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AUTUMN COLLEGE
ON
THE TROPOSPHERE, STRATOSPHERE AND MESOSPHERE

10 September - 19 October 1984

MEASURING TECHNIQUES AND MEASUREMENTS

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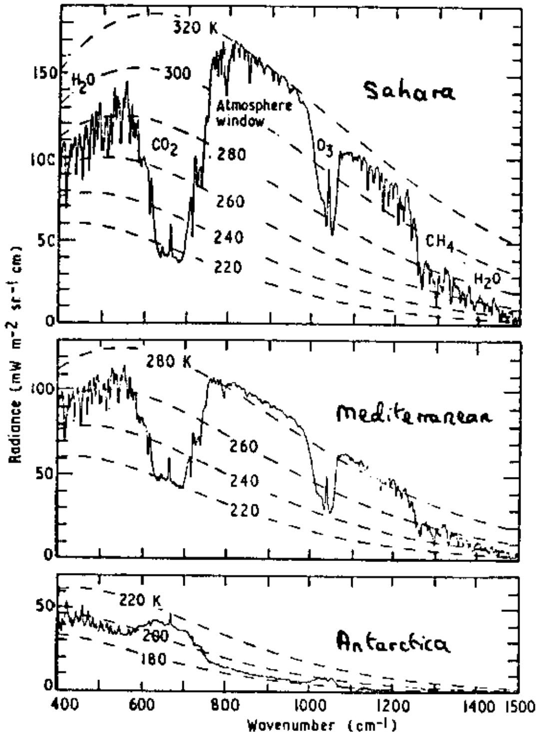
These are preliminary lecture notes, intended only for distribution to College participants. Missing or extra copies are available from Room 230.

Remote Sounding of the Atmosphere – Basic Principles



Nimbus 4 IRIS spectrum (Hanel 1971)

wavelength λ

wavenumber ν

$$\lambda = \frac{1}{\nu}$$

e.g. $15\mu m \equiv 667\ cm^{-1}$

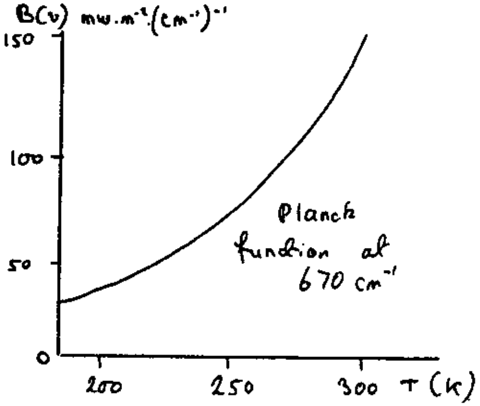
$5\mu m \equiv 2000\ cm^{-1}$

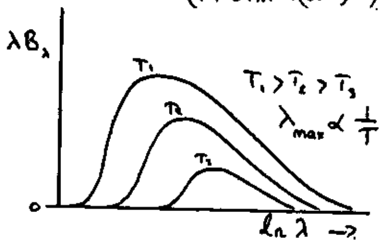
PLANCK FUNCTION:

$$B(\nu) = \frac{2hc\nu^3}{e^{\frac{hc\nu}{kT}} - 1}$$

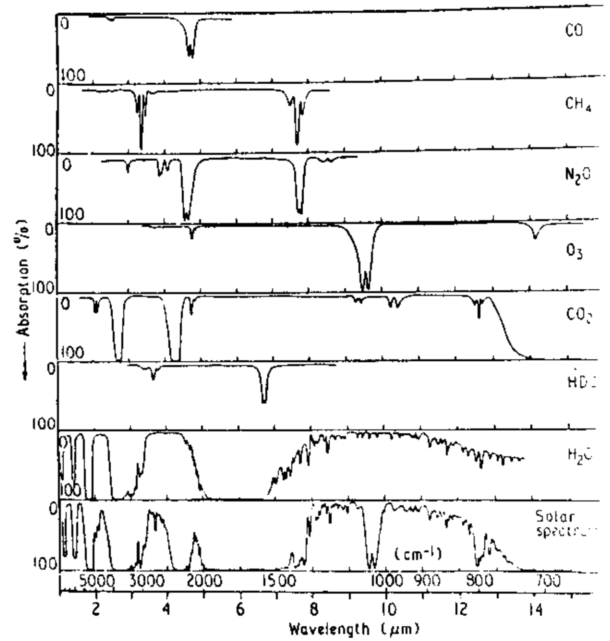
$$= \frac{1.1906 \cdot 10^{-5}\ \nu^3}{e^{1.43879\nu/T} - 1}$$

$(mW.m^{-2}.(cm^{-1})^{-1})$



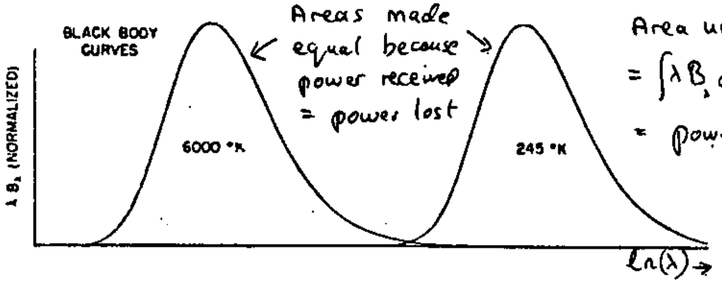


Absorption by vertical path through whole atmosphere (Shaw) →

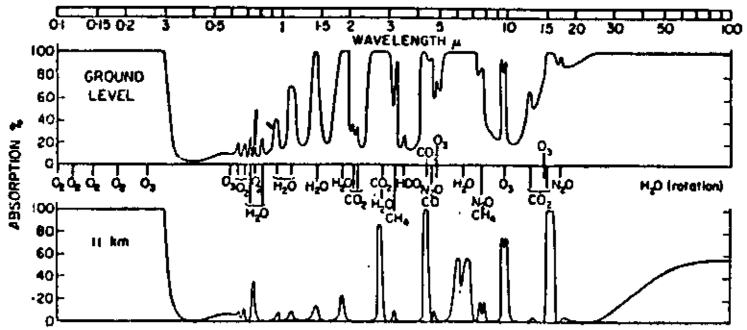


Windows: $3.5\mu m$, $12\ \mu m$

Solar scattering (clouds, aerosol) $< 4\mu m$.



Area under curve $= \int \lambda B_\lambda\, d\ln\lambda = \int B_\lambda\, d\lambda$ = power received.



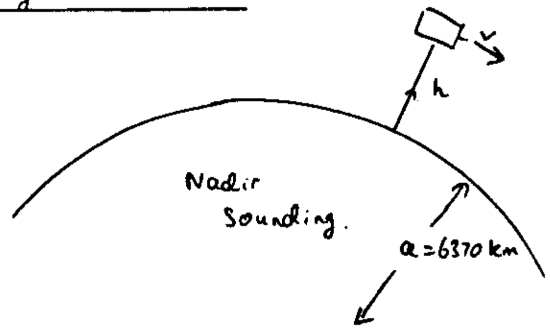
0 to ∞

Absorption by vertical path

11 km to ∞

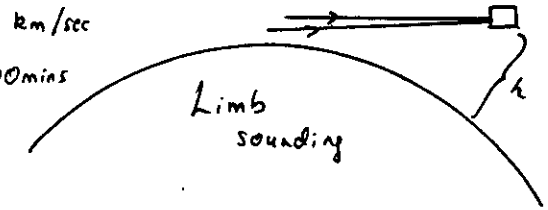
(Goody 1964)

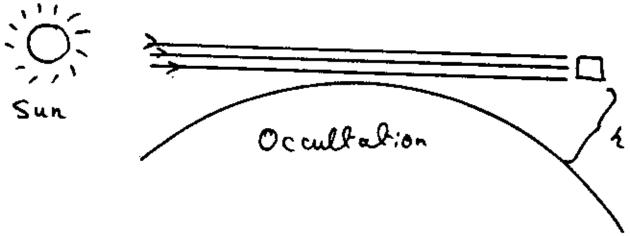
Possible Viewing Geometries.



Orbiters:

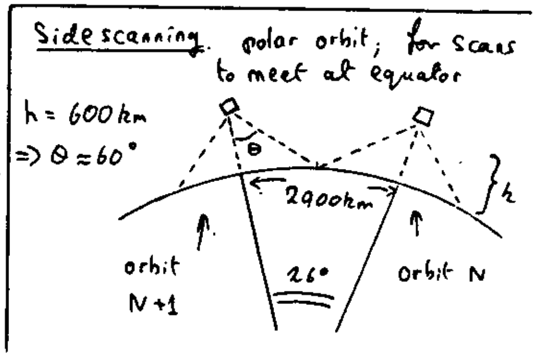
Typically h is 250 – 1000 km
v ~ 7 km/sec
period 100 mins





Geostationary.

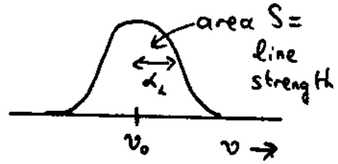
h 30 000 km
v = 0 (relative)
period:
1 solar day absolute
∞ relative to earth



Basic Spectroscopy

1) Lorentz line shape – due to collisions

$$\sigma_L(\nu) = \frac{S}{\pi} \frac{\alpha_L}{(\nu-\nu_0)^2 + \alpha_L^2}$$

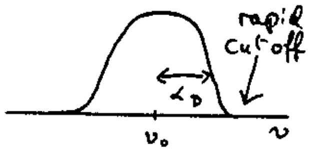


$$\alpha_L = \frac{p}{p_0} \alpha_{L0}$$

↖ Lorentz half width at 1 atmosphere

2) Doppler line shape
- due to velocity of molecules producing Doppler shift

$$\sigma_D(\nu) = \frac{S}{\alpha_D \sqrt{\pi}} e^{-\frac{(\nu-\nu_0)^2}{\alpha_D^2}} \qquad \alpha_D = \frac{\nu_0}{c}\left\{\frac{2\pi RT}{m}\right\}^{1/2}$$



3) Natural line shape.

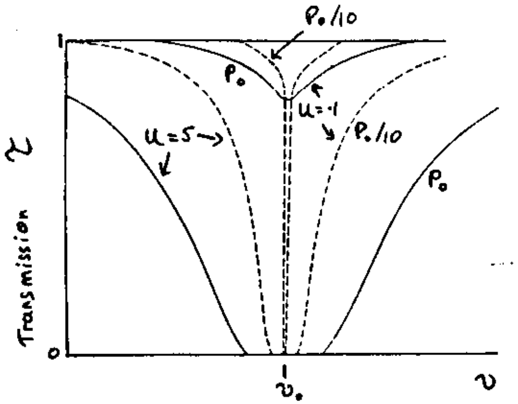
Width much less than α_D or α_L so ignore natural broadening

Convolution — Always need Lorentz because function tails away slowly.

At low pressures also need Doppler.

Convolution of these is Voigt function $= \int_{-\infty}^{\infty} \sigma_D(\nu-\nu')\sigma_L(\nu')d\nu'$

No analytic expression – must evaluate Voigt function numerically.



Lorentz broadening for different pressures and different absorber amounts u.

Transmission $\tau = e^{-\int \sigma \, dm}$

Can multiply transmissions for different absorbers $\tau = \tau_1 \times \tau_2 \times \tau_3$ etc } monochromatic only.

To find average transmission for an interval, must find τ at each ν, then integrate

$$\bar{\tau} \neq \bar{\tau}_1 \times \bar{\tau}_2 \times \bar{\tau}_3 \quad \text{in general}$$

Line-by-Line Calculations.

Add up at each wavelength absorption from each line.

- large computing job. e.g. CO_2 15μm band - thousands of lines; must do at fractions of line width so thousands of wavelengths. Voigt function makes especially time consuming.

Independent Line Assumption

When pressure low enough assume no overlap between lines.

- only 1 line at a time
- can aggregate lines so use say 100 lines with various α_D, α_L, S to represent band

Band Models

Mathematical models used to represent band

e.g. lines are equally spaced
lines are randomly spaced
distribution of S assumed to be some function.

models are chosen so that part or whole job done analytically

Parameterization

To reduce satellite data often need accurate transmissions, every profile. Normally do line-by-line for expected range of conditions and fit empirical model e.g. polynomials in $\ln(p)$, $\ln(u)$, T etc.

Curtis Godson Approximation.

p varies along path in atmosphere

Ideally divide path into series at different pressures and at each ν integrate over each element.

Curtis Godson Approx. says

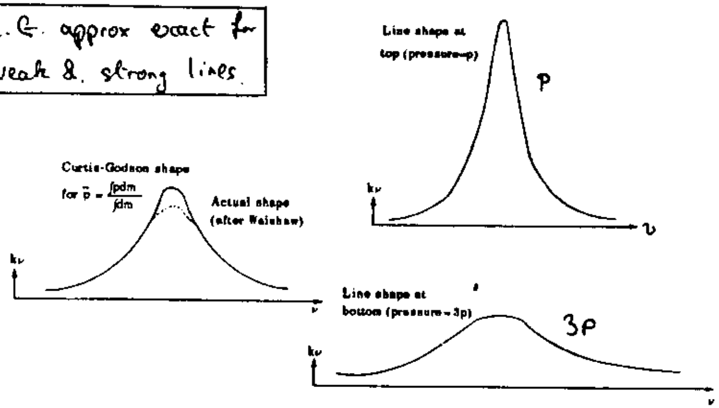
can replace pressure varying path by one path at $\bar{p}$ and absorber amount u

$\bar{p} = \int p\, dm / \int dm$. dm is element of absorber mass along path

$u = \int dm$

Generally use $\bar{T} = \int T dm / \int dm$. if T varies

C.G. approx exact for weak & strong lines.



