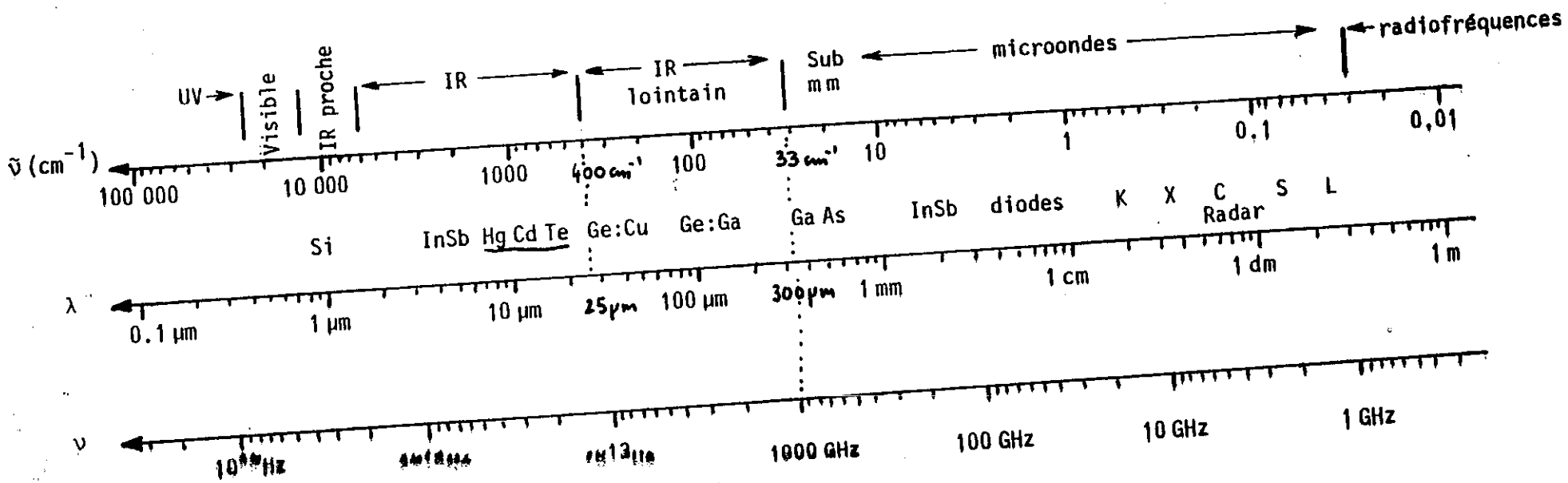
$$\tilde{\nu}\left(cm^{-1}\right)=\frac{10000}{\lambda(\mu m)}$$

| | | |
|---|---|---|
| near | IR | 1 μm ↔ 10000 $cm^{-1}$ |
| thermal | IR | 10 μm ↔ 1000 $cm^{-1}$ |
| far | IR | 100 μm ↔ 100 $cm^{-1}$ |

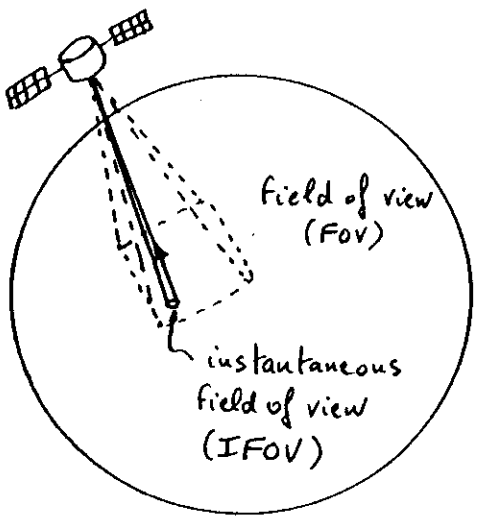
$$\lambda=\frac{c}{\nu} \qquad \tilde{\nu}=\frac{1}{\lambda}$$

⊠ **In the visible air wavelengths are often used in place of vacuu wavelengths**

$$\lambda_{vac}=n\lambda_{air}$$




Domaines spectraux et détecteurs utilisables

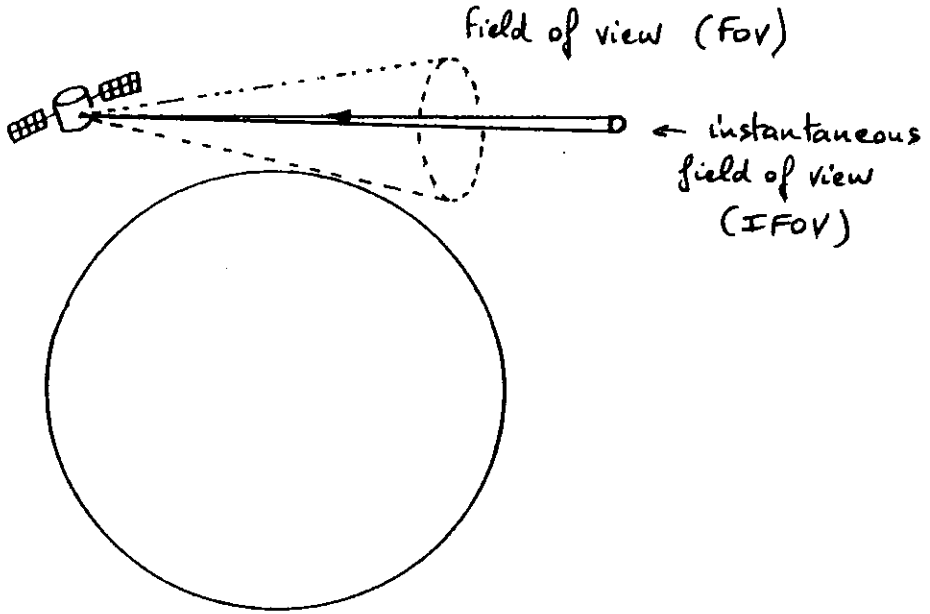



nadir viewing

good horizontal resolution

limited vertical resolution

2 modes:
emission
solar backscatter

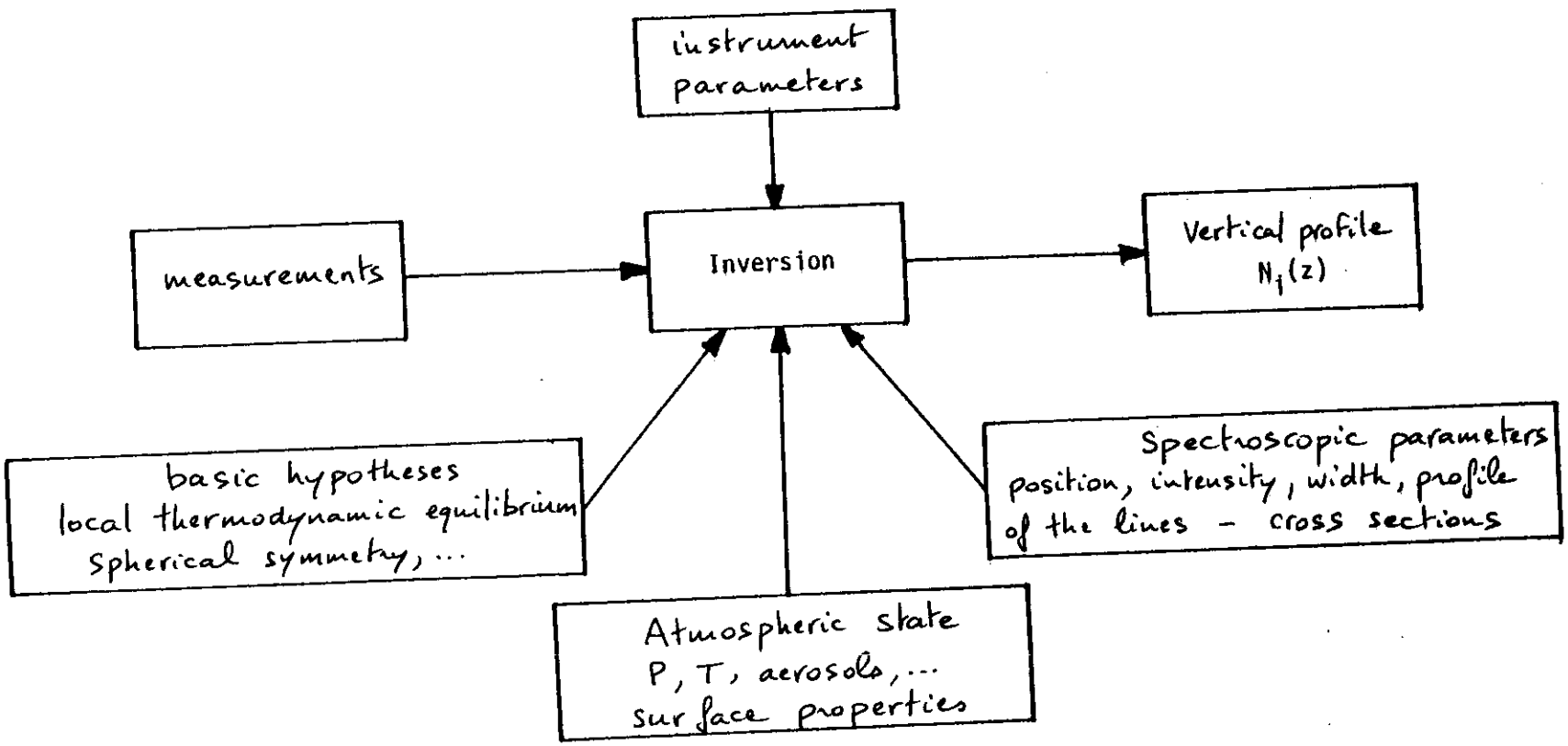



limb viewing

good vertical resolution

limited horizontal resolution

2 modes:
emission
solar occultation


instrument parameters
measurements
Inversion
Vertical profile $N_i(z)$
basic hypotheses
local thermodynamic equilibrium
Spherical symmetry, ...
Spectroscopic parameters
position, intensity, width, profile
of the lines - cross sections
Atmospheric state
P, T, aerosols, ...
surface properties

# Radiative transfer equation in the infrared

Integral form along a given ray:

$$I_{\tilde{\nu}}(s) = I_{\tilde{\nu}}(0)\, \exp\left[-\tau_{\tilde{\nu}}(s,0)\right] + \int_0^s J_{\tilde{\nu}}(s')\, \exp\left[-\tau_{\tilde{\nu}}(s,s')\right] \alpha_{\tilde{\nu}}(s')\, ds$$

$I_{\tilde{\nu}}$ = spectral $\begin{cases} \text{intensity} \\ \text{radiance} \end{cases}$ $\quad W\, cm^{-2}\, sr^{-1} / cm^{-1}$

Optical depth between $s$ and $s'$ along a ray

$$\tau_{\tilde{\nu}}(s,s') = \int_{s'}^{s} \alpha_{\tilde{\nu}}(s'')\, ds''$$

Transmission

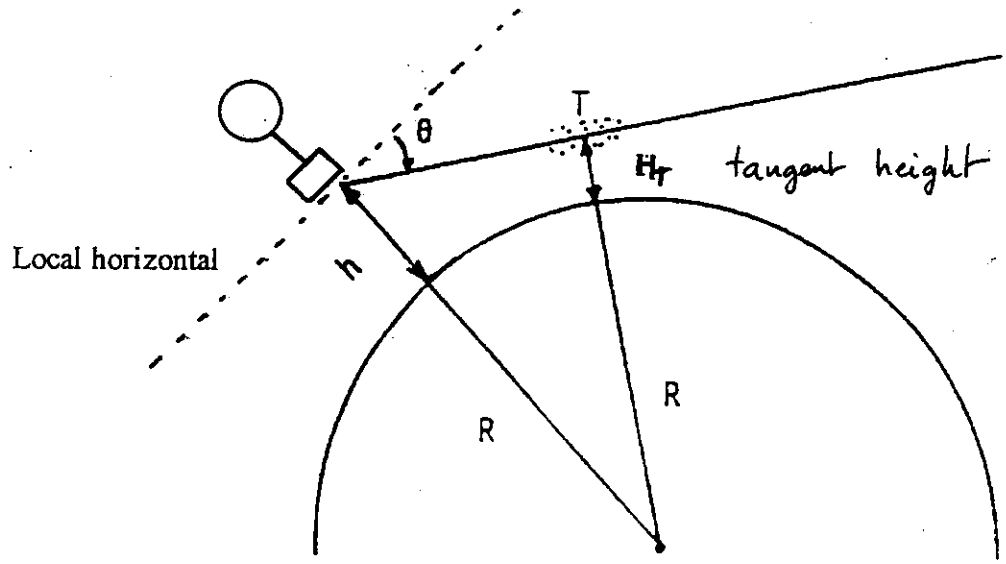
$$T_{\tilde{\nu}}(s,s') = \exp\left[-\tau_{\tilde{\nu}}(s,s')\right]$$

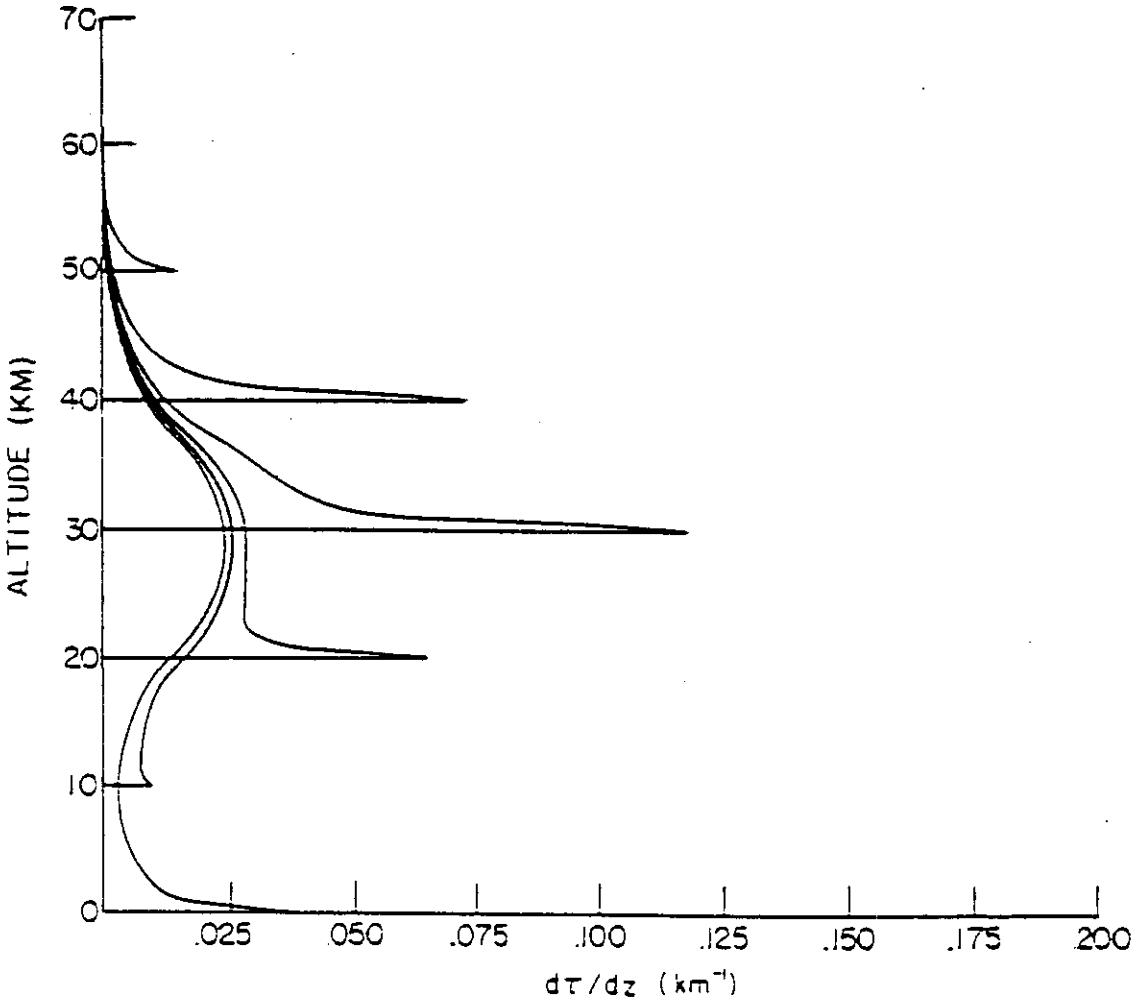
# LIMS

## Limb Infrared Monitor of the Stratosphere

- filter radiometer
- limb viewing
- 6 channels, Hg Cd Te detectors
- cooled to 64 K (solid $NH_3 - CH_4$)
- NIMBUS-7 launch 24 Oct. 1978
  operations → 28 May 1979

# Geometry of the Limb sounding






Ozone transmittance weighting functions for selected tangent heights using an infinitesimal FOV and limb viewing geometry with the 9.6-$\mu$m ozone band.