Comparison of line calculated from Curtis-Godson approximation with the actual line shape for a line of intermediate strength, showing that the approximation is still quite good even in the worst case.

Equation of Radiative Transfer.

Suppose we measure radiation emitted by atmosphere; we look from space at surface via atmospheric path:

$$I = \int_{\tau_0}^{1} B\, d\tau + \tau_0 \left(\epsilon_0 B_0 + (1-\epsilon_0) I_\downarrow \right)$$

- I: measured radiance
- $\int B\, d\tau$: atmospheric emission (B: Planck function; $d\tau$: element of transmission)
- τ_0: transmission to surface
- $\epsilon_0 B_0$: surface emission (ϵ_0: surface emissivity; B_0: surface Planck)
- $(1-\epsilon_0) I_\downarrow$: radiation reflected by surface ($I_\downarrow$: downward radiation at surface)

Reflection: for infra red $\epsilon_0 = 1$
so reflected component unimportant unless $I_\downarrow$ very strong (reflected sunlight at short wavelengths) and τ_0 large.
Normally in I.R. use $I = \int B\, d\tau + B_0 \tau_0$

for microwave ϵ_0 often <1 e.g. 0.5
Then reflection important. $I_\downarrow$ may not be well defined – depends on direction of reflection (planar, specular, etc).
In window $I_\downarrow = 0$ so no problem.

$$I = \int_{\tau_0}^{1} B\, d\tau + B_0 \tau_0$$

change variables $d\tau = \frac{d\tau}{dz}\, dz$

where z is perhaps distance along path or p or $-\ln p$.

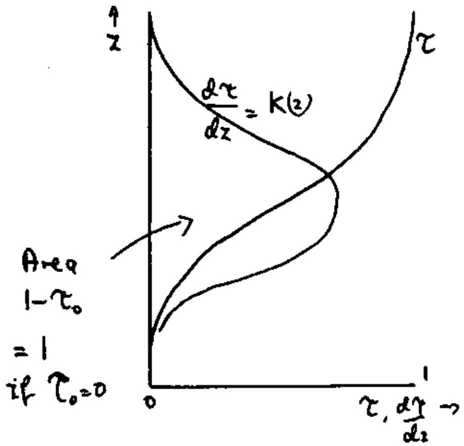
$$I = \int_0^\infty B \frac{d\tau}{dz}\, dz + B_0 \tau_0$$

$$= \int_0^\infty B(z) K(z)\, dz + B_0 \tau_0$$

↑ weighting function

note

$$\int_0^\infty K\, dz = \int \frac{d\tau}{dz}\, dz = \int_{\tau}^{1} d\tau = 1 - \tau_0$$



τ primarily depends on pressure p

so $-\ln(p)$ is good choice for z.

If z is geometric height K depends on surface pressure and more on T profile.

1 scale height ($\Delta \ln p = 1$) $\approx$ 7 km.

Weighting Function Example − Wings of Lorentz line

Monochromatic

$$\tau = e^{-\int \frac{S}{\pi} \frac{\alpha}{(\nu-\nu_0)^2 + \alpha^2}\, dm} \qquad \alpha = \alpha_0 p$$

by definition in wings of line $\alpha \ll |\nu - \nu_0|$

$$\text{so} \quad \frac{\alpha}{(\nu-\nu_0)^2 + \alpha^2} \approx \frac{\alpha}{(\nu-\nu_0)^2} = \frac{\alpha_0}{(\nu-\nu_0)^2}\, p$$

Take vertical path. Mass mixing ratio c

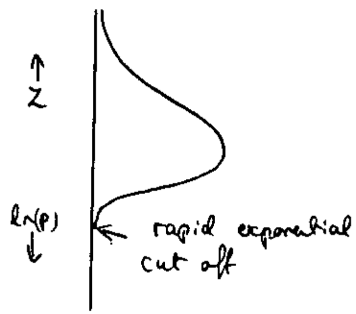
Hydrostatic balance: $dm = -c \frac{dp}{g}$

$$\text{So} \quad \tau(p) = e^{+\frac{S\alpha_0 c}{\pi g (\nu-\nu_0)^2} \int_p^0 p'\, dp'}$$

$$= e^{-\frac{S\alpha_0 c}{\pi g (\nu-\nu_0)^2} \frac{p^2}{2}} = e^{-\beta p^2}$$

where β is a constant related to ν, α_0, S etc.

$$-\frac{d\tau}{d\ln(p)} = -p \frac{d\tau}{dp} = +p \cdot 2\beta p\, e^{-\beta p^2}$$



$$K(z) = 2\beta p^2 e^{-\beta p^2}$$

find K_{max}

$$\frac{dK}{dp} = 0 = 2\beta e^{-\beta p^2} (2p - 2\beta p^3)$$

$$\beta = p_{max}^{-2}$$

$$K(z) = 2p'^2 e^{-p'^2} \quad \text{where } p' = \frac{p}{p_{max}}$$

How wide is function?

for $p' = 1$ (at peak) $\quad K_{max} = 2e^{-1}$

at what p is $\frac{K}{K_{max}} = \frac{1}{2}$?

$$\frac{2p'^2 e^{-p'^2}}{2e^{-1}} = \frac{1}{2}$$

$$2p'^2 = e^{p'^2 - 1}$$

solve numerically (trial and error on calculator)

Roots are $\quad p' = 1.64 \quad (z' = -\ln p' = -0.49)$

$\qquad\qquad\quad p' = 0.48 \quad (z' = \qquad +0.73)$

Half height points occur 0.49 scale heights below peak and 0.73 above.

$0.73 + 0.49 = 1.22$ i.e. ~9km.

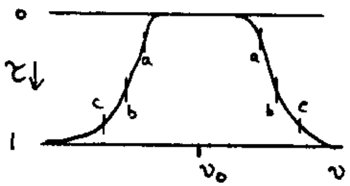
width of function in $\ln p$ (and approx height) is constant.

Height of peak determined by spectroscopy.

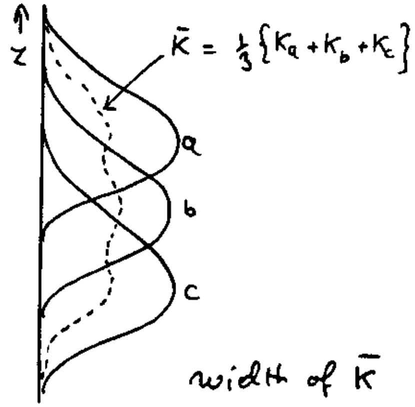
Weighting Function – finite resolution – integration over wavelength.

In microwave can have resolution much finer than wavenumber over which absorption varies so effectively monochromatic.

In infra-red cannot.

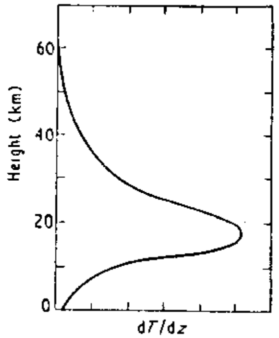


⇒



Effect of averaging weighting function over wavelength.

width of $\bar{K}$ ≫ widths of K_a, K_b, K_c



First satellite temperature sounder – whole 15 μm CO_2 band.

Weighting function for the 15 μm channel of the TIROS 7 MRIR. From Kennedy and Nordberg (1967).

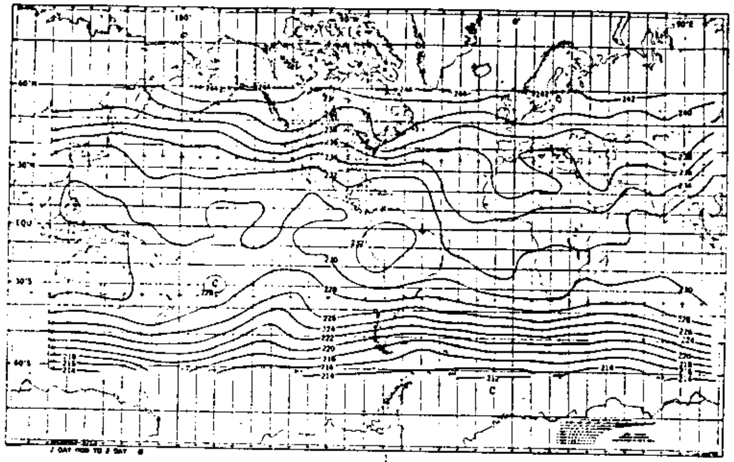
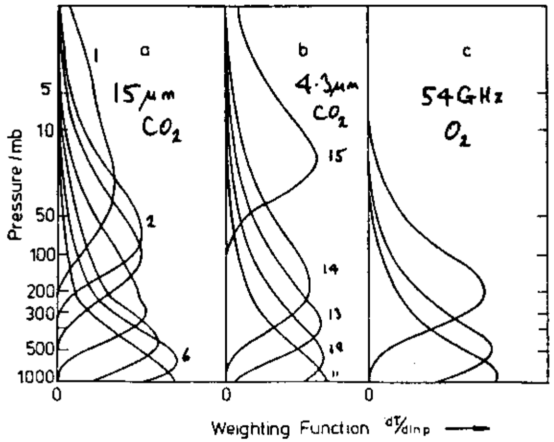


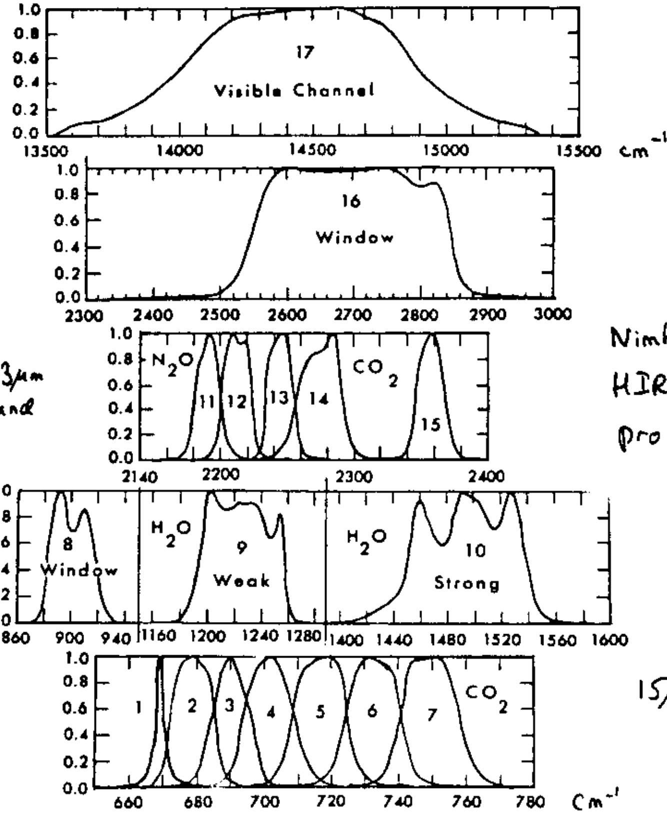
FIG. 2. Isotherms for average equivalent black-body temperatures derived from TIROS VII radiation observations during the period 19 June–28 June 1963. Numbers along isotherms refer to degrees Kelvin. Radiation observations were restricted to nadir angles 0–40°.

Early Tiros 7 map of temperature ↑.

Typical weighting functions



Weighting functions (gradient of transmission with respect to log pressure) for instruments sounding the temperature of the lower atmosphere on the Nimbus 6 satellite: (a) 15 μm channels of HIRS, (b) 4·3 μm channels of HIRS, (c) channels of SCAMS (from Smith and Woolf 1976 and Staelin *et al.* 1975).

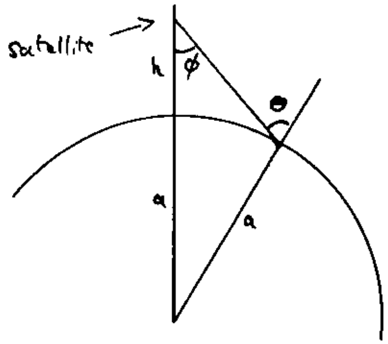


4·3μm band

Nimbus 6 HIRS filter profiles

15μm band

Limb Darkening (different from limb sounding)



satellite scans sideways at angle ϕ

Zenith angle in atmosphere θ

given by $\frac{\sin\phi}{a} = \frac{\sin\theta}{a+h}$.

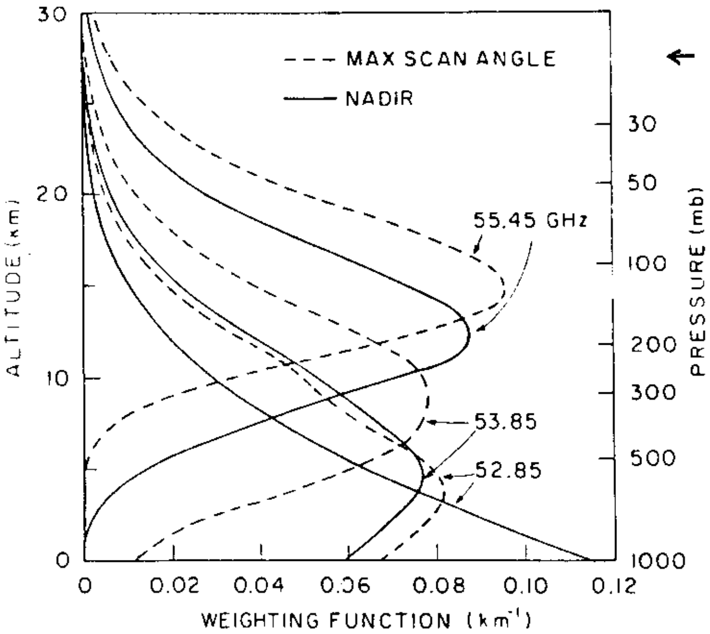
Nimbus 6: $h = 1100$ km.