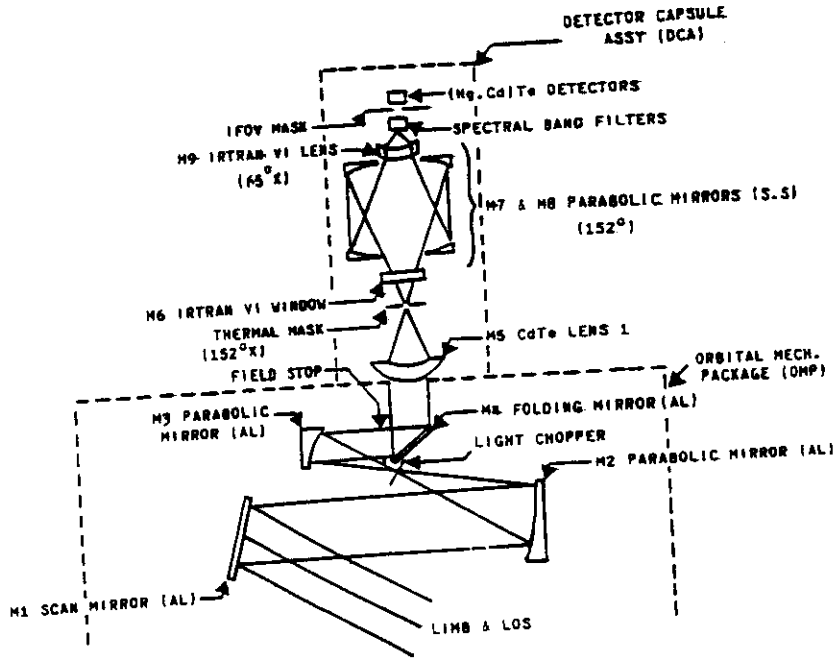
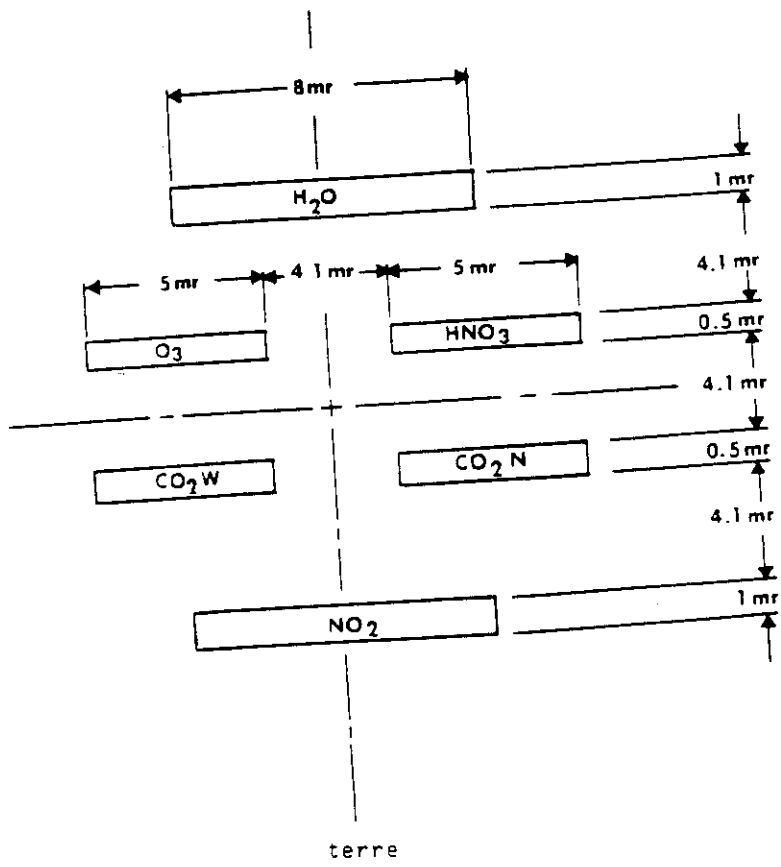



Schéma de l'optique de LIMS

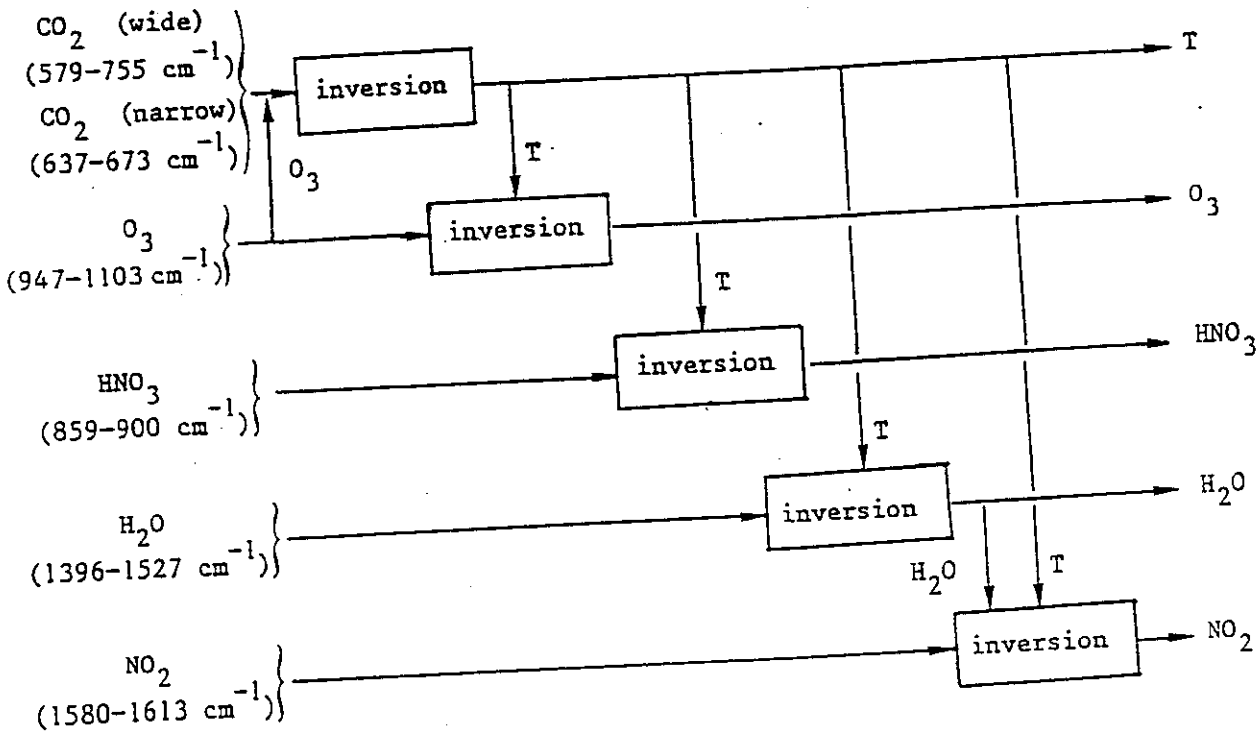


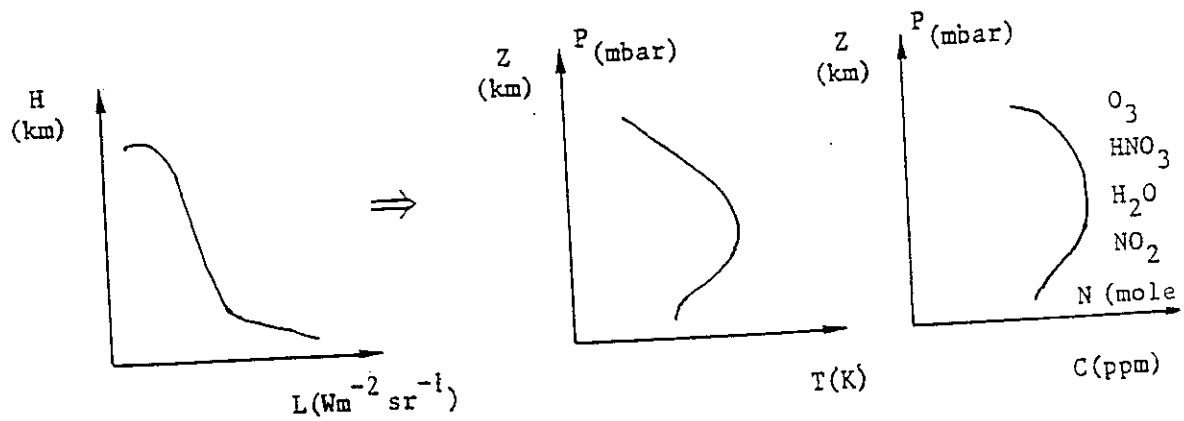

Champs de visée instantanés de LIMS

| No. | Constituant | Bande passante à 5% | Bande passante à 50% | Champ de visée | | Bruit équivalent (radiance en $Wm^{-2}sr^{-1}$) |
|---|---|---|---|---|---|---|
| | | | | Vertical | Horizontal | |
| 1 | $NO_2$ | 1560 – 1630 $cm^{-1}$ (6.4 – 6.1 $\mu m$) | 1580 – 1613 $cm^{-1}$ (6.3 – 6.2 $\mu m$) | 3.6 km | 28 km | 0.0006 |
| 2 | $H_2O$ | 1370 – 1560 $cm^{-1}$ (7.3 – 6.4 $\mu m$) | 1396 – 1527 $cm^{-1}$ (7.2 – 6.5 $\mu m$) | 3.6 km | 28 km | 0.0021 |
| 3 | $O_3$ | 926 – 1141 $cm^{-1}$ (10.8 – 8.8 $\mu m$) | 947 – 1103 $cm^{-1}$ (10.6 –9.1 $\mu m$) | 1.8 km | 18 km | 0.0035 |
| 4 | $HNO_3$ | 844 – 917 $cm^{-1}$ (11.8 – 10.9 $\mu m$) | 859 – 900 $cm^{-1}$ (11.6 – 11.1 $\mu m$) | 1.8 km | 18 km | 0.0015 |
| 5 | $CO_2W$ | 579 – 755 $cm^{-1}$ (17.3 – 13.2 $\mu m$) | 595 – 739 $cm^{-1}$ (16.8 – 13.5 $\mu m$) | 1.8 km | 18 km | 0.005 |
| 6 | $CO_2N$ | 637 – 673 $cm^{-1}$ (15.7 – 14.9 $\mu m$) | 645 – 673 $cm^{-1}$ (15.5 – 14.9 $\mu m$) | 1.8 km | 18 km | 0.0013 |

Caractéristiques spectrales des différents canaux de LIMS

# LIMS INVERSION PROCEDURE




6 radiance profiles each 12 s

1 temperature and 4 concentration pro

# SAMS

Stratospheric And Mesospheric Sounder

# ISAMS

Improved Stratospheric And Mesospheri Sounder

- pressure modulated radiometer (PMR

| Constituant | Bande spectrale |
|---|---|
| $CO_2$ | 4.3 μm and 15 μm |
| $H_2O$ | 2.7 μm and 25 μm to 100 μm |
| CO | 4.7 μm |
| $N_2O$ | 7.7 μm |
| $CH_4$ | 7.7 μm |
| NO | 5.3 μm |

Espèces moléculaires mesurées dans l'expérience S A

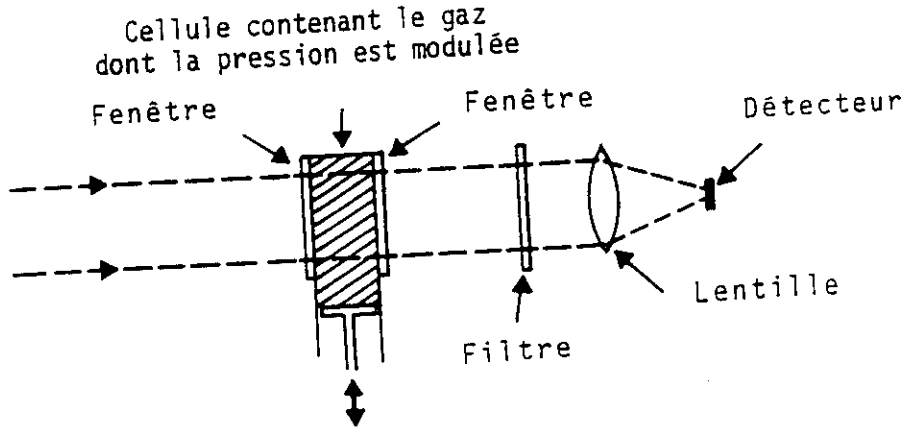
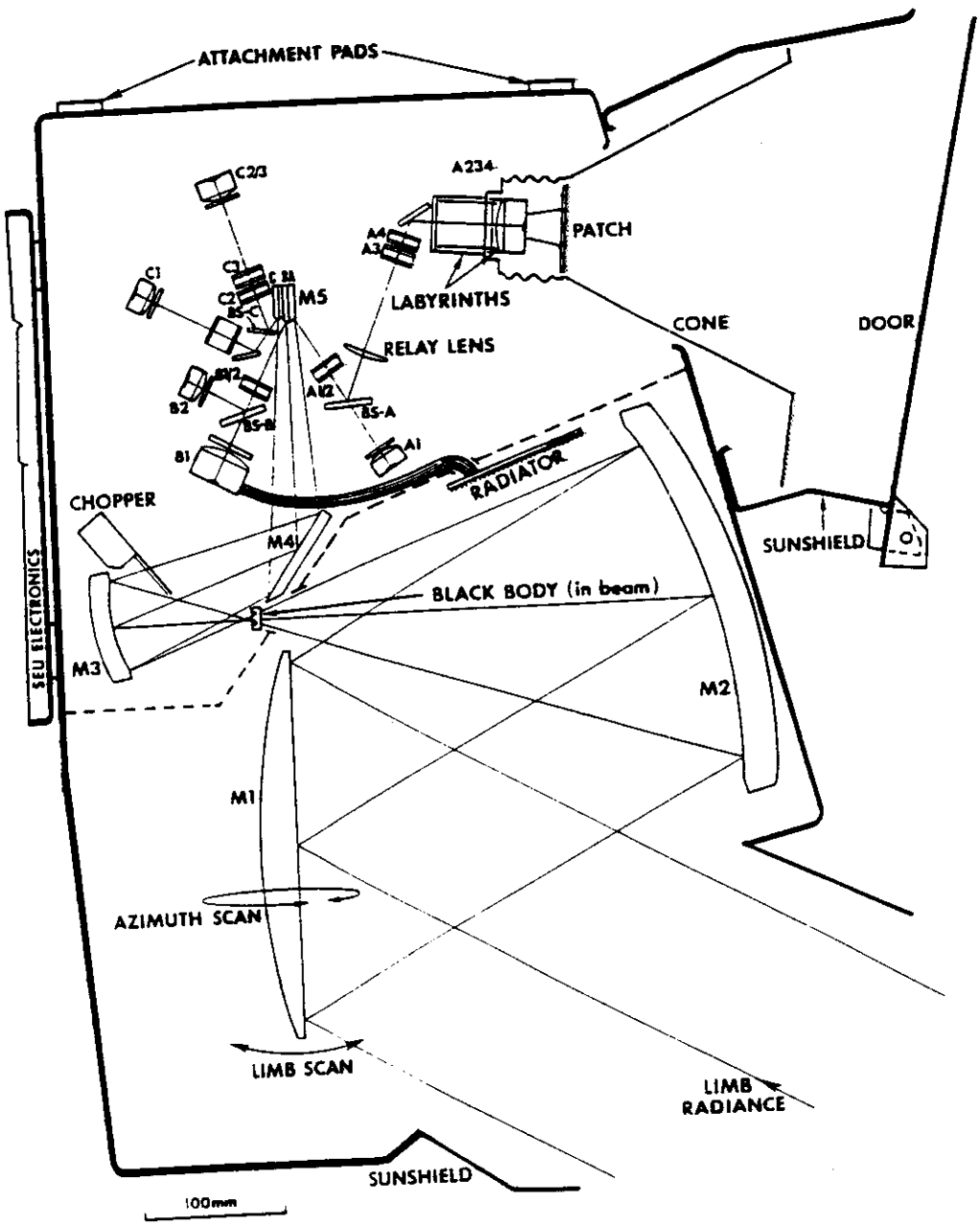
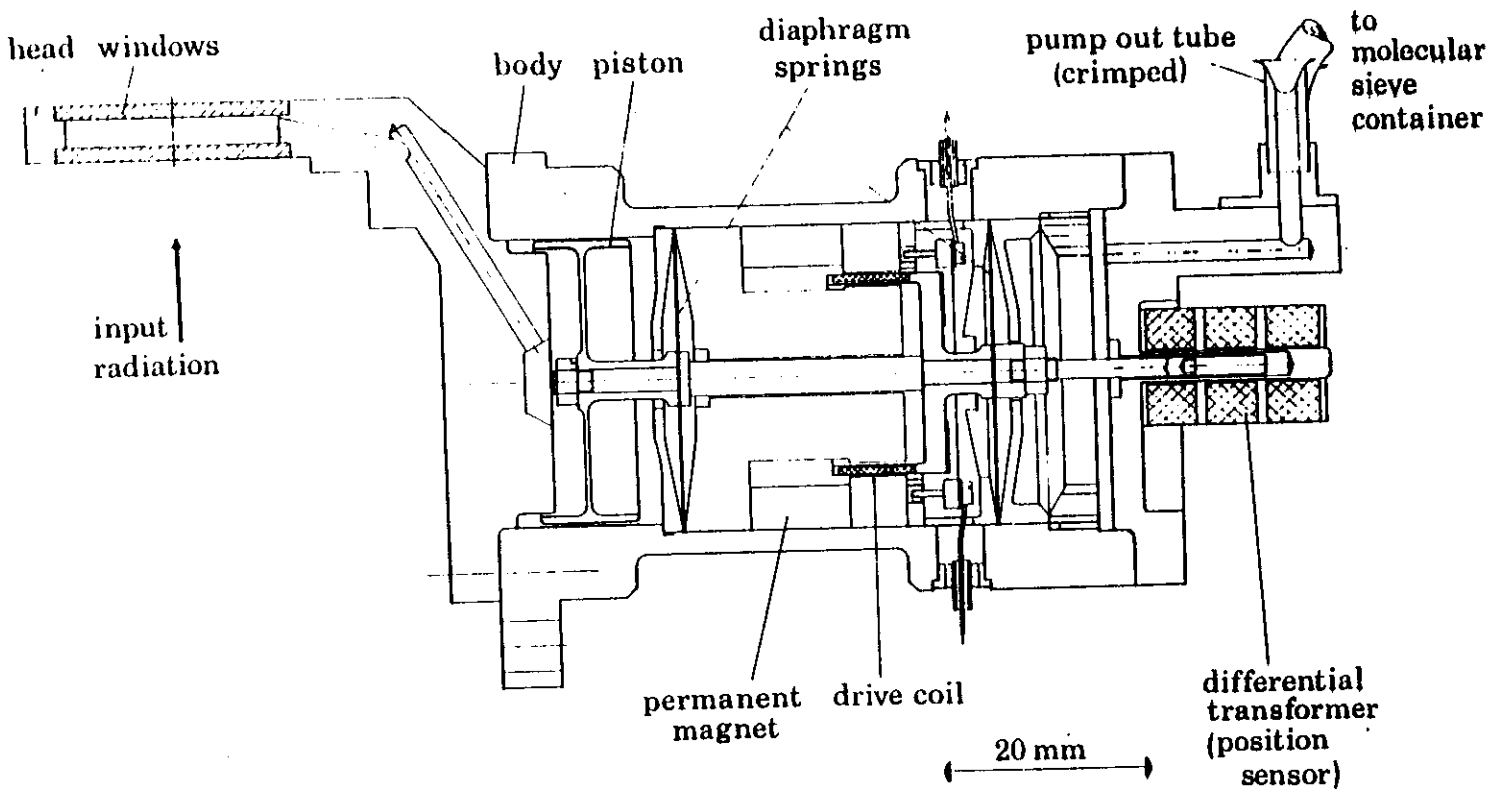


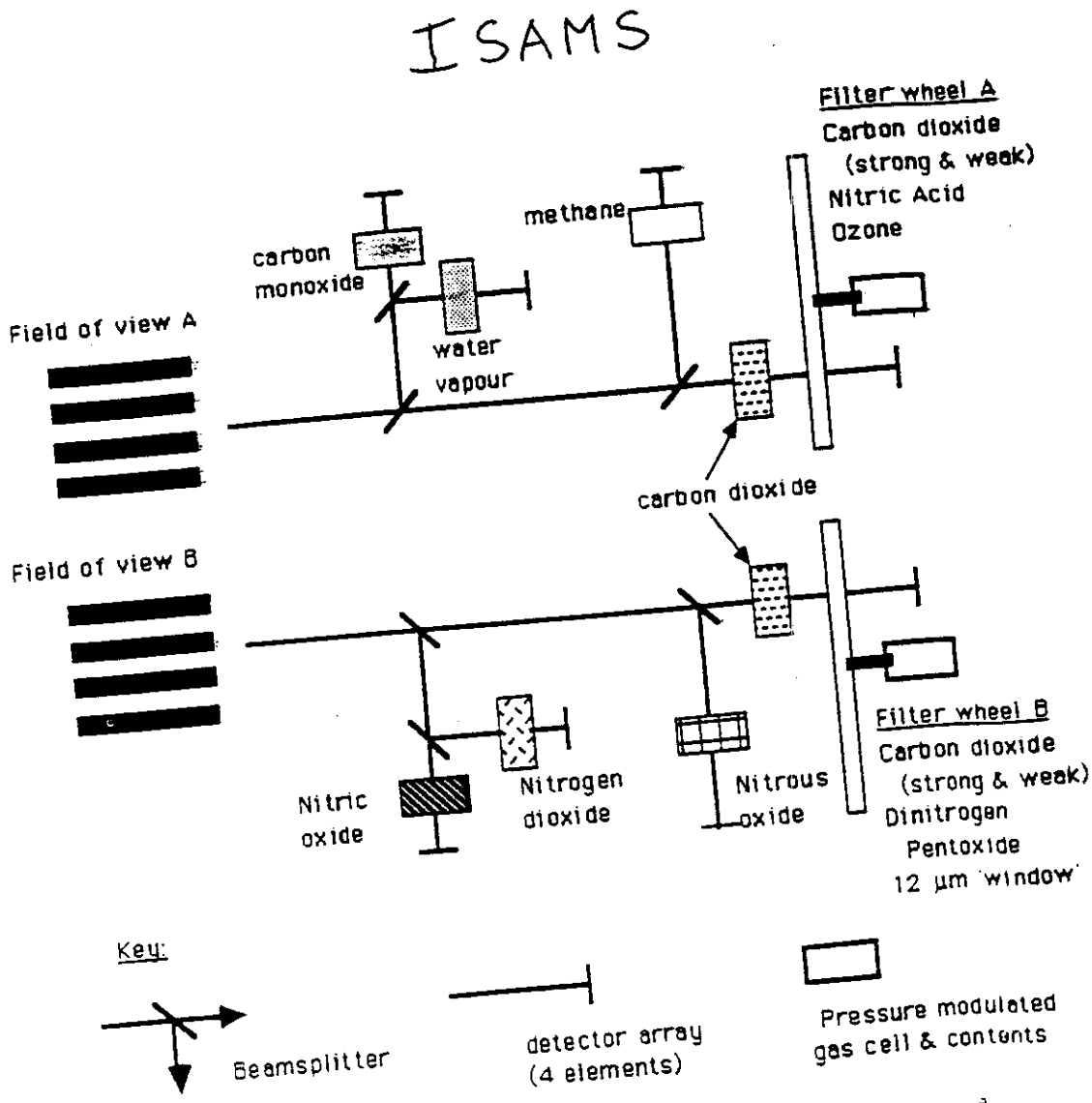

Schéma de principe d'un radiomètre à modulation de press




Montage des différents radiomètres dans l'expérience SAMS




Cross section of a p.m.r. assembly. The body of the PMR is made of titanium with gold 'O' ring seals at each end. The support springs and coil lead-outs are made of beryllium–copper. The thermostatted container of molecular sieve is not shown.




Block diagram of the Improved Stratospheric and Mesospheric Sounder.

| Channel Number | Central Wavelength (μm) | Spectral Bandwidth (cm-1) | Objective |
|---|---|---|---|
| 0 | 4.6 | 82 | CO |
| 1 | 6.8 | 88 | $H_2O$ |
| 2 | 7.9 | 40 | $N_2O$ |
| 3.0 | 15.5 | 34 | $CO_2$ |
| 3.1 | 16.3 | 20 | $CO_2$ |
| 3.2 | 11.3 | 40 | $HNO_3$ |
| 3.3 | 10.0 | 20 | $O_3$ |
| 4 | 5.3 | 102 | NO |
| 5 | 6.3 | 32 | $NO_2$ |
| 6 | 7.4 | 60 | $CH_4$ |
| 7.0 | 15.5 | 34 | $CO_2$ |
| 7.1 | 16.3 | 20 | $CO_2$ |
| 7.2 | 8.1 | 22 | $N_2O_5$ |
| 7.3 | 12.1 | 15 | Window |

ISAMS Spectral Bands.

# MAPS

Measurement of Air Pollution from Satellite

Technological flight on the US Space Shuttle
Nov. 1981 STS-2

Experiment OSTA-1 (Office of Space and Terrestrial Applications)

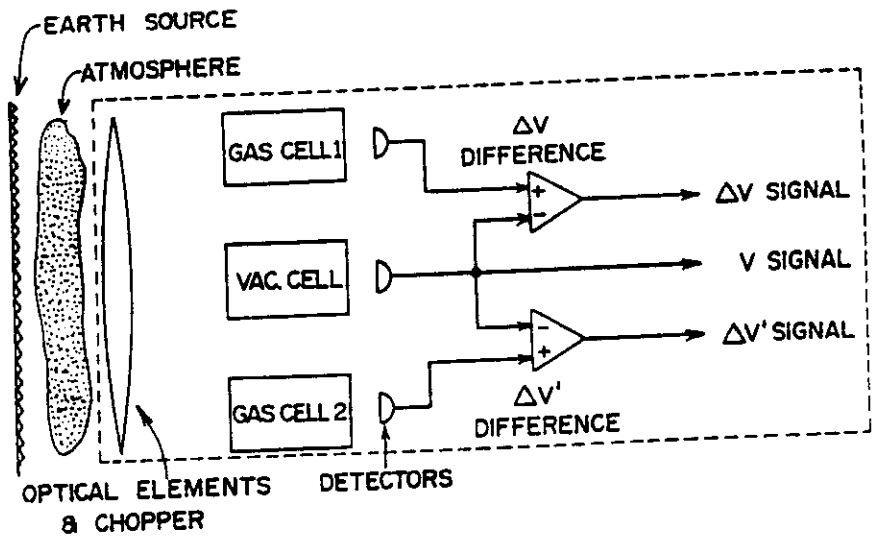
Objective: Measurement of tropospheric CO with gas correlation radiometer (on board CO c

Hypothesis: constant mixing ratio of CO in the troposp

Geometry: nadir viewing

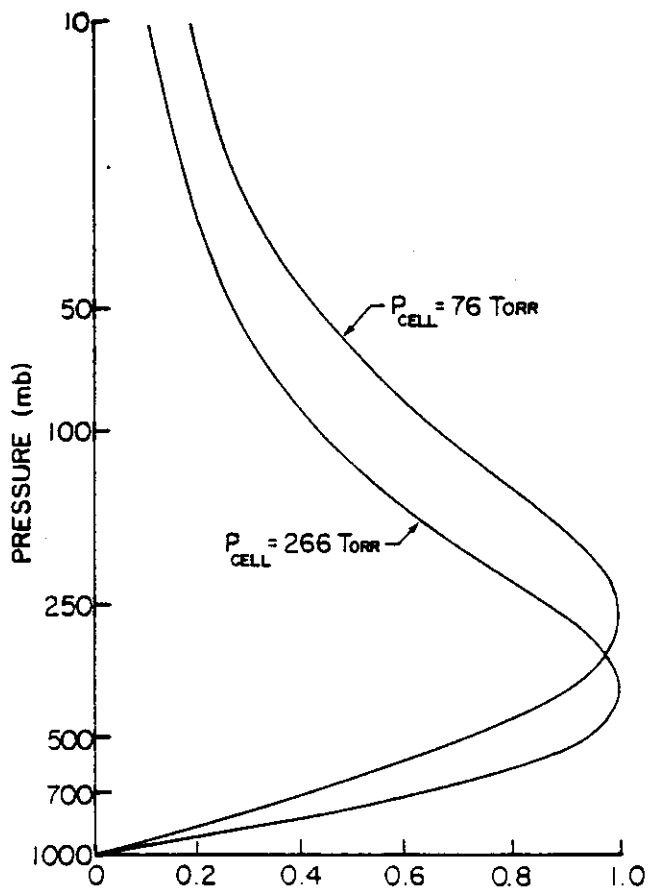
Results: CO mixing ratio between 25 and 115 ppbv

Problem: difference between results obtained with the cell at $P_{CO}$ = 76 Torr and the cell at $P_{CO}$ = 266 Torr




Schematic diagram of a gas filter radiometer.