If $\phi = 43° \Rightarrow \theta = 53°$.

See page 10.

$\Rightarrow \quad dm = -c \frac{dp}{g} \frac{1}{\cos\theta} \quad \Rightarrow \quad \beta \rightarrow \frac{\beta}{\cos\theta} \qquad p_{max} = \sqrt{\frac{\cos\theta}{\beta}}$

Weighting function width unaltered; peak moves up.



← $\phi = 43°$, $\theta = 53°$

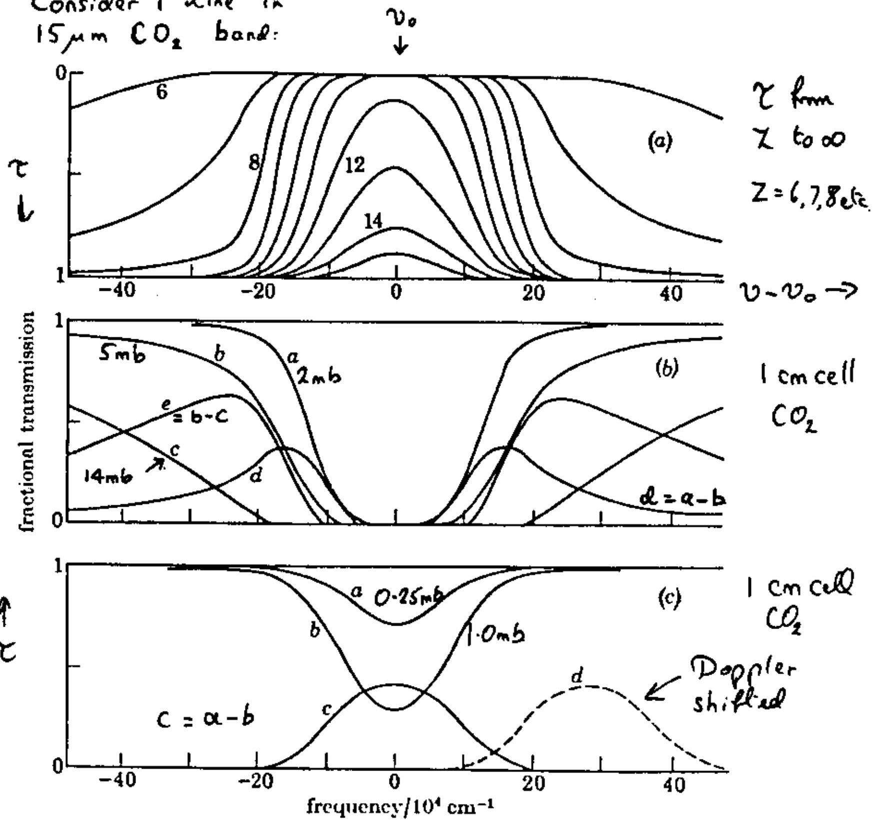
Nimbus 6 SCAMS

Why limb darkening?
If T decreases with height – as move towards limb, planet gets darker.

Gas Correlation Spectroscopy

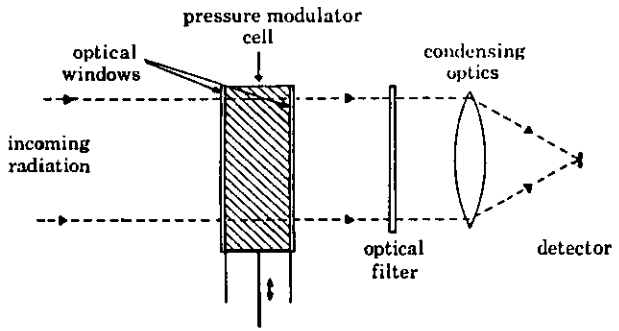
Use cell of gas in radiometer as a filter

Consider 1 line in 15μm CO_2 band:



Illustrating the technique of pressure modulation applied to a single line.
(a) Transmission plotted against frequency for various vertical atmospheric paths from level of pressure p atmospheres to top of atmosphere for single line in ν_2 CO_2 band of strength 2 cm^{-1} (atm cm)$^{-1}$. The number against each curve is $-\ln p$.
(b) Transmission of p.m.r. cell 1 cm long for same line as in (a) above. Pressure of CO_2 in cell is 2 mbar (curve a), 5 mbar (b) and 14 mbar (c). Curve d is $a-b$ and curve e is $b-c$.
(c) As (b) above with cell pressures 0.25 mbar (a) and 1.0 mbar (b). Curve c is $a-b$ and curve d is curve c Doppler shifted by the amount which would occur at an angle of 10° to the vertical from a vertical sounding p.m.r.

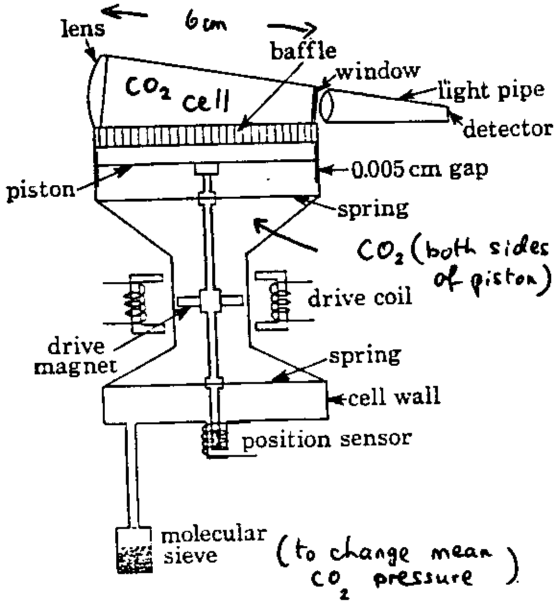
Pressure modulation:



1 cell; oscillate pressure.

Advantages:
just 1 cell; pressure measured.

Disadvantages:
cannot reach zero pressure; not square wave chopping – τ non linear.



⇐ Pressure Modulator Cell from Nimbus 6 PMR.

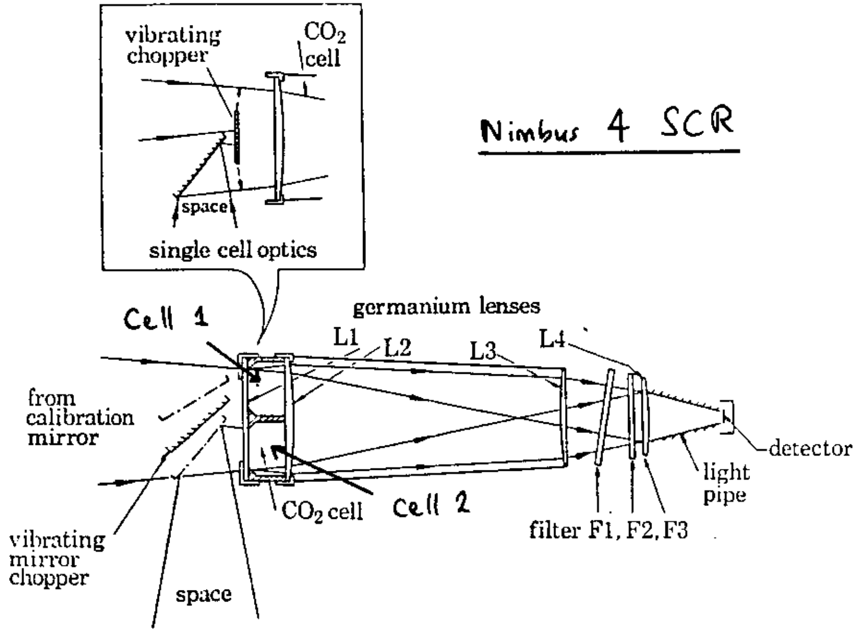
Piston driven at resonance ~ 40 Hz
(use frequency to measure cell pressure)

Balanced PMC.

Single piston PMCs vibrate instrument synchronously with chopping. Use 2 opposed pistons to balance.

Selective Chopping.

2 cells with different pressures – chop between.



Nimbus 4 SCR

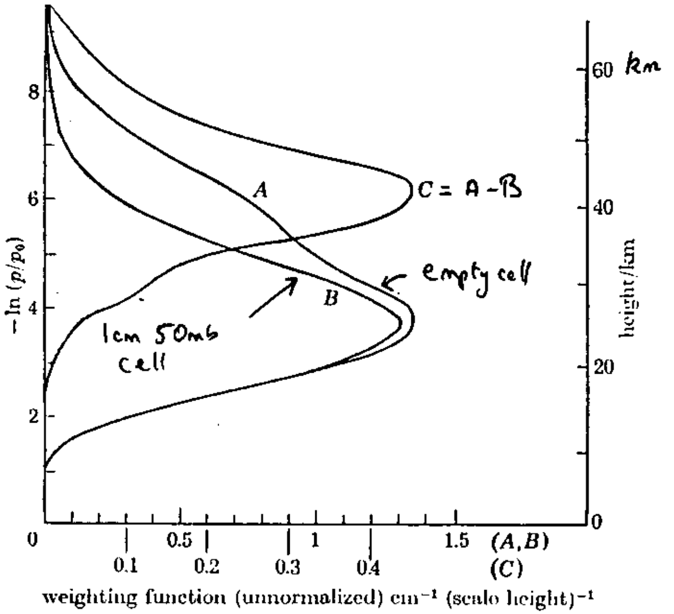
Advantages One cell can be empty

square wave chopping – just 2 pressures so easier spectral calculation

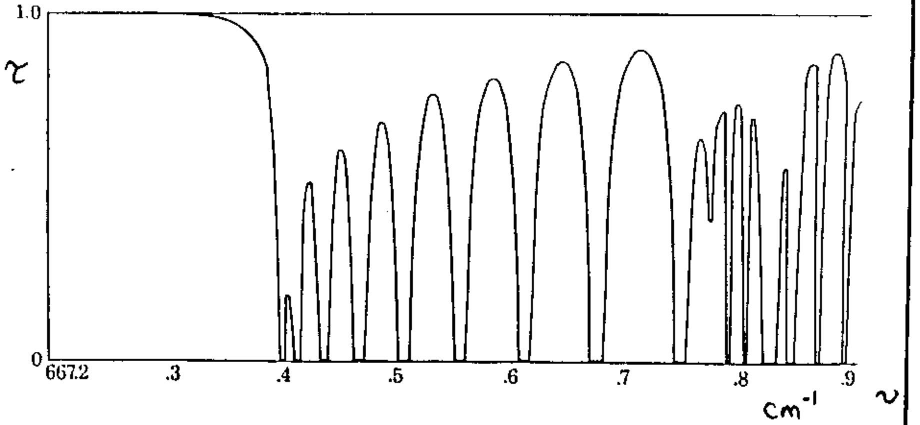
Disadvantages Cell windows might be different – major problem.

Difficult to get symmetric chopping

cell pressures need to be measured (because cells may leak).



Demonstrating the effect of selective chopping. Weighting function for (A) a 5 cm^{-1} interval centred at 668 cm^{-1}; (B) the same interval as (A) but with a path of CO_2 of 1 cm at 0.05 atm pressure. $C = A - B$ is the weighting function for selective chopping between A and B.

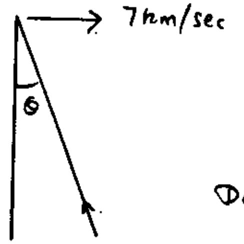


The transmission of a cell containing 1 cm path of CO_2 at 0.05 atm pressure for a small region of the Q branch of the ν_2 vibration-rotation band near 667 cm^{-1}. This is also the effective spectral response for this region of the radiometer with a weighting function (C).

Doppler Shifts

In mesosphere line centres have Doppler shape.
Width given by molecular speed $\simeq$ speed of sound
$\simeq \frac{1}{3}$ km sec^{-1}

Spacecraft velocity 7km ~ 20× molecular speed.



View forward in 'radio' mode

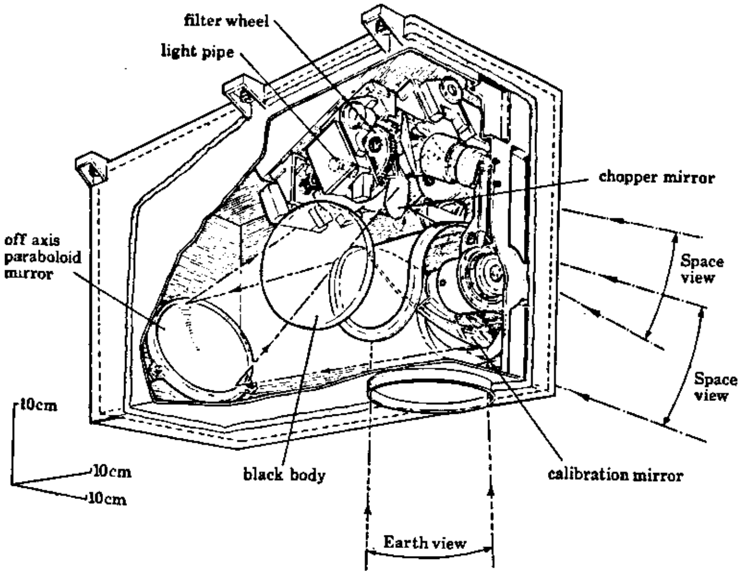
Doppler shift = 1 line width at $\theta = \frac{1}{20} = 3°$.