MAPS

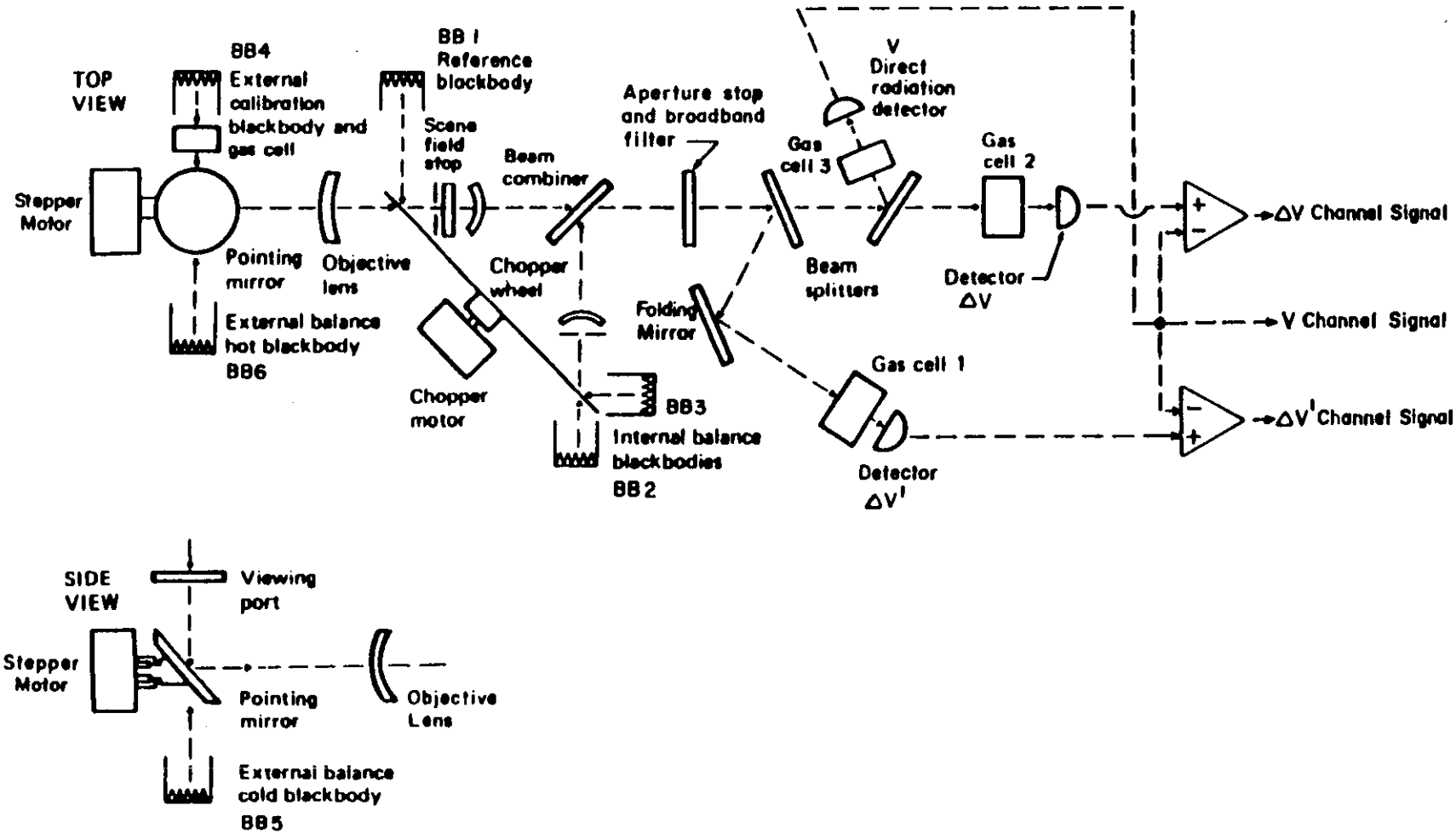



Normalized MAPS signal functions for 110 ppbv carbon monoxide.

OSTA-1/MAPS Instrument Characteristics

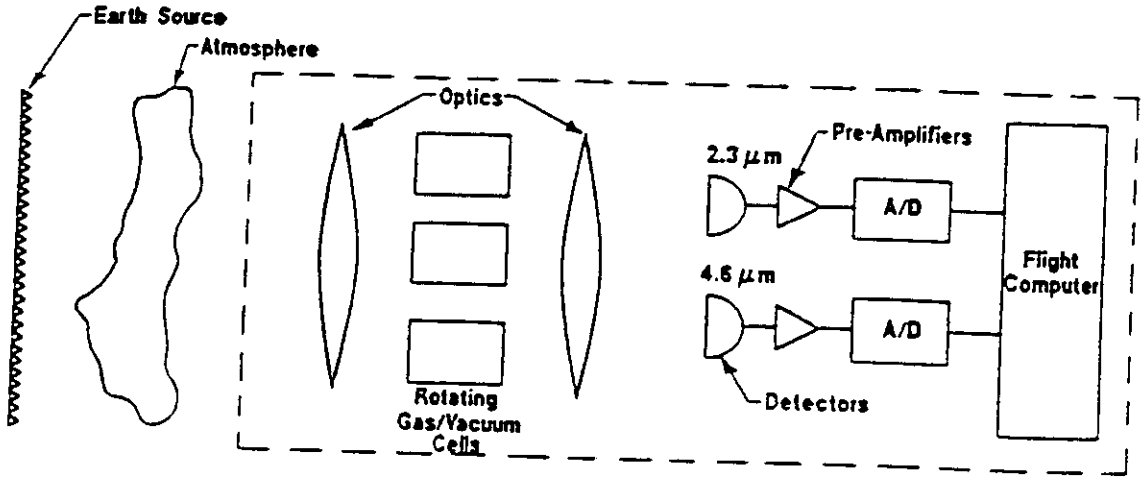
| Parameter | Value |
|---|---|
| Detected gas | carbon monoxide |
| Spectral band | 2080–2220 $cm^{-1}$ |
| Detector type | PbSe, cooled to 195 K |
| Field of view | 4.33° |
| Entrance aperture | 2.94 × 2.94 cm |
| Bandwidth | 0.14 Hz |
| Gas cell pressure | |
| Cell 1 $\Delta V'$ | CO, 76 torr; He, 2 torr; $N_2$, 0 torr |
| Cell 2 $\Delta V$ | CO, 266 torr; He, 2 torr; $N_2$, 0 torr |
| Cell 3 vacuum | CO, 0 torr; He, 76 torr; $N_2$, 0 torr |
| Calibrate | CO, 140 torr; He, 2 torr; $N_2$, 550 torr |
| NEL $V$ | $1.7 \times 10^{-7}$ W $cm^{-2}$ $sr^{-1}$ |
| NEL $\Delta V$, $\Delta V'$ | $5.7 \times 10^{-9}$ W $cm^{-2}$ $sr^{-1}$ |
| Size | 0.90 × 0.76 × 0.56 m |
| Mass | 84 kg |
| Power, average in vacuum | 73 W |
| Temperature range (baseplate) | 273–288 K |
| Data rate | 1 sample set (40 bits $s^{-1}$) |
| Data storage | 107 hours maximum |
| Camera | 35 mm, aerial, 1 photo every 23 s when surface of earth illuminated |
| Film | Aerochrome 2443 false-color infrared |

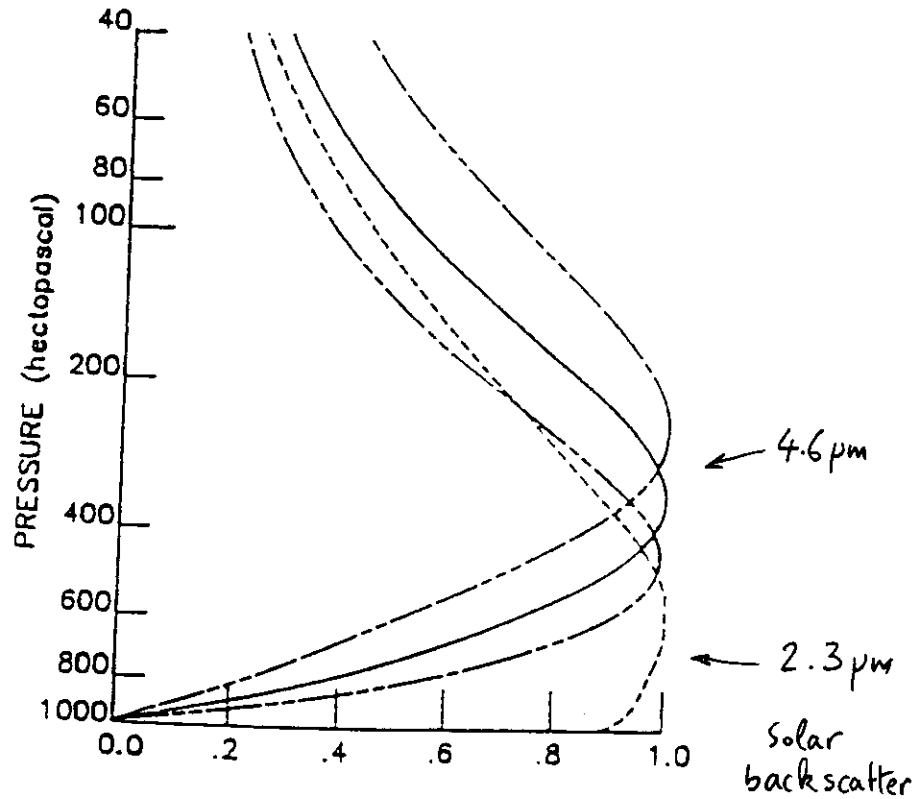
NEL is noise equivalent radiance.




Electro-optical layout of the instrument.

# TRACER → MOPITT (on Terra)



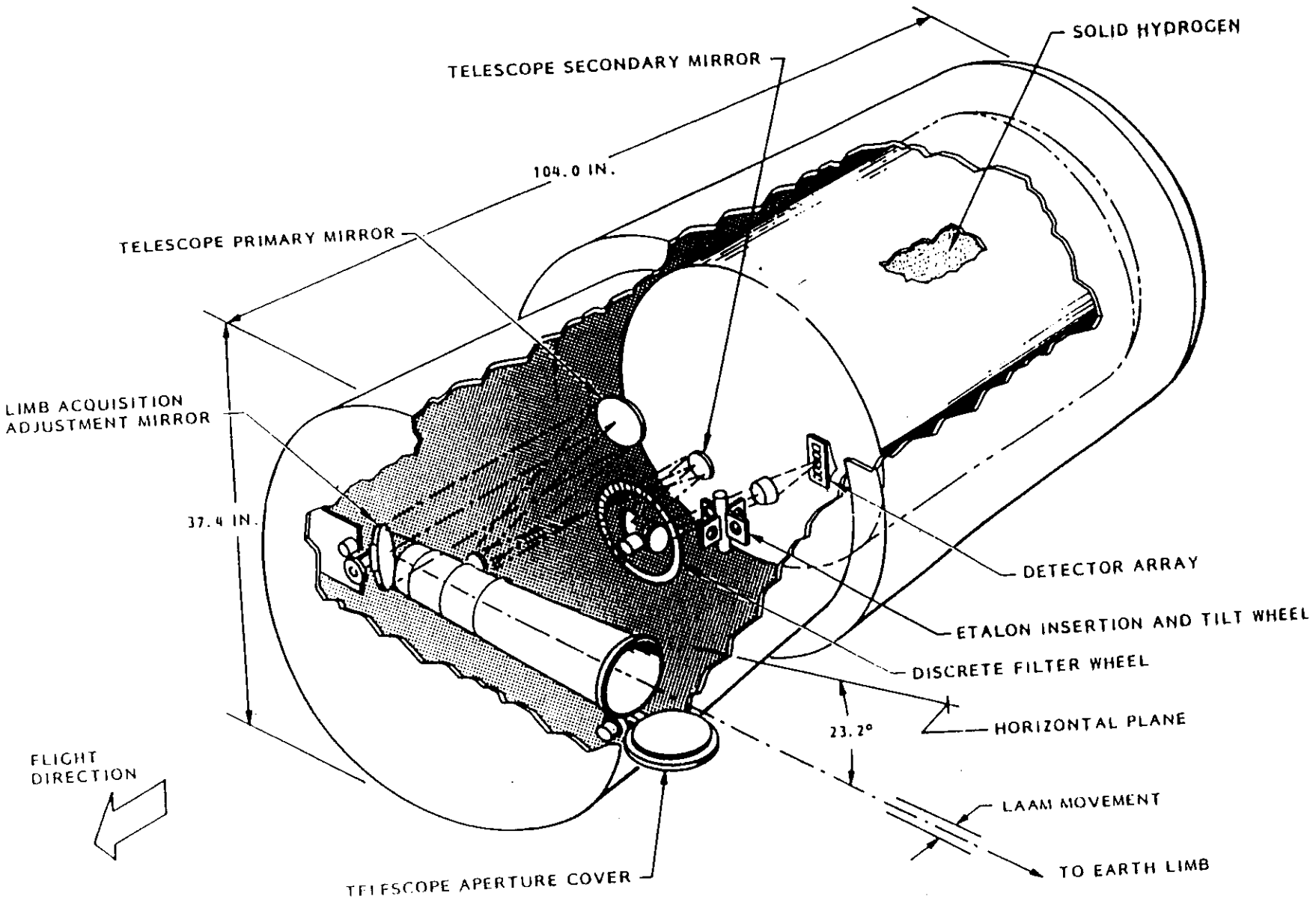
# CLAES

## Cryogenic Limb Array Etalon Spectrometer

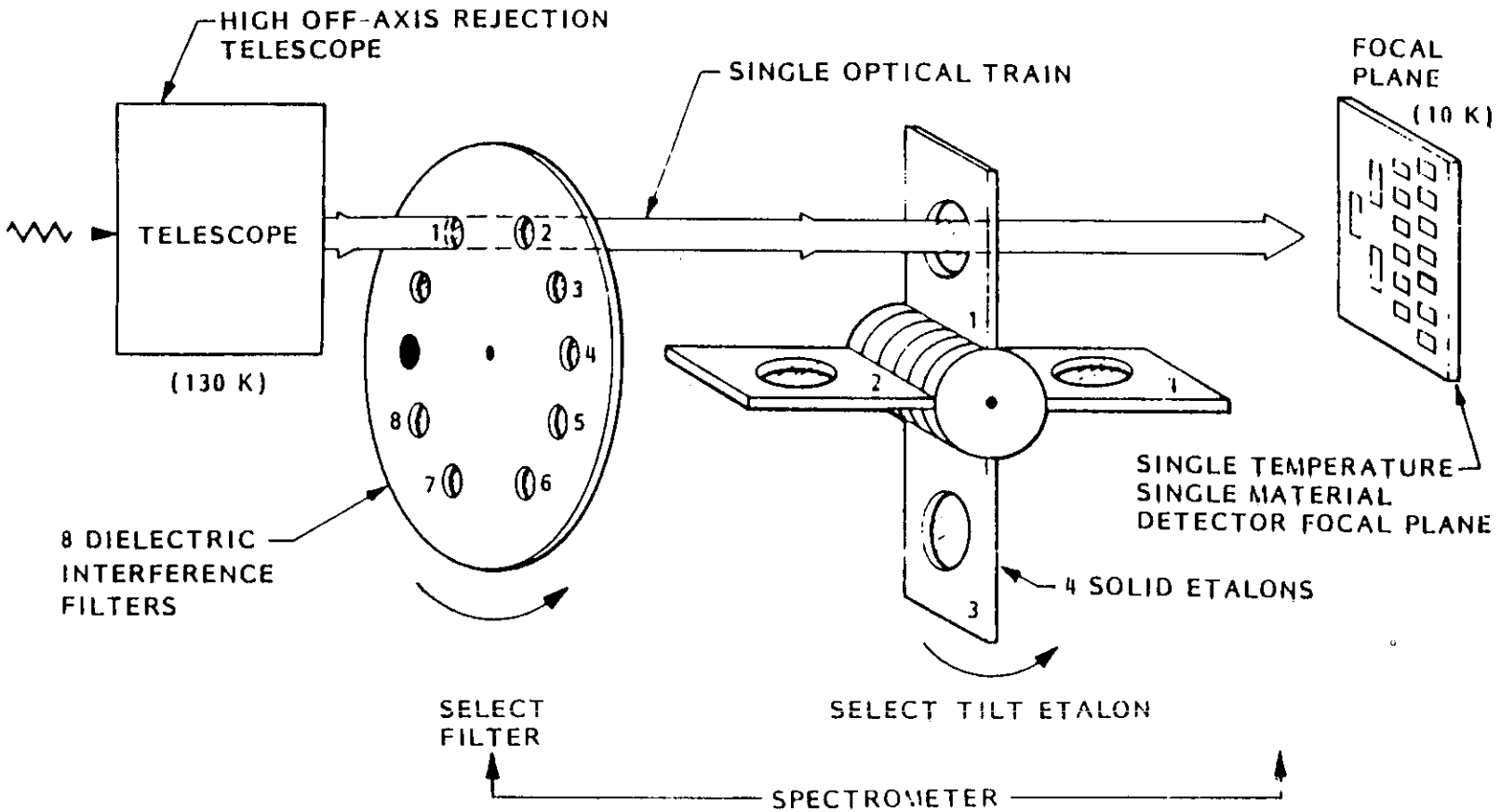
- Cooled Fabry-Pérot etalon
- limb emission
- spectral resolution : $\Delta\tilde{\nu} = 0.25\ cm^{-1}$
- limb between 10 and 60 km
- scan of the limb in 64 s

## Upper Atmospheric Research Satellite

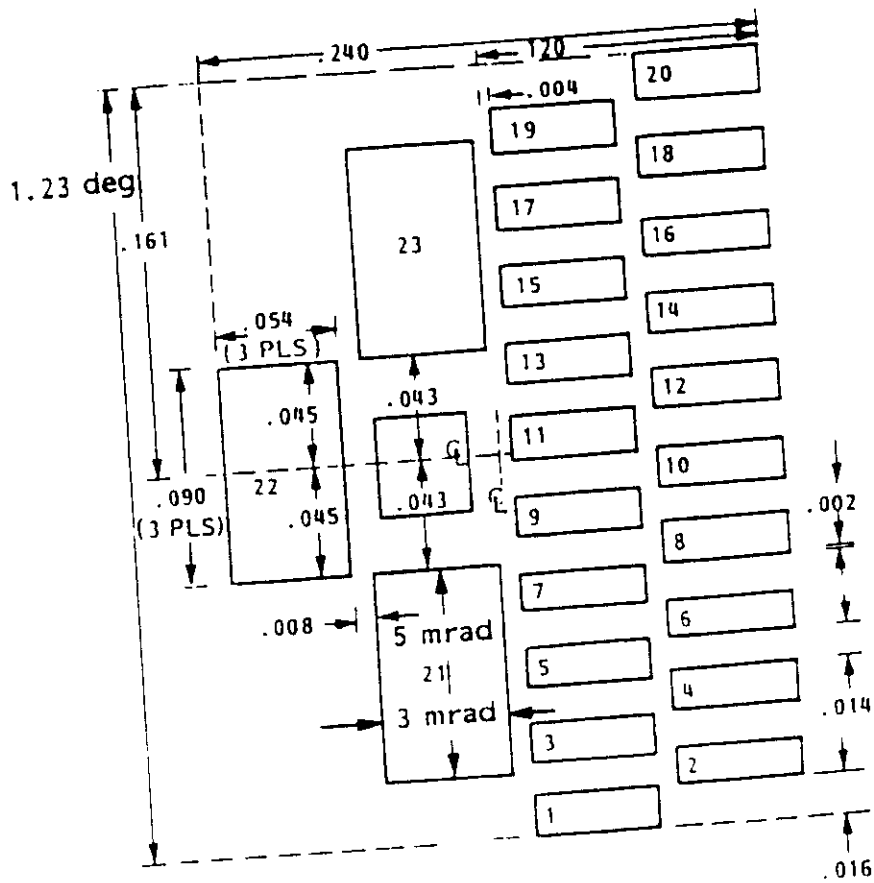
(UARS)


SOLID HYDROGEN
TELESCOPE SECONDARY MIRROR
104.0 IN.
TELESCOPE PRIMARY MIRROR
LIMB ACQUISITION
ADJUSTMENT MIRROR
37.4 IN.
DETECTOR ARRAY
ETALON INSERTION AND TILT WHEEL
DISCRETE FILTER WHEEL
HORIZONTAL PLANE
23.2°
FLIGHT
DIRECTION
LAAM MOVEMENT
TO EARTH LIMB
TELESCOPE APERTURE COVER

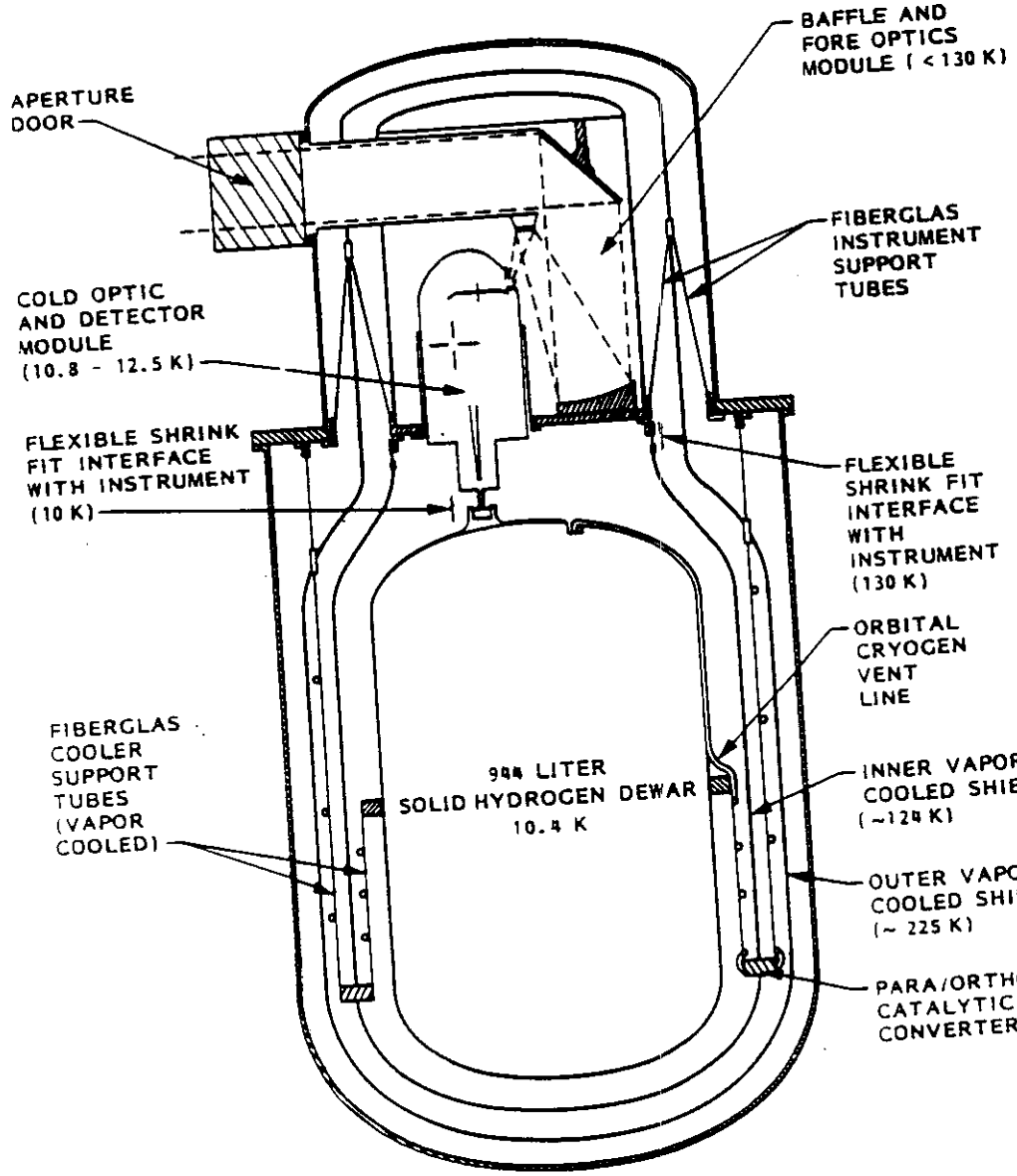
(31)



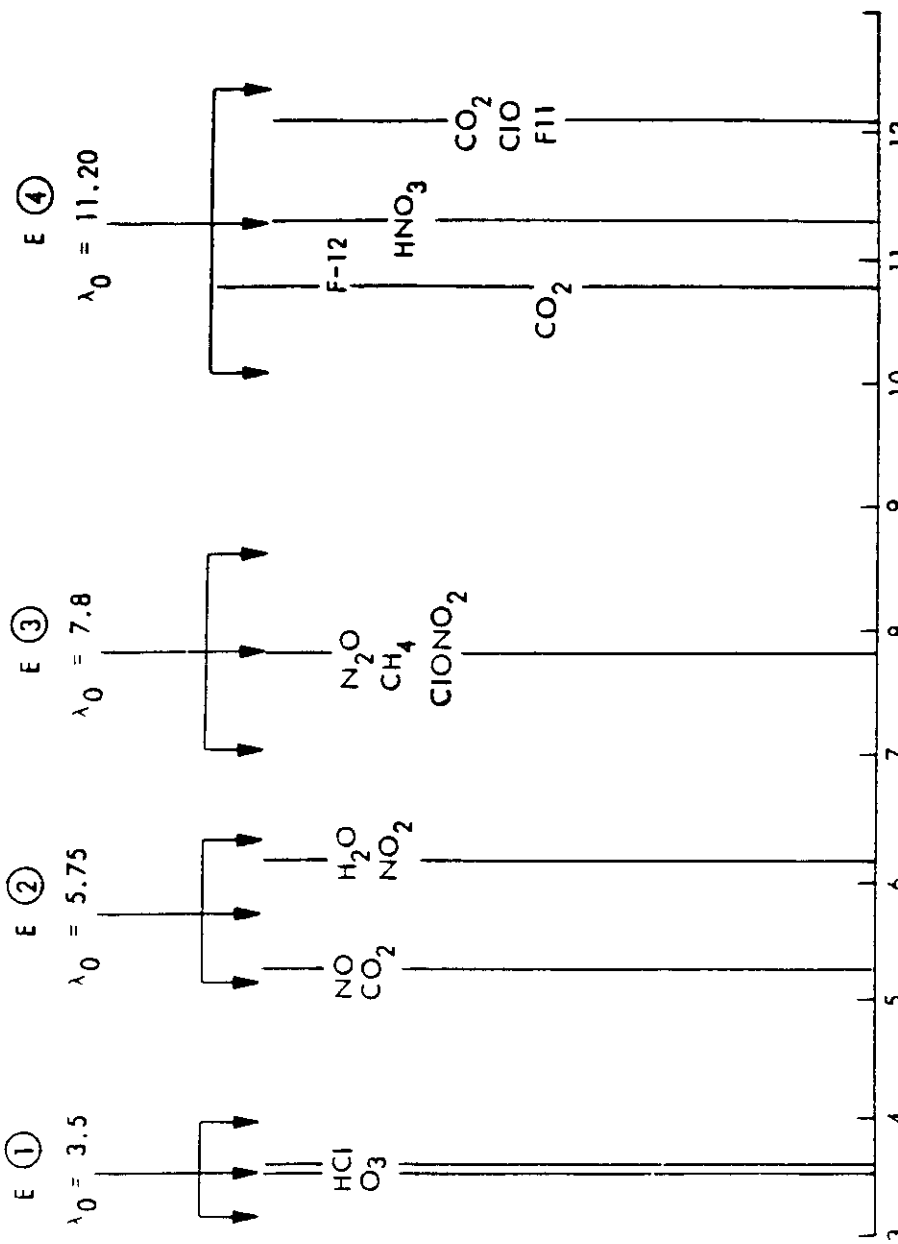

CLAES functional diagram.



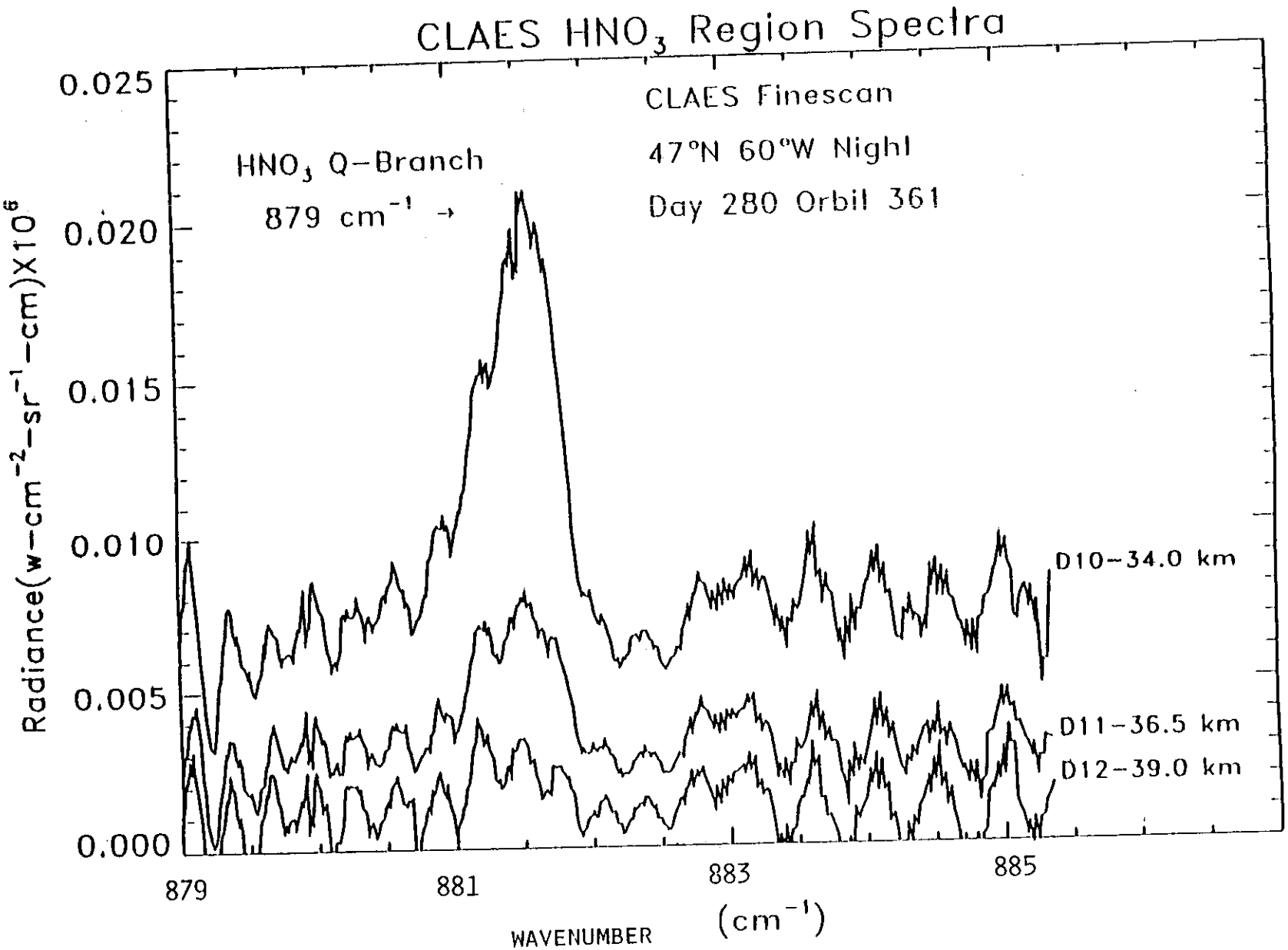

CLAES focal plane.




CLAES instrument/cooler schematic.




Etalon and blocker spectral placement.