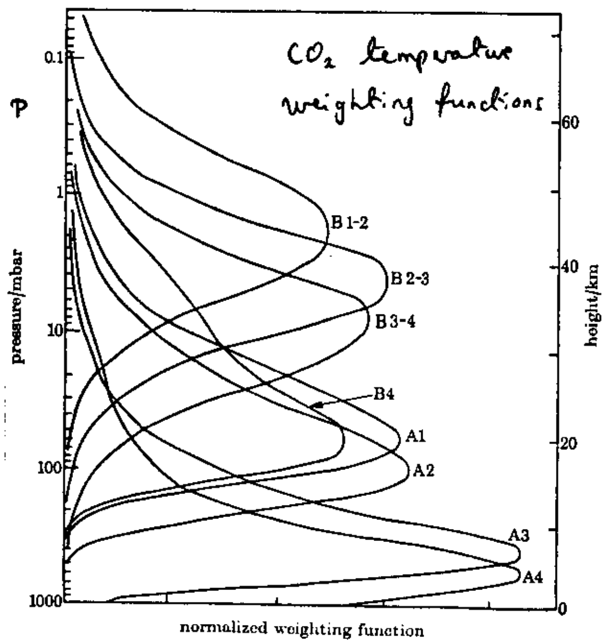
Limb viewing – if view along velocity vector large shifts - OK if large cell pressures

– in microwave use frequency offset to match shift

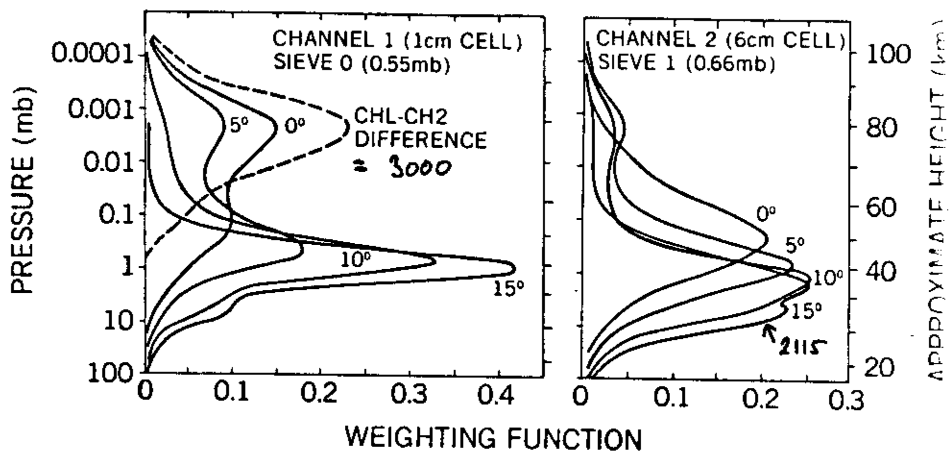
– SAMS / ISAMS view perpendicular to velocity (still have earth rotation).

Nimbus 5 SCR. 1972 – 1980

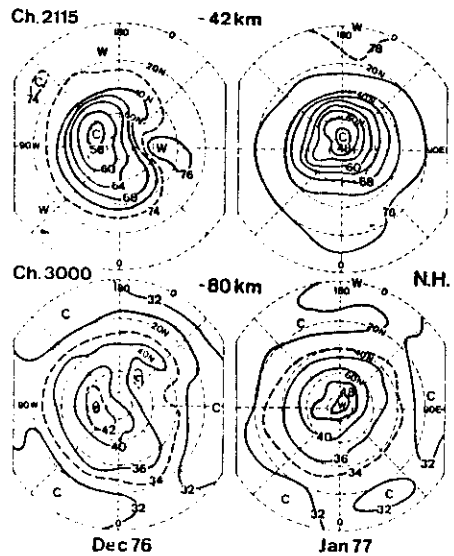




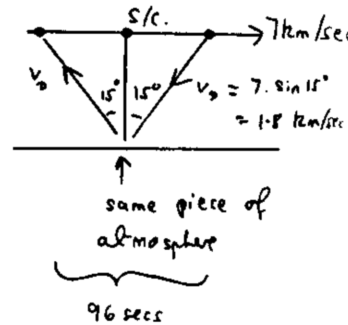
Nimbus 6 PMR. 1975 – 1978



2 Channels (both pressure modulated)



scanned from 15° in front to 15° behind to get Doppler shifts.



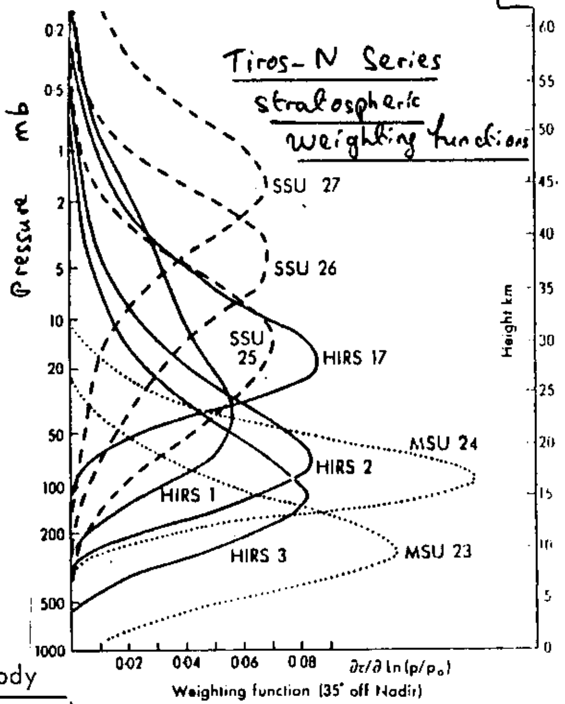
(also Field of View compensation).

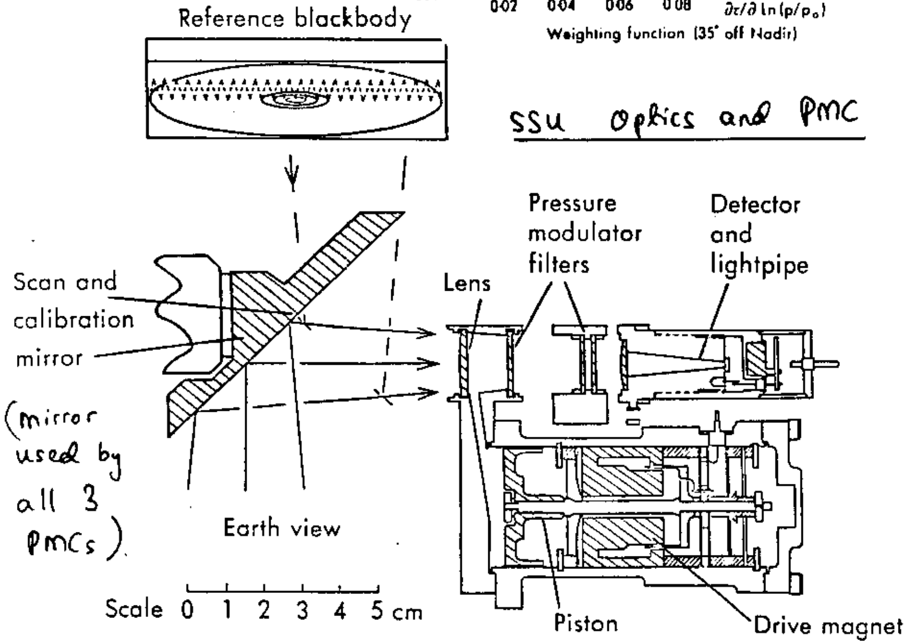
ch 2115 = ch 2 15°

ch 3000 = 1.67 × (ch 1 0°) − 0.67 (ch 2 0°)

SSU.

Stratospheric Sounder Unit.





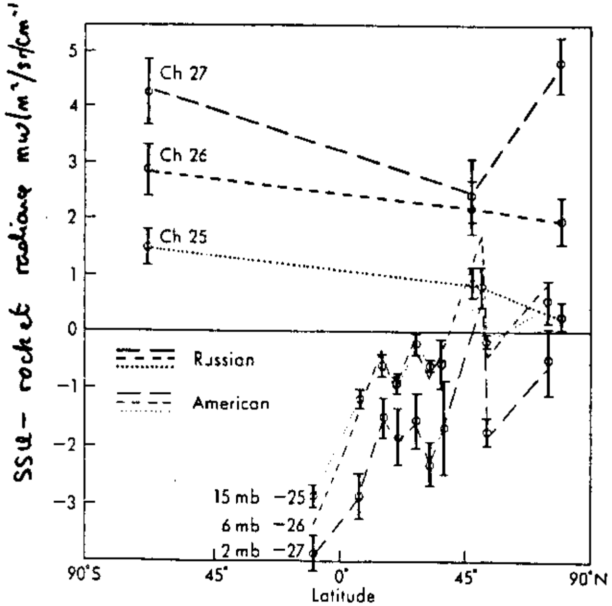
Tiros-N Series SSUs

spacecraft	orbit	dates
Tiros-N	A	Oct. 78 - Feb. 81 (spacecraft failed)
NOAA6	B	June 79 - June 83 (best SSU, MSU O.K. AVHRR problems, HIRS failed). Now being reactivated.
NOAA7	A	June 81 - currently operational (SSU ch.26 drifted out of cal. range)
NOAA8	B	Mar. 83 - June 84 (spacecraft clock problem which may be temporary)

Planned satellites with SSUs:

NOAA F	B?	On standby for possible late 84 launch
NOAA H		1986
NOAA I		1988
NOAA J		1989

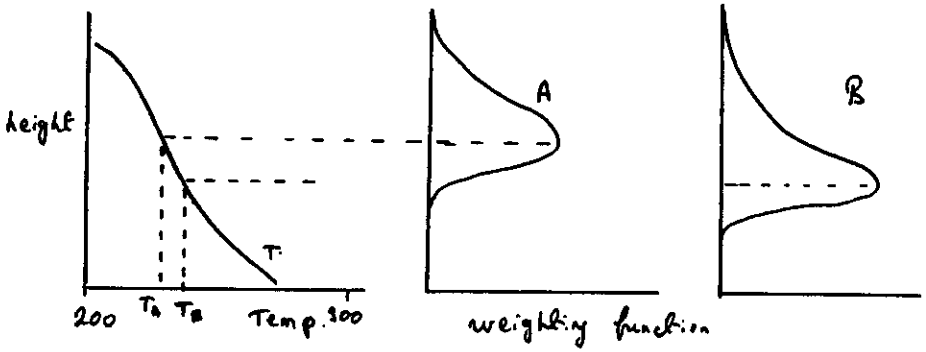
Orbits: A is 0730/1930 approx. B is 0130/1330 approx.



Comparison between NOAA6 SSU and rocket temp. profiles. July 1980 - July 1981.

Radiance from rocket/radiosonde profile obtained using SSU weighting function.

Constituent Sounding by emission – 'nadir' view



A and B are weighting functions for different H_2O profiles.

Brightness temp. for A $T_A \simeq 225K$
$T_B \simeq 230K$.

A corresponds to less H_2O than B

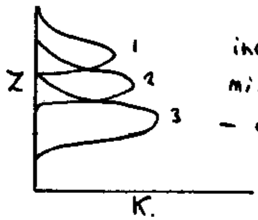
Hence more H_2O → lower brightness temp.

If know T profile and measure brightness temp. T_A can estimate H_2O concentration (must assume height dependence).

Does not work if T profile isothermal

{in this case $T_A = T$ always}.

Normally have several channels at different opacities.



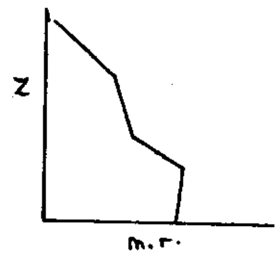
increase H_2O mixing ratios – all peaks move up.

Retrieval of mixing ratio profiles.

Suppose we have several channels and know temp. profile. – Various considerations –

1) Measured radiances have experimental error – misleading to try to fit measurements better than this error

2) Represent mixing ratio profile by polynomials or series of straight lines.



Serious problems if (a)

(a) try to find mixing ratio at heights where weighting function not large

(b) if try to fit more points than have channels

(c) if try to extract profile to finer resolution than inherent thickness of weighting functions (5 – 10 km)

Retrieval approaches.

I use of direct model:

→ Think of profile of mixing ratio;
Calculate radiances which would be measured;
Agree within experimental error?
N – try another ↺ (back to start)
Y – have found solution ↓ exit.

How do we invert new profiles?

I (a) at random – could take forever!

I (b) relaxation – mixing ratio at level z only affects channels with weighting function area below z.

so work down from top (onion peeling)

→ For chan 1: is radiance too high or low – adjust m.r. at that level, recalculate radiances

For chan 2: is ch 2 rad. too high or low. adjust m.r. near ch 2. recalculate radiances

etc.

iterate until all channels fit within expt. err.

I (c) <u>linearise</u> – equation of transfer $I = \int K B dz$

write as matrix summation $\underline{I} = \underline{K}\,\underline{B}$

where $\underline{I}$ is a vector of radiances

$\underline{B}$ " " " " planck functions (perhaps at equal z intervals)

$\underline{K}$ is weighting function matrix

vary B and K:

$$\Delta \underline{I} = \underline{K}\,\Delta\underline{B} + \underline{B}\,\Delta\underline{K}$$

↑ temp. sounding: known K, unknown B

↖ constituent soundings: known B, unknown K; K ⇒ mixing ratio

Here B known so $\Delta B = 0$

ΔK depends on mixing ratio m at every level.

For one channel

$$\Delta \underline{K} = \underline{A}\,\Delta\underline{m} \quad \text{or} \quad \Delta K_i = A_{ij}\Delta m_j$$

$$\text{so} \quad \Delta I = \sum_{i,j} B_i A_{ij} \Delta m_j = \sum_j K'_j \Delta m_j$$

where $K'_j = \sum B_i A_{ij}$ is a mixing ratio weighting function.

For all channels $\Delta \underline{I} = \underline{K}'\,\Delta\underline{m}$

where K'_{ij} gives the dependence of channel i radiance on level j mixing ratio.

I <u>Exact solution</u>

We have a guess at mixing ratio profile m_0

so have I_0; also have observations I

so have $\Delta I = I - I_0$.

If $\underline{K}'$ is square $\quad \Delta\underline{m} = (\underline{K}')^{-1}\Delta\underline{I}$

$$\text{so } \underline{m} = \underline{m}_0 + (\underline{K}')^{-1}(\underline{I} - \underline{I}_0)$$

II <u>Least Squares fit.</u>

Here we have more ΔI elements than Δm

– over constrained – cannot fit all ΔI exactly,

so will try to get smallest $\sum_i (\Delta I_i - \Delta I'_i)^2$

where ΔI_i is observed, $\Delta I'_i$ is given by retrieval

Adopt the summation convention where sum over pairs of suffixes:

$$\text{Sum} = S = (\Delta I_i - \Delta I_i^r)(\Delta I_i - \Delta I_i^r)$$

$$= (\Delta I_i - K'_{ij}\Delta m_j)(\Delta I_i - K'_{i\ell}\Delta m_\ell)$$

put $\frac{\partial S}{\partial m_j} = 0 = -2\Delta I_i K'_{ij} + 2K'_{i\ell}\Delta m_\ell K'_{ij}$

$$\underline{K}'^T \Delta \underline{I} = (\underline{K}'^T \underline{K}')\Delta \underline{m}$$

$$\Delta \underline{m} = (\underline{K}'^T \underline{K}')^{-1} \underline{K}'^T \Delta \underline{I}$$

clearly it is a minor extension to weight channels differently to take into account varying accuracies.

Can also calculate goodness of fit S and relate to expected noise.

<u>Summary</u> of <u>linearisation</u> with <u>iteration</u> and <u>direct model</u>

Take first guess profile m_0

→ calculate radiances I_0

calculate different weighting functions K'

$\underline{m} = \underline{m}_0 + (K'^T K')^{-1} K'^T (\underline{I} - \underline{I}_0)$

is profile good fit

No — put $m_0 = m$ (loop back to "calculate radiances")

Yes → Success

Id) <u>Sequential Estimation.</u>

This applies to methods Ib or Ic.

Suppose working along orbit performing retrievals.

Use retrieval at one place as first guess for next.

If sufficiently close converge in 1 iteration.

Must be careful about statistics

II) <u>No direct model</u> - complete linearisation.

When problem very linear (rare!) and do not need to iterate can get

$$\underline{m} = \underline{m}_0 + \underline{P}(\underline{I} - \underline{I}_0) + \underline{Q}(\underline{B} - \underline{B}_0)$$

Find $\underline{P}$ and $\underline{Q}$ by regression from many test cases.

Can include higher orders $(\underline{I} - \underline{I}_0)^2$, $(\underline{I}_i - \underline{I}_{0i})B_j$, etc.

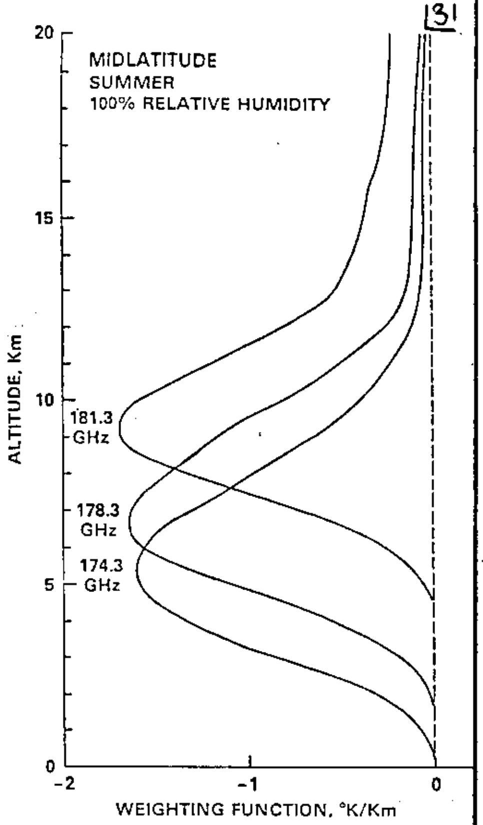
- possibly worthwhile for operational weather satellite type work where very large number of retrievals performed.

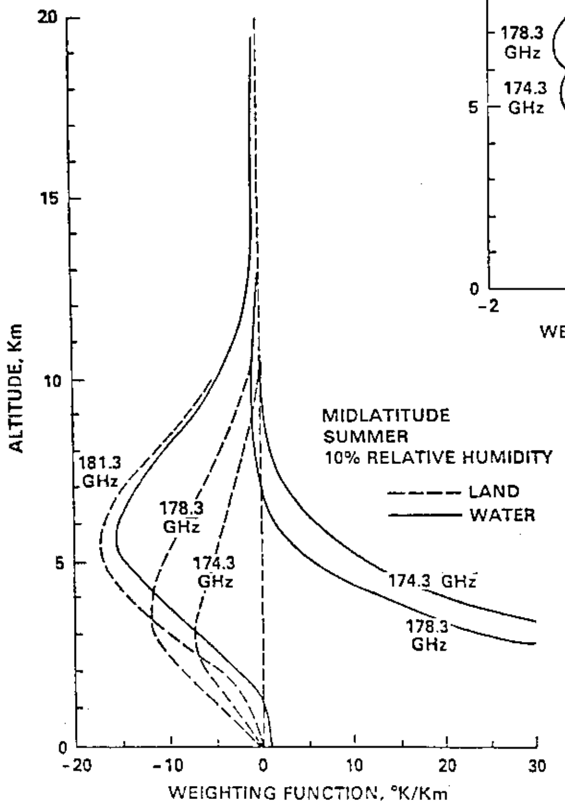
Relative Humidity Weighting Functions

Advanced Microwave Sounder (AMSU)

Tiros-N series 1989 – ?

Functions –ve because ⇒ increase of mixing ratio moves K up to point of lower T.





10% humidity – can see surface $\tau_0 \neq 0$.

Surface emissivity $\epsilon \sim 0.5$ for water, ~ 0.9 .. land

Why 10% humidity 174.3 & 178.3 GHz weighting functions +ve over sea?

$$I = \int_{\tau_0}^{1} B\,d\tau + \tau_0 \left(\epsilon_0 B_0 + (1-\epsilon_0) I_a \right)$$

$$= \bar{B}_A (1-\tau_0) + \tau_0\, 0.5 B_0 + \tau_0\, 0.5\, I_a$$

putting $\epsilon_0 = 0.5$

in microwave $B \propto T$

B_A (mean atmospheric temp) corresponds to ~ 250K

$0.5 B_0$ 140K

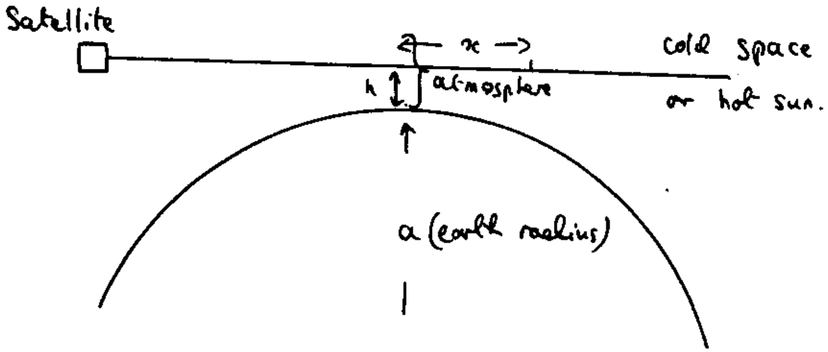
as τ_0 decreases due to more H_2O

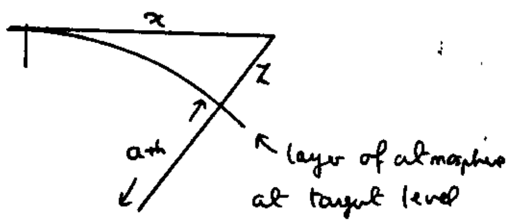
T_A decreases slowly

but relative weight of B_0 decreases

⇒ higher radiance

Limb Sounding





$$x^2 = z(z + 2(a+h))$$
$$\simeq 2a'z \quad (a' = a+h)$$
$$x\,dx \simeq a'dz$$
$$dx = \frac{a'dz}{\sqrt{2a'z}}$$

Find total number of mols in path.

mols $m = \int_{-\infty}^{\infty} \rho\, dx = \rho_0 \int_{-\infty}^{\infty} e^{-z/H} dx$

↑ density   ↑ assume isothermal - constant H

$$= \rho_0 \int_{-\infty}^{\infty} e^{-\frac{z}{H}} \sqrt{\frac{a'}{2}}\, \frac{dz}{\sqrt{z}}$$

$$= \rho_0 \sqrt{2a'H} \int_{-\infty}^{\infty} e^{-u^2} du$$

put $u^2 = \frac{z}{H}$
$2u\,du = \frac{dz}{H}$
$\frac{dz}{\sqrt{z}} = 2H^{\frac{1}{2}} du$

$$m = \rho_0 \sqrt{2\pi a' H}$$

put $a = 6370$; $h = 50 \Rightarrow a' = 6420$
$H = 7.5$

$\Rightarrow$ $m = 550\rho_0$.

ρ_0 is density at tangent level
no of mols equiv to 550km path at this level.

[compare for vertical path from $z=0$ to ∞ i.e. this level to space

$$m = \int_0^{\infty} \rho_0 e^{-z/H} dz = \rho_0 \left[e^{-z/H}\right]_{\infty}^{0} H = \rho_0 H = 7.5\rho_0$$

Ratio limb path / vertical ≈ 70.]

Advantages of Limb Sounding

1) 70x more absorber in path than vertical path
2) Background chosen to optimize – cold space of zero radiance for emission or hot sun
   Vertical sounding has varying background, clouds, surface, reflected sunlight, etc.
3) Vertical resolution limit ~1-3km instead of ~10km for nadir view

(1) and (2) primarily help constituent sounding
(3) aids constituent and temperature sounding

Disadvantages of Limb Sounding

1) Severe requirements for satellite pointing stability
2) Need to measure pressure level (satellite knowledge inadequate)
   - for nadir sounding this arises from choice of channels.
3) Small field of view – 1km at limb $\sim \frac{1}{60}^\circ$
   so need FOV $0.02 - 0.15^\circ$
   For vertical viewing can be up to 10°.
   – less energy grasp – optical design problems.
4) Clouds limit use in troposphere.

Infinitesimal Limb view Weighting Function

(Optically thin case).

Emission $I = \int_{-\infty}^{\infty} B(x) \frac{d\tau}{dx} dx$

Occultation $I = I_0 \tau = I_0 \int_{-\infty}^{\infty} \frac{d\tau}{dx} dx$

$$\tau = e^{-\int k(x) dx} \simeq 1 - \int k\, dx \quad \text{if optically thin}$$

$\frac{d\tau}{dx} = k(x)$ optically thin only

Transform to vertical coordinate z

$$\frac{d\tau}{dx} dx = 2 \frac{d\tau}{dx} \frac{dx}{dz} dz$$

(2 because $-\infty$ to ∞ maps twice on $0-z$)

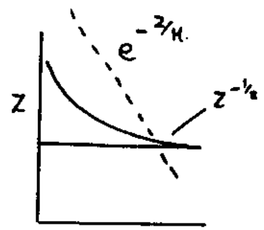
form of $\frac{d\tau}{dx}$: suppose $k \propto p^b \propto e^{-bz/H}$

we also have $z \simeq \frac{x^2}{2a'}$

so $k = e^{-\frac{bx^2}{2a'H}}$

i.e. along path Gaussian. Not normalized because $\int d\tau$ 1 in general

$$\frac{dx}{dz} = \sqrt{\frac{a'}{2}} \frac{dz}{\sqrt{z}} \Rightarrow \frac{d\tau}{dx} dx = K(z) = 2\sqrt{\frac{a'}{2}}\, k_0 \frac{e^{-\frac{bx^2}{2a'H}}}{\sqrt{z}}$$



typical $b=1$, $b=2$ etc.

$$K(z) = \sqrt{2a'}\, k_0 \frac{e^{-\frac{bz}{H}}}{\sqrt{z}}$$

Only applies $z > 0$

Consider z very small so $e^{-bz/H} \sim 1$.

$K(z) \propto \frac{1}{\sqrt{z}}$

$K(z)$ behaves as $\frac{1}{\sqrt{z}}$ near tangent point

Tail cuts off faster few km above.

can integrate this vertically to find distribution of area $\Rightarrow \mathrm{erf}\{(\frac{bz}{H})^{1/2}\}$. What is z where ½ area above ½ below

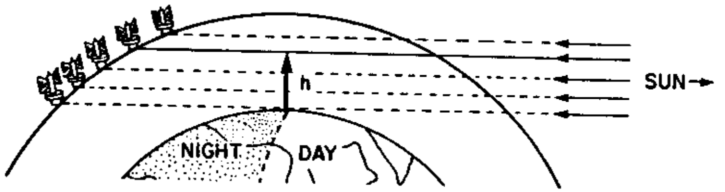
Results.