CLAES $HNO_3$ Region Spectra
CLAES Finescan
47°N 60°W Night
Day 280 Orbit 361
$HNO_3$ Q-Branch
879 $cm^{-1}$ →
D10-34.0 km
D11-36.5 km
D12-39.0 km
Radiance(w-$cm^{-2}$-$sr^{-1}$-cm)X$10^6$
0.025
0.020
0.015
0.010
0.005
0.000
879
881
883
885
WAVENUMBER ($cm^{-1}$)

# HALOE

## HALogen Occultation Experiment

Filter radiometer and gas correlation radiometer

Solar occultation, absorption

Still operating on board UARS

Limb between 10 and 65 km

# HALOGEN OCCULTATION EXPERIMENT (HALOE)

J. M. Russell, III
*Langley Research Center*

Table 1
HALOE Instrument Parameters

| |
|---|
| Type of measurement: Solar occultation, infrared atmospheric absorption |
| Type of instrument: Gas correlation and filter radiometers |
| Geophysical parameters determined: HF, HCl, $CH_4$, NO, $CO_2$, $H_2O$, $O_3$, $NO_2$, and pressure |
| Wavelength coverage: 2.43 to 10.25 $\mu$m |
| Viewing geometry: Spacecraft sunrise and sunset |
| Spectral resolution: 20 to 120 1/cm |
| Vertical resolution: 2 km at limb |
| Horizontal resolution: 6.2 km at limb |
| Instrument mass: 111.7 kg |
| Average power: 110 watts |
| Data rate: 4000 bps |

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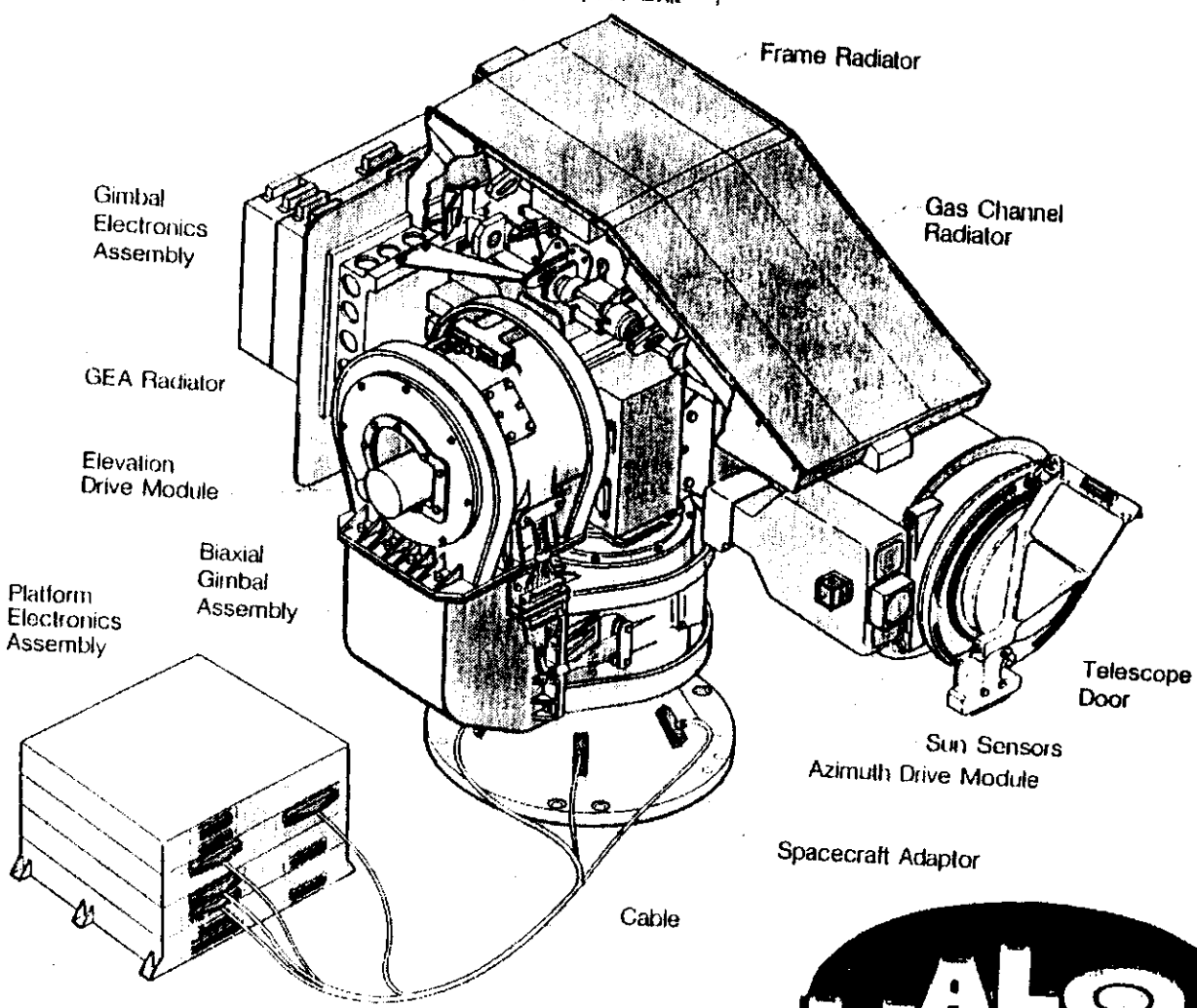
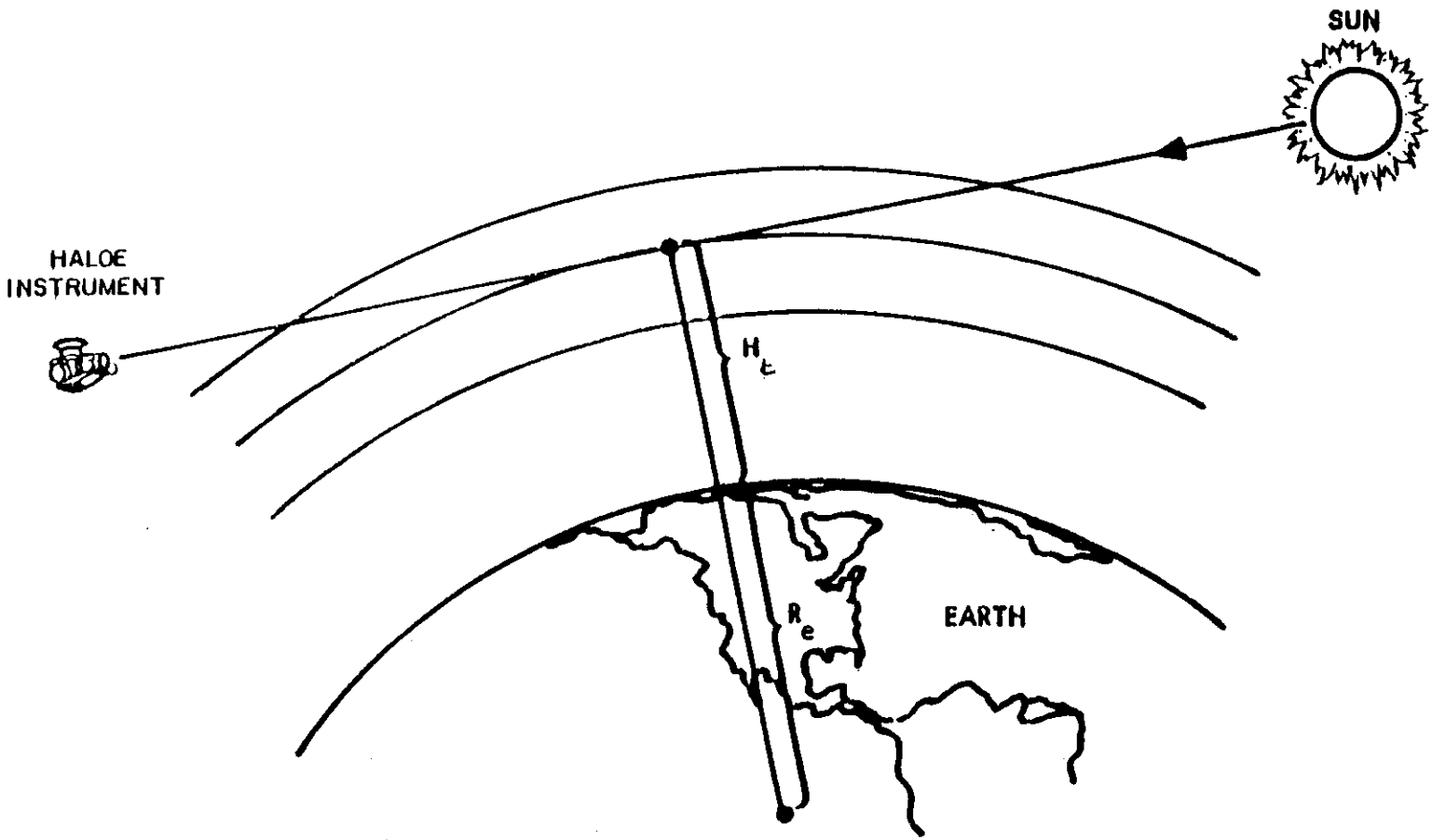
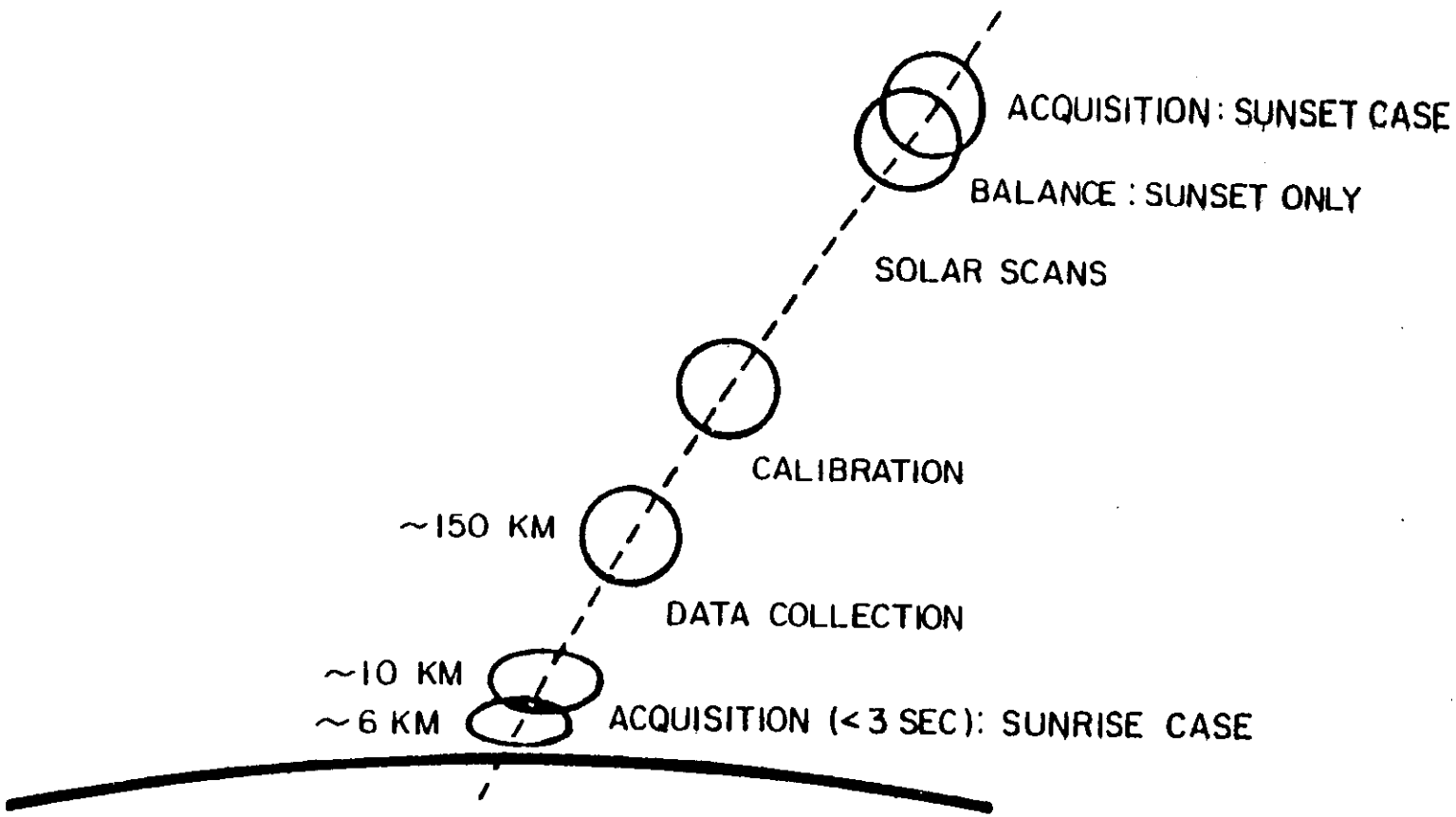
*National Oceanic and Atmospheric Administration*

# HALOE INSTRUMENT

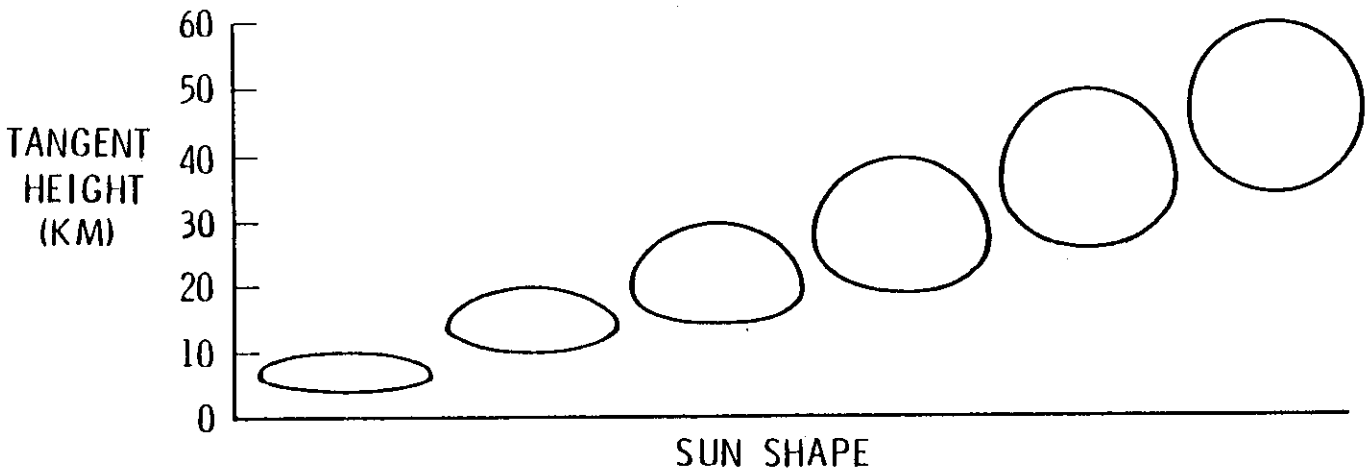





EXPERIMENT GEOMETRY




SEQUENCE OF HALOE OPERATIONS DURING SUNSET AND SUNRISE EVENTS




SUN SHAPE CHANGE DUE TO REFRACTION

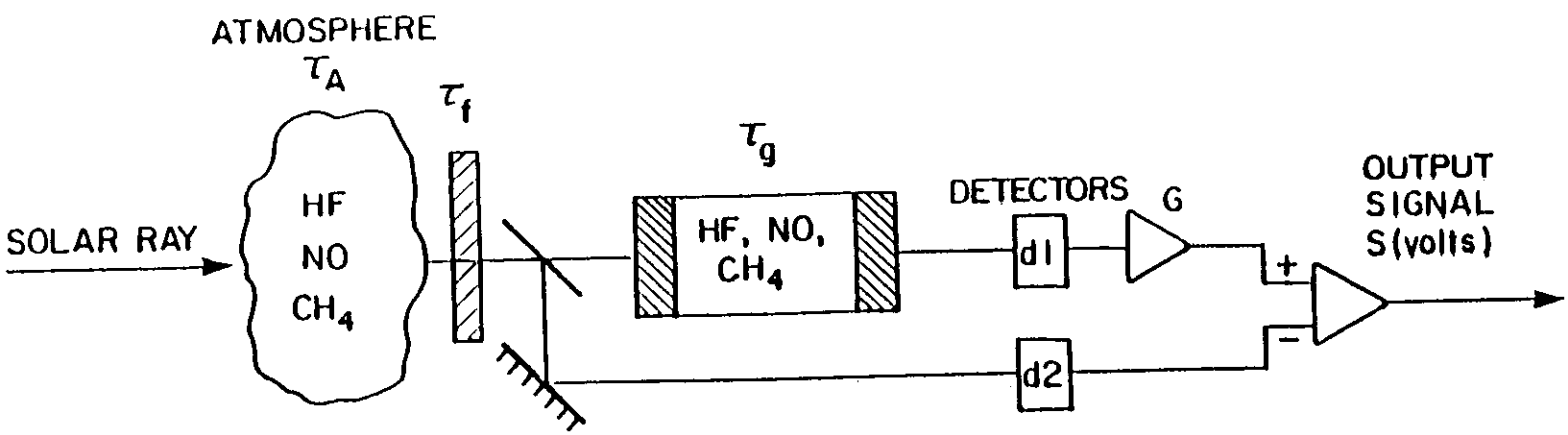
## HALOE FILTER SPECIFICATIONS

- IN BAND

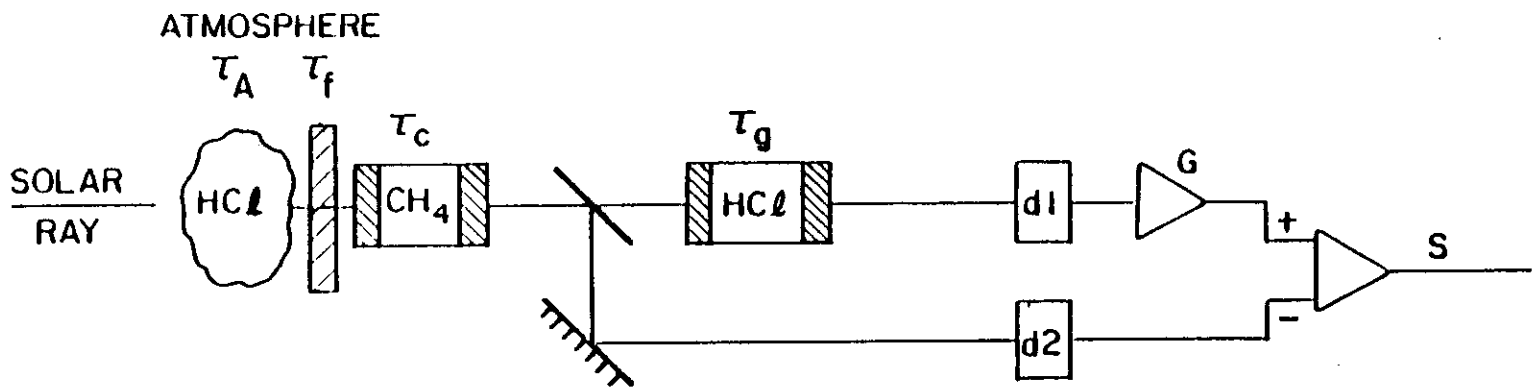
| GAS | CENTER, $cm^{-1}$ ($\mu m$) | 50% POINTS ($cm^{-1}$) | MAX 5% POINT WIDTH, $cm^{-1}$ |
|---|---|---|---|
| HF | 4078 (2.452) | 4047±6 4109±6 | 117 |
| $HC\ell$ | 2940 (3.401) | 2910±6 2970±6 | 1108 |
| $CH_4$ | 2891 (3.459) | 2870±6 2912±6 | 82 |
| NO | 1900 (5.260) | 1883±6 1917±6 | 62 |
| $CO_2$ | 3572 (2.799) | 3537±6 3608±6 | 128 |
| $H_2O$ | 1514 (6.605) | 1506±6 1522±6 | 29 |
| $O_3$ | 996 (10.040) | 976±6 1017±6 | 78 |
| $NO_2$ | 1600 (6.250) | 1591±5 1607±5 | 29 |

- OUT OF BAND

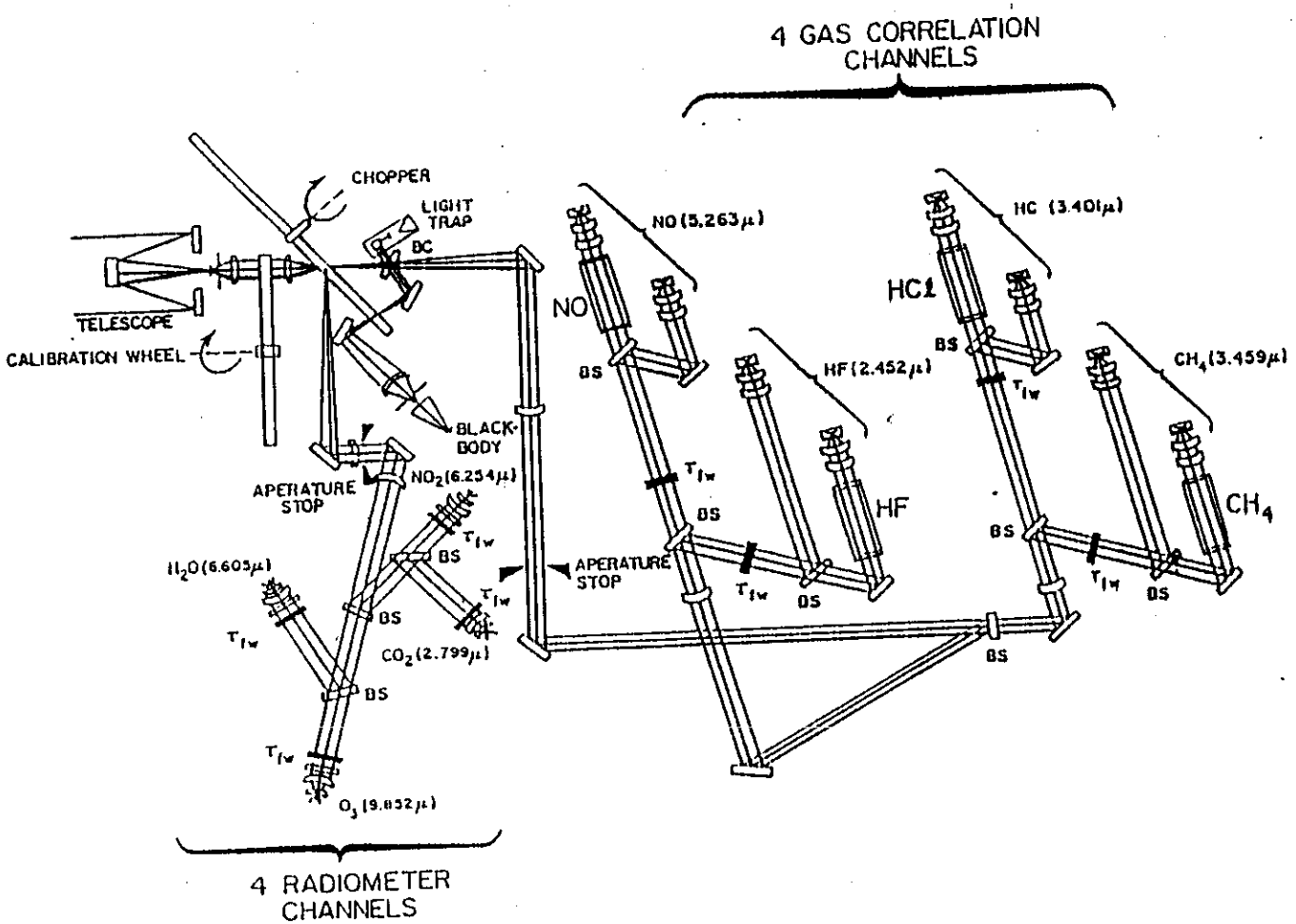
  < 0.001% For All Channels



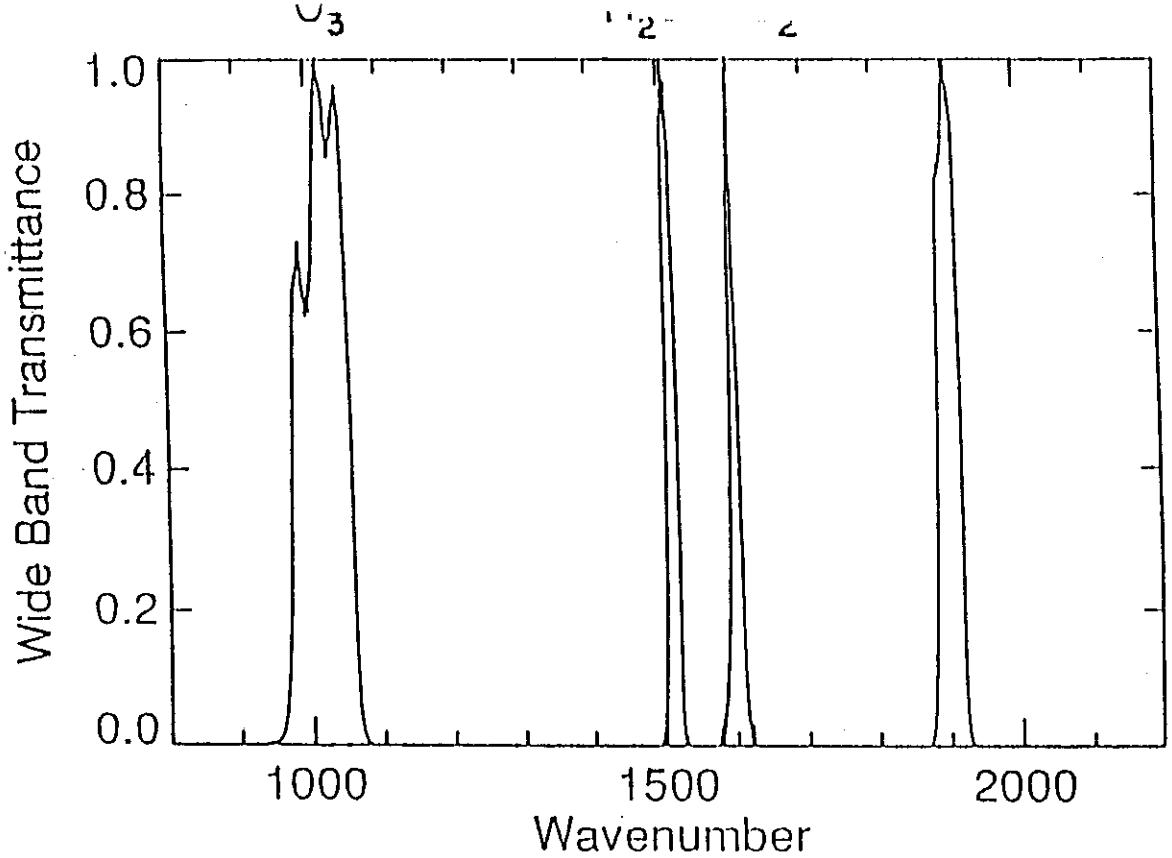

SCHEMATIC OF HF, NO, $CH_4$ GAS CHANNELS



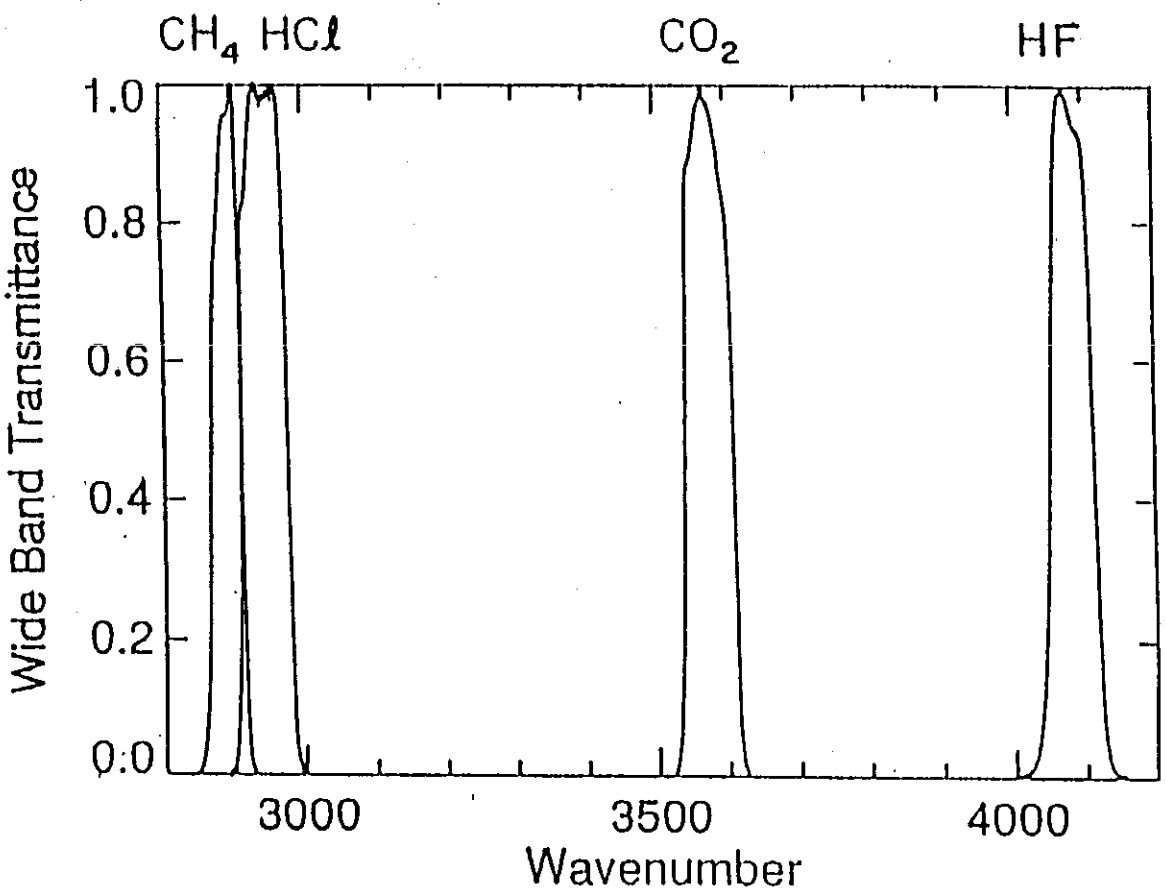

SCHEMATIC OF HCℓ GAS CHANNEL SHOWING THE $CH_4$ BLOCKING CELL




...or Optical Diagram




HALOE broadband end-to-end spectral response for the $O_3$, $H_2O$, $NO_2$, and NO channels.



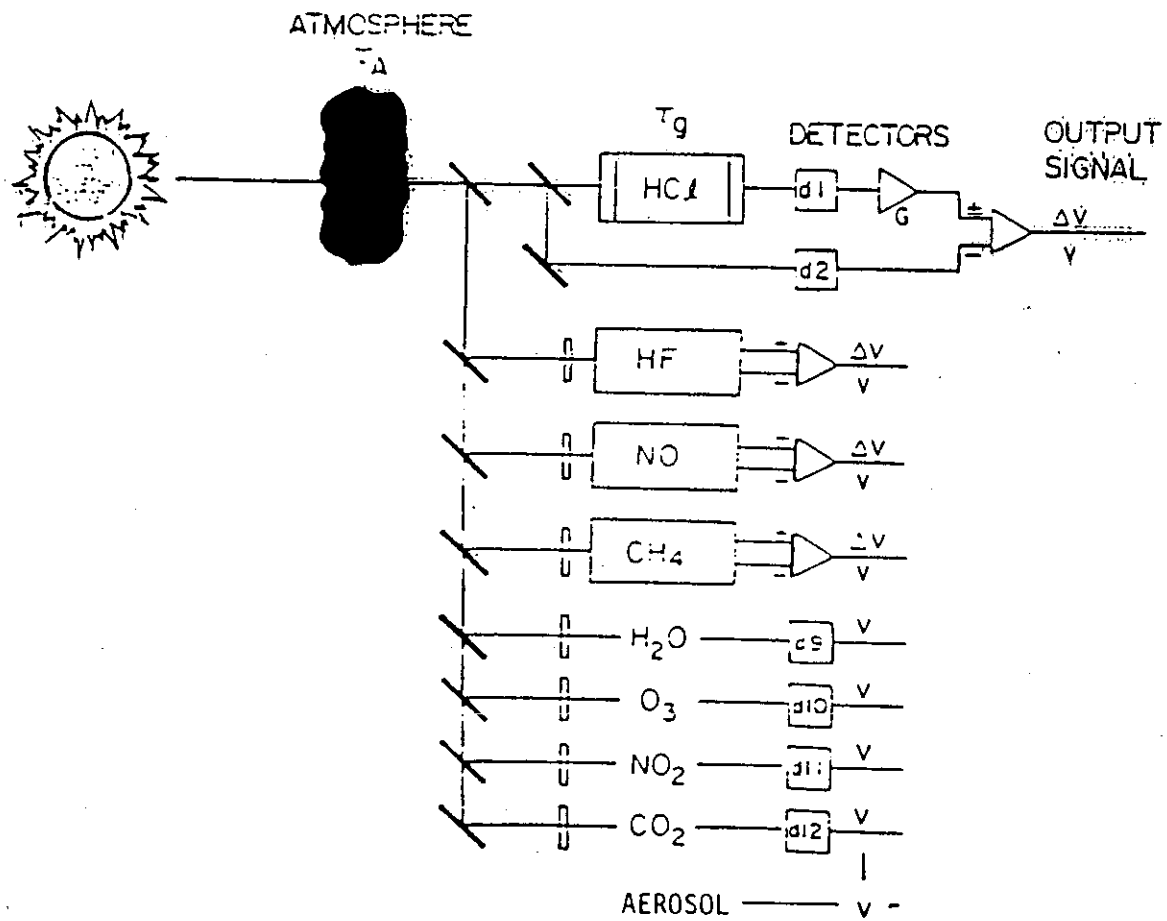

HALOE broadband end-to-end spectral response for the $CH_4$, HCℓ, $CO_2$, and HF channels.