$b = 1/2$ ie	$k \propto p^{1/2}$	$z' = 3.2$km	$2x' = 404$ km	(x' corresp to z')
$b = 1$	$k \propto p$	1.6km	286 km	
$b = 2$	$k \propto p^2$	0.8km	202 km.	

Occultation - stellar or solar.

stellar difficult - stars faint but simple optics - view whole star.

solar disc ~ 20 km high from low orbit
- normally track part of disc - avoid sunspots



Note h is vertical (unlike emission (limb sounding)) measurement is at sunrise/set

$$I(z) = I_0 \; \tau(z)$$

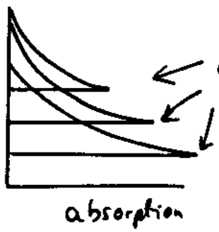
measure during occultation at various z; measure at large z

$$\Rightarrow \tau(z) = \frac{I(z)}{I_0}$$

{this assumes radiation emitted by atmos. $\ll I_0$}

Optically thin case - treated earlier

Plot shows where absorption occurs. Area under $= \tau$.



$$k \propto \rho \, f(T) \, h(p)$$

ρ: density; $f(T)$: T dependence of line strength and width; $h(p)$: pressure dependence - very strong for Lorentz lines

$\rho \propto \frac{1}{T}$ hence

$$k \propto \frac{f(T)}{T} h(p)$$

τ primarily depends on tangent pressure (as opposed to height) and absorber density at the tangent level.

Effect of temperature:

(a) Spectroscopy changes $f(T)$

(b) density changes - no of mols change $\frac{1}{T}$

(c) geometry changes. Above assumed height $\propto -\ln(p)$ i.e. isothermal
- ray now spends more time at some pressures and less at others

Temperature effects are not serious but need to be taken into account.

Occultation Constituent Sounding

measure τ for gas of known mixing ratio eg CO_2
- use to find ρ at each point

Also measure τ for unknown gas. Knowing ρ can find mixing ratio.

Effectively measure mixing ratio relative to mixing ratio of known gas.

Try to find wavelength where $\frac{f(T)}{T}$ = const.

Occultation Temperature Sounding

In above may know relative heights of measurements i.e. have $h(p)$. Then use

$$dp = -\frac{\rho g}{RT} dh \quad \text{(hydrostatic relation)}$$

to find $T = -\frac{g}{R} \frac{dh}{d\ln p}$ - need high accuracy $h(p)$

Better to find another wavelength CO_2
where $\frac{f(t)}{T}$ very temperature dependent.

2 wavelengths allow T and p to be found.

Iterative problem
- find P(h) first
- find T(h)
- check h(p) consistent with T (perhaps adjust p)
- reiterate

<u>Refraction</u>. – important with occultation in low stratosphere.

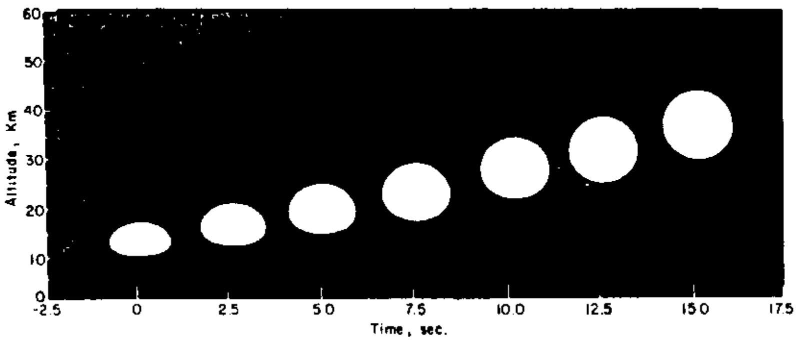


Figure 2
Composite of photographs taken during Apollo–Soyuz mission showing refraction effects on the Sun image (after PEPIN *et al.*, 1977).

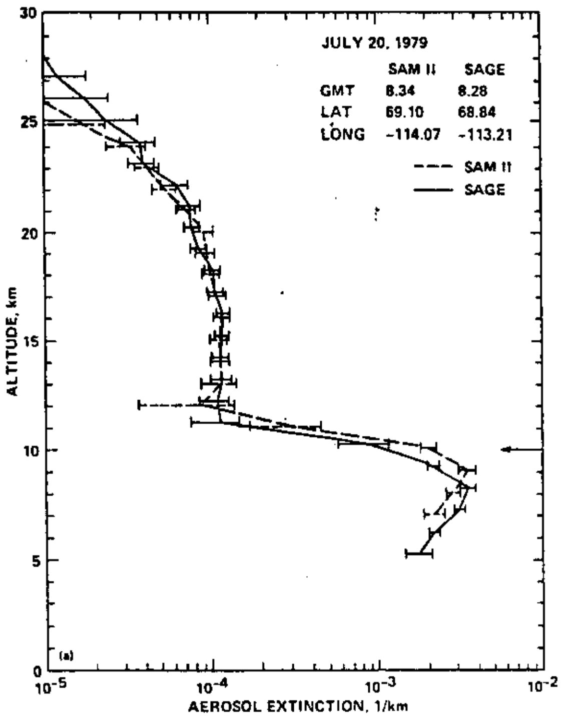
Refraction is important problem
- affects (a) height registration
  (b) path length in atmosphere
  – beam wraps round earth.

<u>Doppler Shift</u>. – have no choice of viewing direction – must view sun – may have Doppler problem.

<u>Occultation examples</u>.

<u>Atmos</u>. Spacelab 3 1985 Michelson Interferometer
2 μm – 16 μm × 0·01 cm⁻¹ resolution 250 kg
2 km vertical resolution 130–190 W.
Occultation speed 2 km/sec (orbital height 300 km)
Time for 1 scan 1 sec / 2 sec.

Gases CO_2, HF, HCl, HBr, CH_3Cl, CH_3F, CH_3Br, N_2O, H_2CO, HOCl, H_2O, HDO, NO, O_3, CH_4, CO, NO_2, H_2O_2, COF_2, SO_2, N_2O_5, HO_2, CFM, $ClONO_2$, NH_3, HNO_3 etc. also cirrus clouds?



SAM II / SAGE
⇐ Aerosol sounding.

<u>Haloe</u> – gas filter radiometer
2 μ – 6 μm
2 km vert. resolution
30 – 65 km.
HCl, HF, CH_4, NO, O_3, H_2O, CF_2Cl_2, CO_2

Limb emission Sounding

$$I = \int_{\tau_0}^{1} B \, d\tau + \tau_0 B_0$$

↑ space so $B_0 = 0$

$$\simeq \bar{B} \, \epsilon \quad \text{where} \quad \epsilon = 1 - \tau_0$$

= 'atmospheric emissivity'.

Temperature sounding – emissivity $\epsilon(z)$ known
$B(z)$ unknown

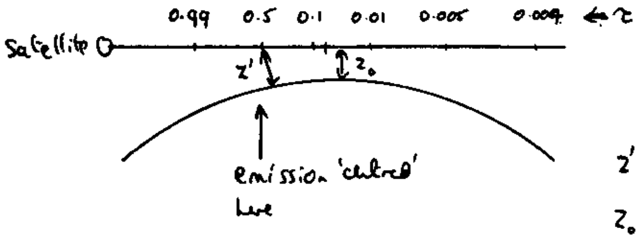
Constituent sounding – $B(z)$ known
find $\epsilon(z)$ hence mixing ratio profile.

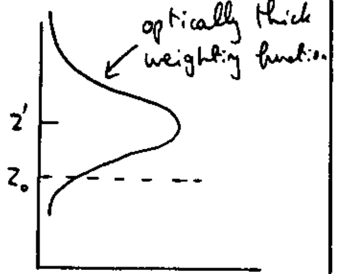
optically thin ($\epsilon < 0.5$) case has been delt with

– weighting functions of form $\frac{1}{\sqrt{z - z_0}}$.
~ 2km wide (+ smoothing due to field of view)

– along path emission centred a target point (e^{-x^2})

optically thick ($\epsilon > 0.5$)





essentially have nadir-type sounding – broad weighting function
– location offset from target point by several hundred km.

Limb Sounding T and p retrieval

We measure emission from gas of known mixing ratio e.g. CO_2 in infra red, O_2 in microwave.

$I \doteq \bar{B} \epsilon$. As for occultation $\epsilon = \frac{f(T)}{T} h(p)$ for optically thin case.

For optically thick $\epsilon \simeq 1$ so $I \simeq \bar{B}$; however $\bar{B}$ is averaged over thick layer (> 10km)

(a) microwave. $B \propto T$ so $I \propto T \frac{f(T)}{T} h(p)$
$\propto h(p)$ if $f(T) = \text{const}$

Hence if choose wavelength when spectral properties temperature independent, emission I gives pressure directly $p = h^{-1}(I)$.

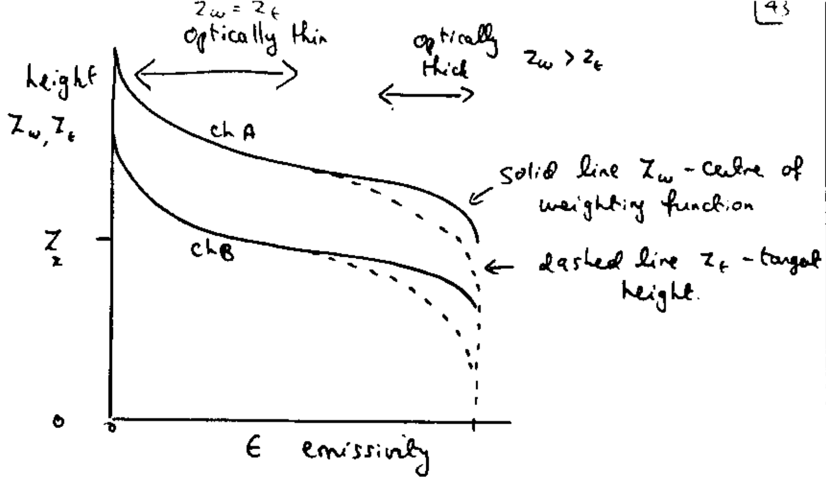
{Then choose wavelength where $f(T)$ varies with T to find temperature profile}

(b) infra red. $B \propto T^4$ approx.

If could find wavelength where $f(T) \propto T^{-3}$ could measure p directly – not possible.

Pick 2 wavelengths where opacities of gas different, e.g. centre of 15μm CO_2 band (ch A) and edge of band. (ch B).

Take as starting point profiles of I_A and I_B as functions of <u>relative</u> geometric <u>height</u>



Consider channel A. At very high altitude $z_w = z_t$ (actually z_w 1-2 km above z_t). As scan down z_w and z_t stay together until $\epsilon > \sim 0.5$.

Now z_w always above z_t. $z_w = z_x$ when $z_t = 0$ many km below. At this point $\epsilon = 1$ closely so $I = \bar{B}$ where $\bar{B}$ is mean for level z_x (broad layer).

Channel B chosen so that $\frac{\partial \epsilon}{\partial z_t}$ large at z_x

This occurs where $\epsilon \simeq 0.5$. Suppose $\epsilon = \epsilon_x$ at z_x

At this level $I_B = \epsilon_x \bar{B} = \epsilon_x I_A$

Find this point on I_B curve - this must be level z_x!

Assumes <u>horizontal stratification</u>

i.e. T function of z, not of lat./long.

(channel A radiance originates at correct pressure but horizontally several hundred km nearer spacecraft)

At z_x I_B corresponds to much thinner layer than I_A - no problem - average I_B vertical to match weighting function of I_A.

Now have pressure at one point on scan and T. Can now integrate away from that point - use T and hydrostatic relation to find p at other heights; from p calculate ϵ_A and ϵ_B; from I_A or I_B find T at new level etc.

<u>Normal procedure</u> Above outlines schematic method - shows where information comes from - not how we actually do retrieval.

Normally do least squares fit (like constituent retrievals) - highly non-linear. Don't use $\epsilon > 0.9$ because of horizontal gradient problem. Pressure level information originates from range of levels around z_x.

Allow smooth (linear) drift of satellite altitude during scan. $\frac{d\theta}{dt}$ = constant where θ = s/c roll angle.

SAMS retrieval uses sequential estimation $\Rightarrow \underline{p}, \underline{T}, \theta, \frac{d\theta}{dt}$

LIMS takes 2 scans (1 up, 1 down) to determine $\underline{T}$, $\underline{p}$, θ, $\frac{d\theta}{dt}$ independently for that set.

Constituent Sounding from Limb emission measurements

For gas of unknown mixing ratio, measure $I(h)$.
The T, p retrieval tells us pressure registration ie $h(p)$,
so have $I(p)$. Also have $T(p)$.
Wavelength should be chosen so optically thin, $\epsilon \ll 1$.

optically <u>thin</u>: $I = \bar{B}\,\epsilon$ $\quad \epsilon(p) = \dfrac{I(p)}{\bar{B}(p)}$

$\epsilon(p) \Rightarrow$ mixing ratio (p)

Same kinds of retrieval as discussed for nadir.

<u>No problems with zero lapse rate</u> as with nadir.

optically <u>thick</u>
- just like nadir sounding
- lapse rate problems if $\frac{dT}{dz} = 0$
- poor vertical resolution
- horizontal gradient problems.