## HALOE MEASUREMENT OBJECTIVES

| ATMOSPHERIC CONSTITUENT | SPECTRAL RANGE*, $CM^{-1}$ | ALT. RANGE, KM<br>VERT. RESOL., KM | HORIZONTAL RESOLUTION | TEMPORAL RESOLUTION | SINGLE PROFILE ACCURACY, % |
|---|---|---|---|---|---|
| HCl | 2886 TO 2994 (3.40 μM) | 10 TO 40<br>2 | • ZONAL MEAN ALT. VS. LAT CROSS SECTION<br>• ALT. VS. LONG. AT A GIVEN LAT.<br>• GLOBAL COVERAGE | BIWEEKLY, MONTHLY, SEASONAL | 10 TO 15 |
| HF | 4019 TO 4136 (2.45 μM) | 10 TO 40<br>2 | | | 5 |
| $CH_4$ | 2850 TO 2932 (3.46 μM) | 10 TO 55<br>2 | | | 10 TO 15 |
| NO | 1869 TO 1931 (5.26 μM) | 10 TO 45<br>2 | | | >5 |
| $H_2O$ | 1500 TO 1528 (6.60 μM) | 10 TO 45<br>2 | | | |
| $O_3$ | 957 TO 1035 (10.04 μM) | 10 TO 65<br>2 | | | |
| $NO_2$ | 1586 TO 1614 (6.25 μM) | 10 TO 45<br>2 | | | |
| $CO_2$ (PRESS.) | 3508 TO 3636 (2.80 μM) | 10 TO 55<br>2 | | | |

* SPECTRAL FILTER SET POINTS

# *HALOE Channels & Filters*




| FILTER ($cm^{-1}$) | ($\mu m$) | |
|---|---|---|
| 2886 - 2994 | 3.40 | GAS FILTER CHANNELS |
| 4019 - 4136 | 2.45 | |
| 1869 - 1931 | 5.26 | |
| 2850 - 2932 | 3.46 | |
| 1500 - 1528 | 6.60 | RADIOMETER CHANNELS |
| 957 - 1080 | 10.04 | |
| 1586 - 1614 | 6.25 | |
| 3508 - 3636 | 2.80 | |
| all channels | | |


HALOE HCl 600.00 K Surface Cross Section, Sunrise on 22-MAR to 02-APR-1995

# ATMOS

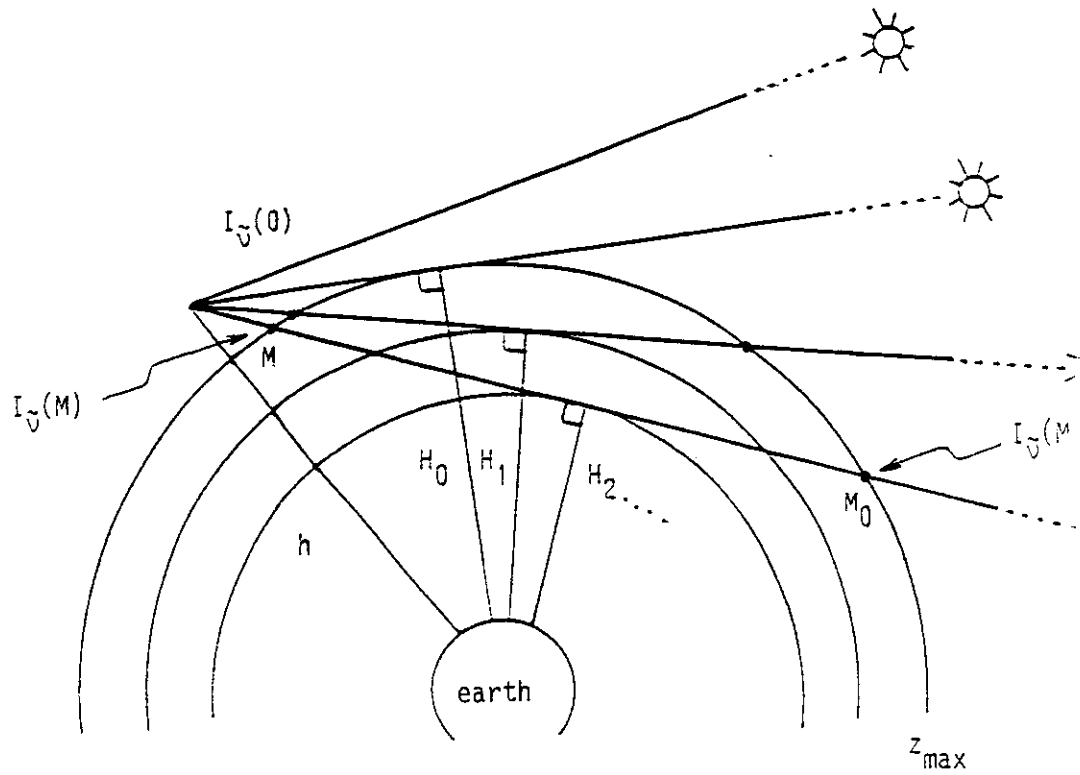
Atmospheric Trace MOlecules Spectrosco

- Fourier transfor spectrometer
- Space Shuttle missions

  SPACELAB 3 (1985)
  ATLAS 1 (1992)
  ATLAS 2 (1993)
  ATLAS 3 (1994)

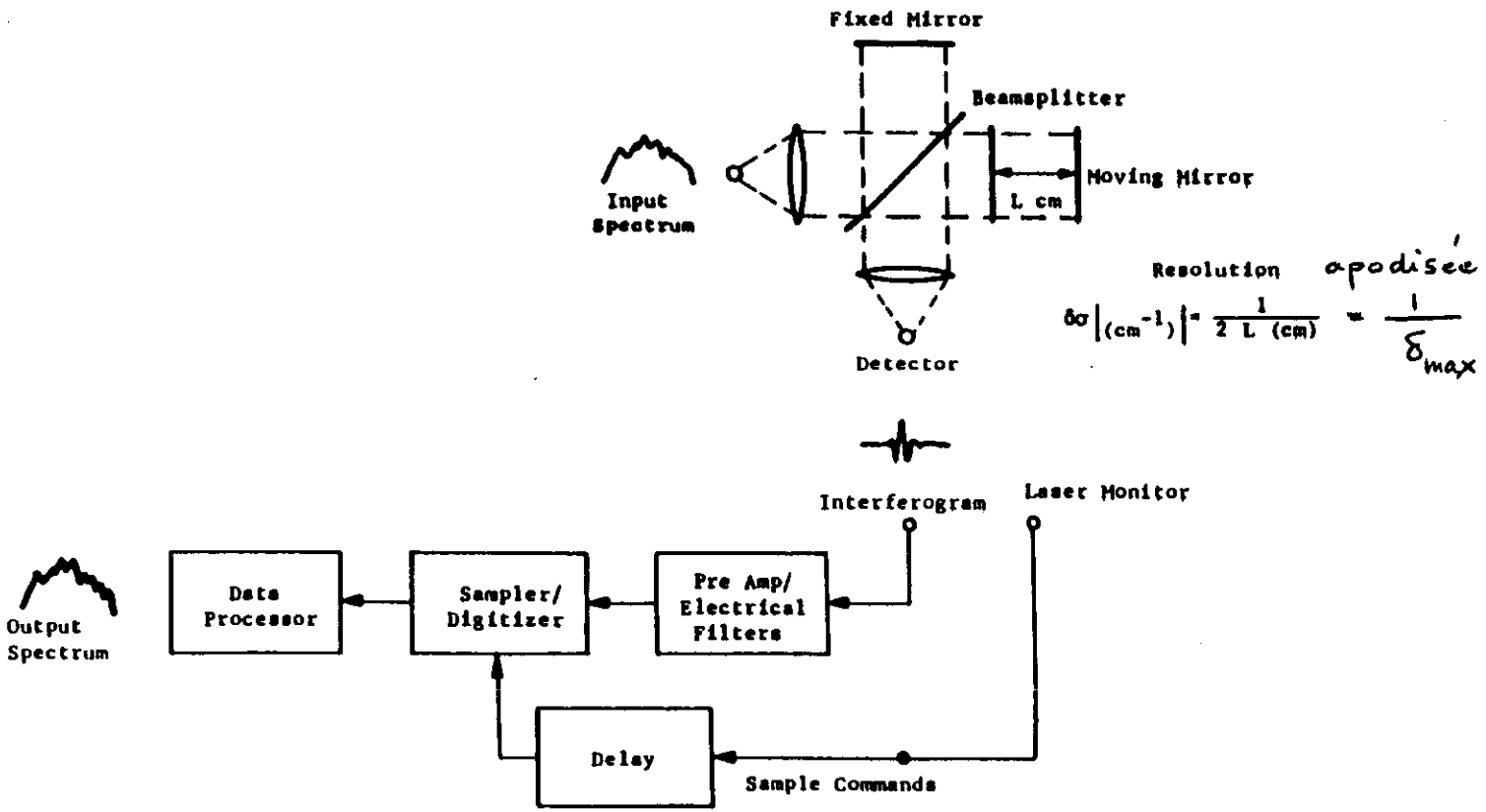
- Solar occultation
- more than 20 molecular species

SOLAR OCCULTATION GEOMETRY



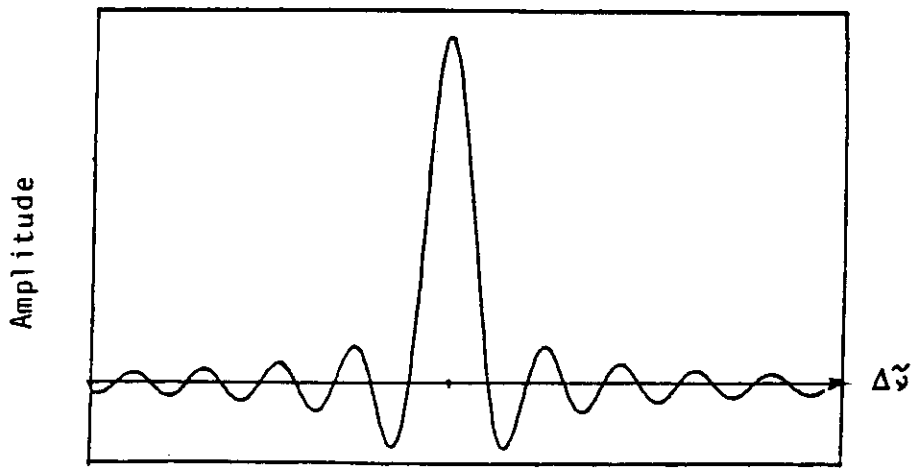

$H_0, H_1 H_2$ ... series of successive tangent heights

$I_{\tilde{\nu}}(0) = I_{\tilde{\nu}}(M_0)$ out of atmosphere intensity




Fourier Transform Spectrometer optical and electrical schematic

# Fonction d'appareil en TF




Fonction non apodisée :

$$f(\Delta\tilde{\nu}) = \frac{\sin(2\pi\,\Delta\tilde{\nu}\,\delta_{max})}{2\pi\,\Delta\tilde{\nu}\,\delta_{max}}$$

$\delta_{max}$ = différence de marche maximum

= $2 \times L$ $\quad$ $L$ déplacement maximum du miroir

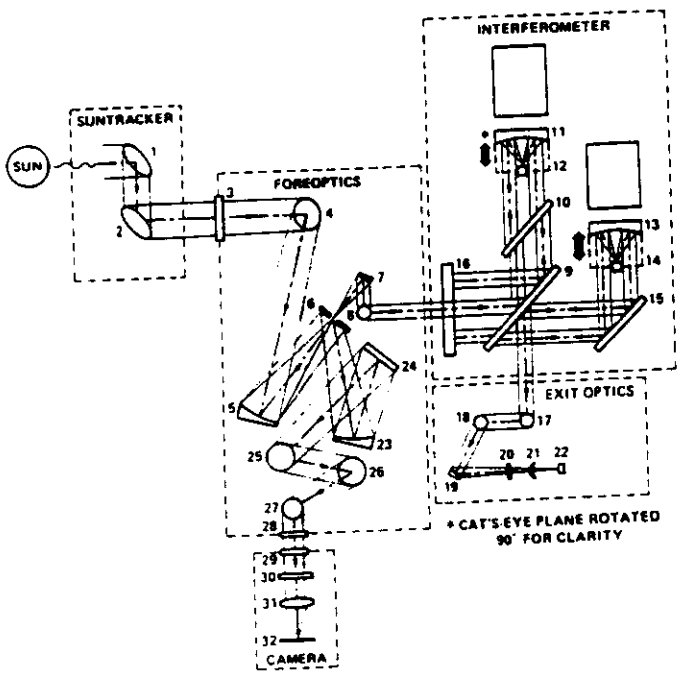
largeur à mi-hauteur (FWHM)

(full width at half maximum)

$$\Delta\tilde{\nu}_{\substack{\text{non}\\ \text{apodisé}}} = 1.207\,\frac{1}{2\,\delta_{max}}$$

après apodisation :

$$\Delta\tilde{\nu}_{apodisé} \simeq \frac{1}{\delta_{max}}$$




1. ELEVATION MIRROR
2. AZIMUTH MIRROR
3. ZnSe WINDOW-AR COATED, WEDGED
4. FOLD MIRROR
5. F/3 PARABOLOIDAL MIRROR
6. FIELD STOP MIRROR (1 OF 3)
7. F/3 PARABOLOIDAL MIRROR
8. FOLD MIRROR
9. KBr BEAMSPLITTER, WEDGED
10. KBr COMPENSATOR, WEDGED
11. CAT'S-EYE PRIMARY MIRROR } ARM 1
12. CAT'S-EYE SECONDARY MIRROR }
13. CAT'S-EYE PRIMARY MIRROR } ARM 2
14. CAT'S-EYE SECONDARY MIRROR }
15. FOLD MIRROR
16. RETRO MIRROR
17. FOLD MIRROR
18. FOLD MIRROR
19. SPHERICAL MIRROR
20. BANDPASS FILTER (1 OF 6), WEDGED
21. ZnSe FIELD LENS-AR COATED
22. HgCdTe DETECTOR
23. ELLIPSOIDAL FIELD TRANSFER MIRROR
24. FOLD MIRROR
25. FOLD MIRROR
26. FOLD MIRROR
27. FOLD MIRROR
28. BK-7 COVER WINDOW
29. ND FILTER/WINDOW
30. BANDPASS FILTER
31. FIELD CORRECTION LENS
32. FILM PLANE

**Optical diagram of the foreoptics and interferometer of the ATMOS sensor.**

# ATMOS INSTRUMENT CHARACTERISTICS

| | |
|---|---|
| SPECTRAL INTERVAL COVERED | 550-4800 $cm^{-1}$ (2.1 TO 18 MICRONS) |
| SPECTRAL RESOLUTION | 0.01 $cm^{-1}$ UNAPODIZED (50 cm OPD) |
| SPECTRAL PRECISION | 0.001 $cm^{-1}$ (HE-NE REFERENCE LASER) |
| SPATIAL RESOLUTION | 1 TO 2.5 Km |
| FIELD OF VIEW | 1, 2, OR 4 MRAD, SELECTABLE |
| APERTURE | 75 mm DIAMETER |
| SCAN TIME | 1 SECOND |
| POINTING ACCURACY | 0.1 MRAD (2-AXIS SUNTRACKER) |
| DETECTOR | HgCdTe (77K) |
| DATA RATE | 15.76 MEGABITS/SECOND |
| MASS | 250 Kgm |
| VOLUME | ~1 STERE (INCL. ELECTRONICS) |
| AVERAGE POWER | 350 WATTS |