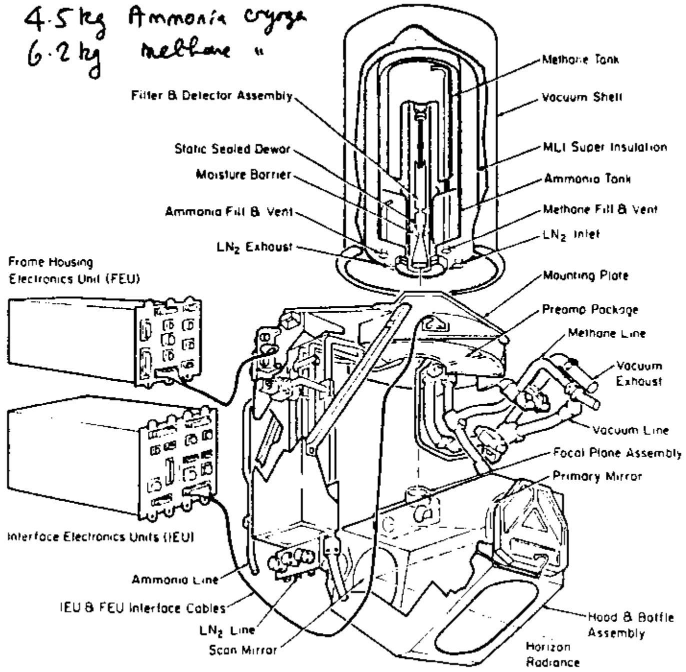
Limb Emission Instruments.

Nimbus 6 LRIR	1975-6	CO_2 (for Temp), O_3, H_2O	
Nimbus 7 LIMS	1978-9	CO_2 (for temp), O_3, H_2O, HNO_3, NO_2	

Nimbus 7 SAMS	1978-83	CO_2 (Temp), H_2O, CO, NO, N_2O, CH_4	
SME	1981-	Air (temp), O_3, NO_2	visible scattering
		(CO_2 IR) (temp)	

<u>LIMS.</u> 3 axis stabilized satellite. Scanning by moving mirror. 1° movement ≡ 60km.

4.5 kg Ammonia cryogen
6.2 kg methane "

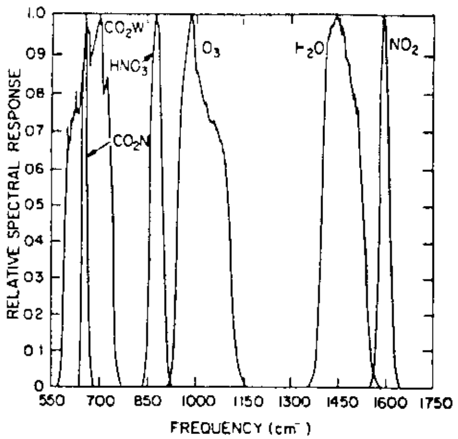


FOV.
2km for CO_2, O_3, HNO_3

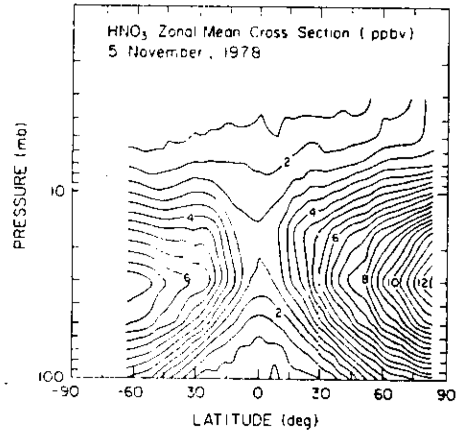
4km for H_2O, NO_2

7 months life

27 watts 68 kg with cryogen
Cooled detectors 63K
Cooled optics 150K.



LIMS filter profiles

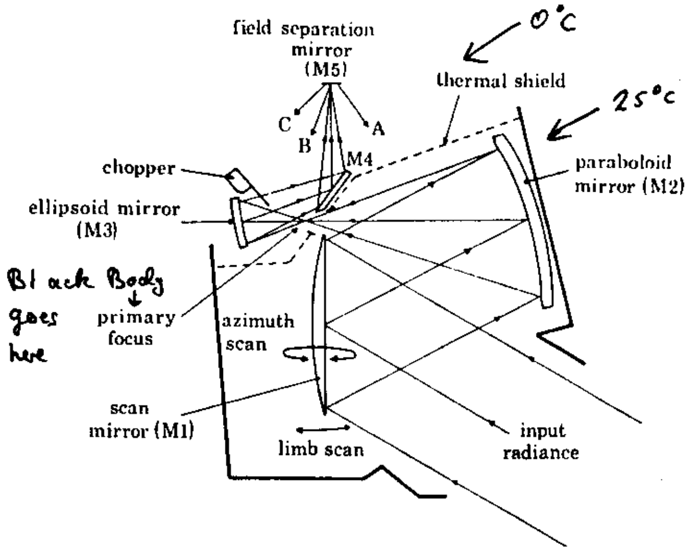


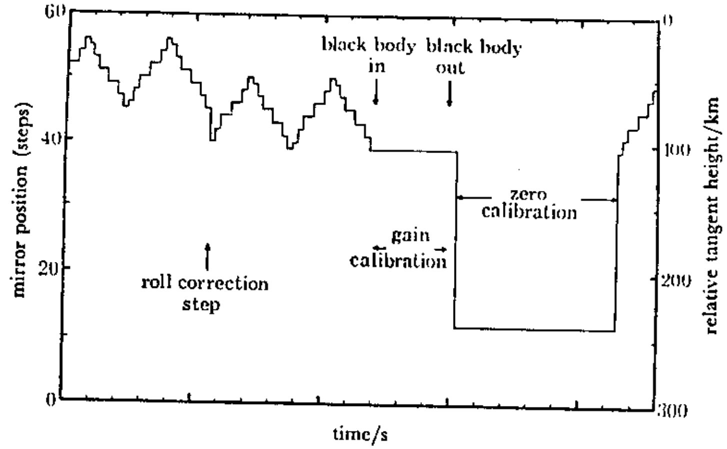
Zonal mean HNO_3 cross section for November 5, 1978. Contour interval 0.5 ppbv.

LIMS HNO_3 field

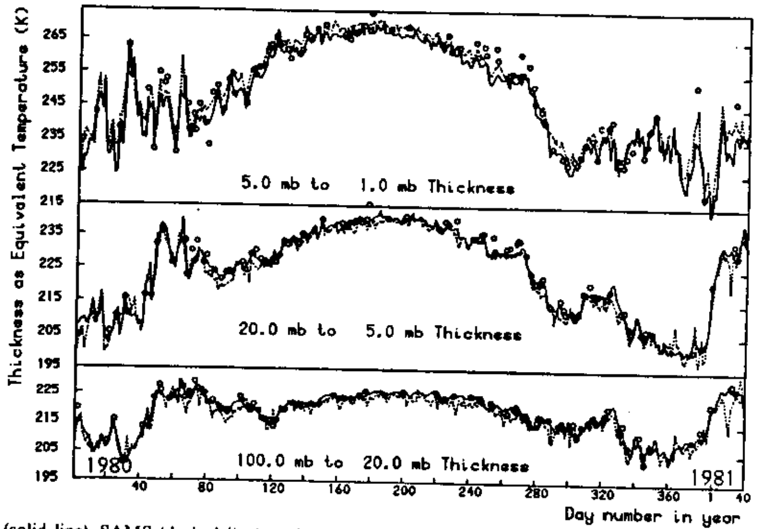
See JGR vol 89 no D4 June 30 1984 Nimbus 7 special issue – many LIMS, SAMS, SBUV, etc papers

SAMS – Nimbus 7 1978–83

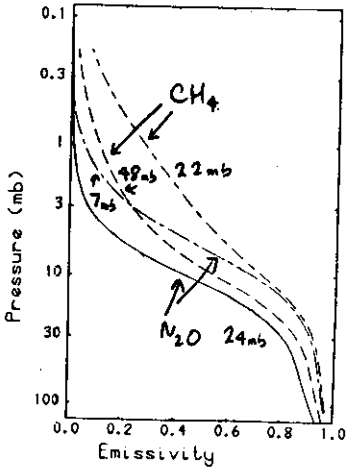




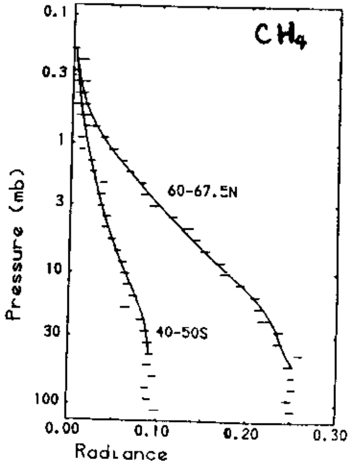
SAMS employs PMCs. for all channels. Each PMC gives 2 measurements I radiation chopped by PMC II radiation transmitted by gas cell in mean (– called PMR and wideband)



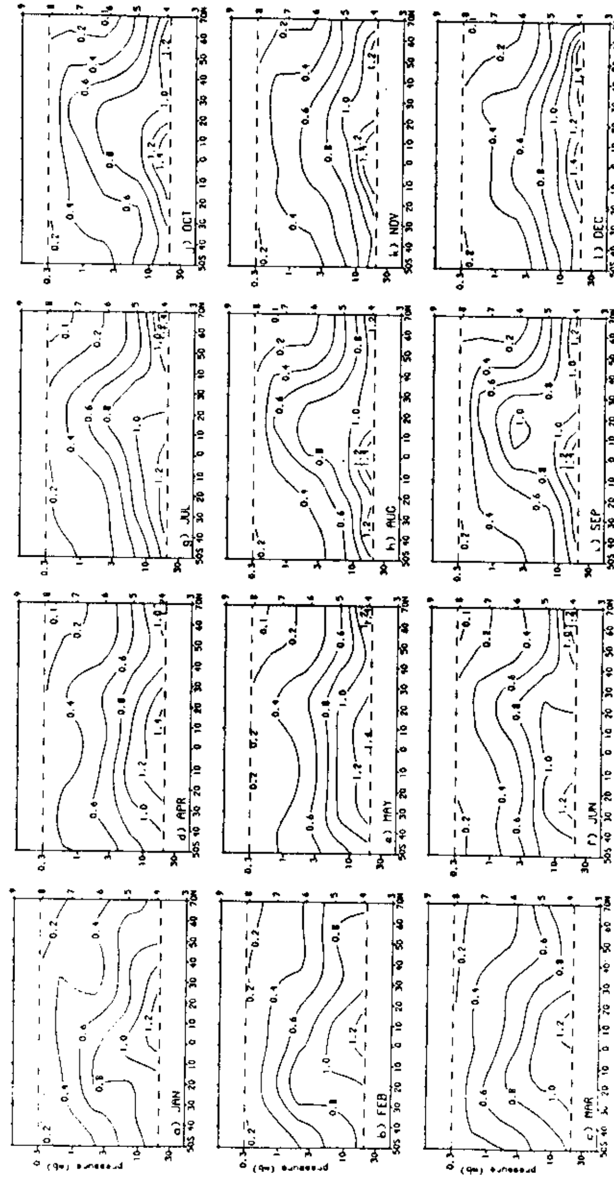
SSU (solid line), SAMS (dashed line), and rocket (open circles) thicknesses expressed as equivalent layer mean temperature over Primrose Lake rocket station (55°N, 110°W).



N_2O and CH_4 emissivities for different gas pressures in PMC



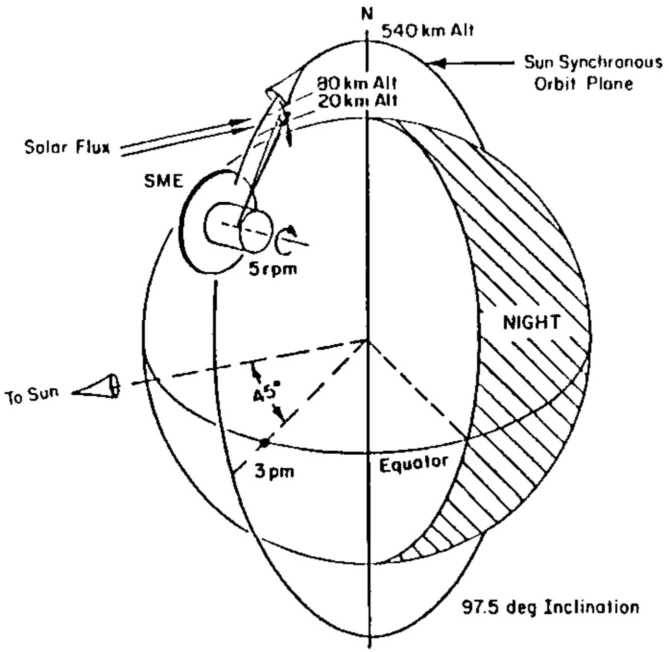
SAMS zonal mean radiance profiles. Solid lines are retrieval fit to measurements.



Monthly mean cross section of CH_4 (ppmv) between 50 S and 70°N for 1979 measured by the NIMBUS 7 SAMS.

SAMS CH_4 cross sections for one year. ppmV

SME. Solar Mesosphere Explorer



3a.m./3pm.

Sun synch. orbit.

Limb scan achieved by satellite rotation.

3.5 × 3km FOV on limb.

312 – 647nm ×.3 (spectrometer)

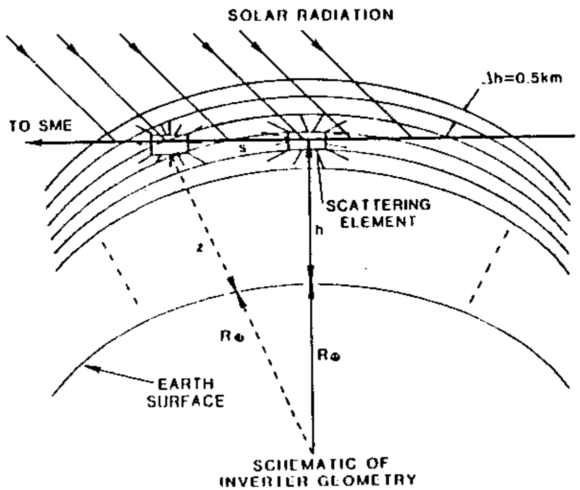
Scattering due to air mols – Rayleigh scattering. (Also aerosols)

Absorption free wavelength → ρ (h) (get T(p) from $\frac{d\rho}{dh}$)

O_3, NO_2 absorbing wavelength → O_3, NO_2

NO_2 20-40km

O_3 – 80km.



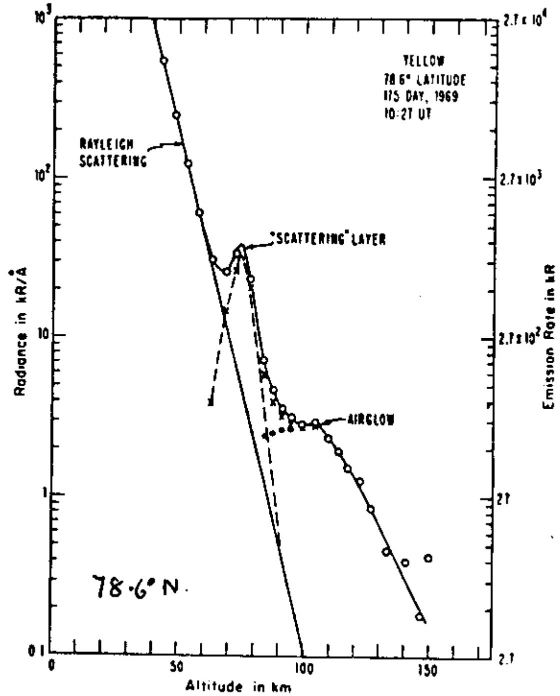
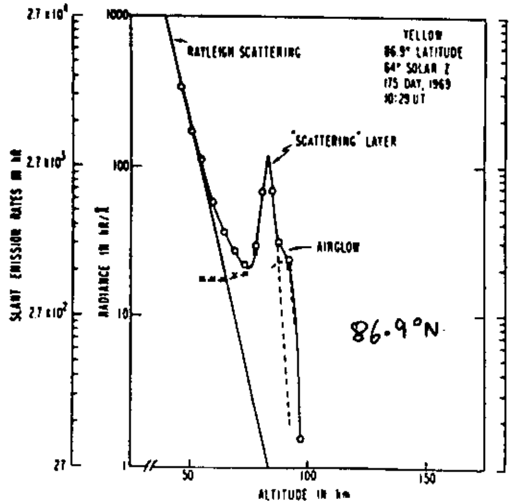


Figure 14

Slant emission rates observed by OGO-6 airglow photometer at 5890 Å above the horizon as function of the altitude of the closest approach of the line of sight for 78.6 N



Aerosol Clouds

UV and visible limb viewing strongly affected by dust, aerosol.

– Good way to see clouds.

IR much less affected.

Spacecraft Orbits. – Circular only.

Most earth viewing spacecraft have accurately circular orbits. Calculations not difficult if assume spherical earth and circular orbit – spherical triangles etc.

Prograde orbits – satellite goes round same way as earth in inertial space e.g. geostationary orbit

retrograde – go other way.

Inclination – angle between plane of orbit and equatorial plane
between 0° and 90° for prograde
90° .. 180° .. retrograde
(e.g. 60° and 120° have same satellite track, but satellites go opposite way).

90° = true polar.

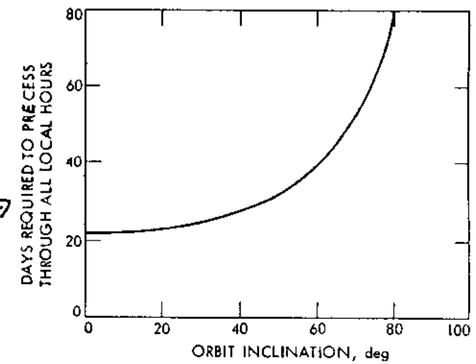
Precession of orbit plane

Orbit plane precesses because earth not spherical (strictly because surfaces of constant g not spherical).
Zero precession rate for true polar orbit (90°); this relative to inertial space.

Sun synchronous orbit – obtained when precession rate is once / year relative to inertial space

in same direction that sun 'goes round' earth.
Achieved with inclination about 99° (depends on height – about 99° for few hundred km height).
e.g. 81° inclination would achieve correct precession rate but wrong way – rel. to inertial space would precess 1 cycle / year, rel. to earth-sun line 2 cycles per year.

This is time to precess ½ cycle i.e. plane of orbit to rotate 180° relative to earth-Sun line →



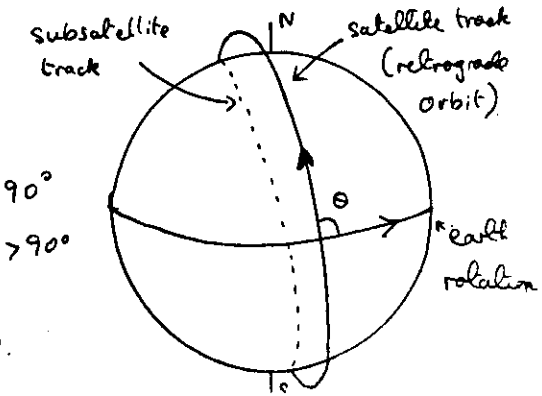
Effect of orbit inclination on time to precess through all local hours at the equator (orbital height = 600 km)

sun synchronous orbits loosely called polar orbits.

Latitude coverage.

If inclination is θ satellite travels between $\pm\theta$ if $\theta < 90°$
$\pm(180-\theta)$ if $\theta > 90°$

e.g. $\theta = 99°$
$\Rightarrow$ 81°S to 81°N.



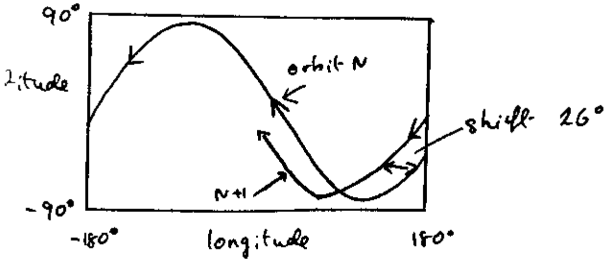
Longitude coverage

Orbit track repeats every orbital period in inertial space (except for slight shift due to precession)

Low orbit ~14 orbits/day

Earth rotates under orbit ≃ 26° per orbit

Hence successive orbits ~ 26° further west



Repeating orbits

Exact orbital period depends on height.

Sometimes adjust height to give exact repeat after n days e.g. 13.66667 orbits/day ⇒ repeat after 3 days. Over 3 days orbits spaced by

$\frac{360}{3 \times 13\frac{2}{3}}$ ° ≃ 9°.

For Landsat n = 18

Radio altimeters to measure ocean height use repeating orbits.

Limb Sounders

Nimbus 7 orbit (950km altitude) – limb 30° away

UARS ,, (600km) ,, 23° ,,

a) viewing along velocity vector – tangent point track same as subsatellite track

b) Right angles to satellite velocity.

e.g. SAMS views to right of satellite

at N. pole view across pole.

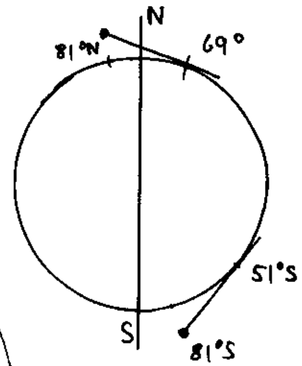
s/c at 81° N ; tangent point at

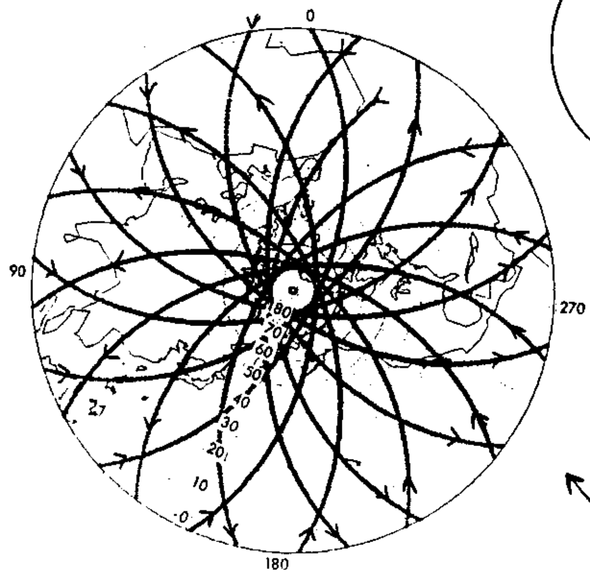
180 – (81+30) = 69° N

at S. pole

s/c at 81° S ; tangent point at

81 – 30 = 51° S.





Limb scanner geographical coverage (Northern Hemisphere) with fixed azimuth angle = 90 deg (orbital inclination = 56 deg, orbital height = 600 km) for one day

{Limb Scanner tangent point track from 56° inclination orbit. (rt. angle view) (UARS orbit).

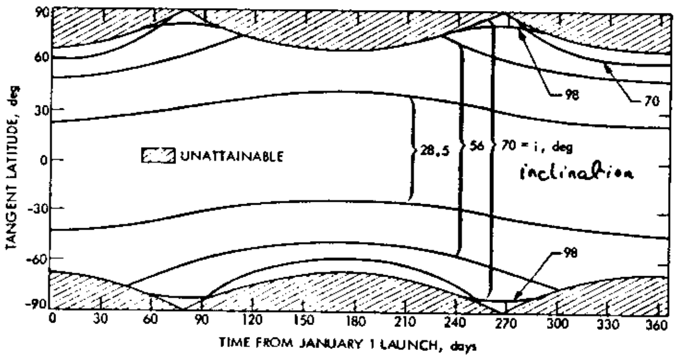
[view is to left of velocity vector]

Occultation

2 occultations per orbit – sunrise / sunset (some orbits have none).

Sunrise occulations lie on ring around earth – every 26° long. Ditto Sunset. Occultation latitudes vary slowly with
a) season as sun moves North / South
b) as orbit plane precesses round.

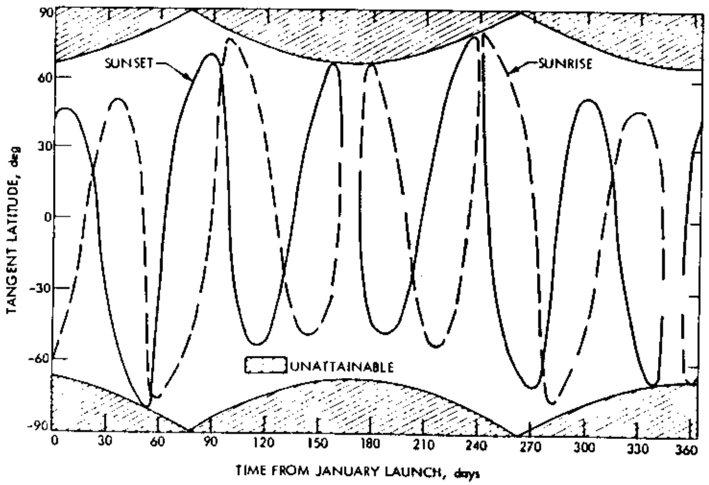
Only get full range by precession, over 1 cycle
[98° sun synch. so special case – no precession]



Effect of orbit inclination on latitude coverage envelope for solar occultation (orbital height = 600 km)

Example 56° inclination

Problem with orbits is that text books treat general case – very complex. Incomprehensible. Normally



Latitude coverage for solar occultation during one-year mission (orbital inclination = 56 deg, orbital height = 600 km)

Choice of orbit.

Difficult if there are conflicting requirements from different instruments.

1) Geostationary – excellent for cloud imaging, also vertical sounding (VASS). Not polar caps. Only see ~120° longitude. 24 hr coverage. Large distance problem in instrument design.

2) Sun synchronous (99° inclination), low altitude. Near global coverage. Nearly always used for meteorological satellites (except geostationary). Gives same local times always – need several satellites to study diurnal, semidiurnal cycles – this problem studying radiation budget properly or chemistry with strong diurnal variation eg NO_2. Occultation just gives 2 latitudes.

3) Low altitude not sun synchronous. Less rocket power needed – 0° needs least. Occultation latitudes scanned by precession. Overpass times scan slowly through all local times during precession cycle – chance to study diurnal cycles.
Not global coverage of subsatellite point – but might help limb scanners. Better coverage at latitude extremes.

If orbit precesses instruments must be designed to withstand sunlight from all directions (UARS will turn round every 1/2 precession cycle to avoid this). {Sun synchronous satellites have a permanently dark side}. Important if sunlight shines into optics and affects measurement.

4) Orbit height. (geostationary 30000 km – no choice).
Some heights suffer strong particle radiation – spikes in data – may destroy electronics.

Low heights – easier optical design – better energy grasp, etc. But sidescanning requires large angles for orbits to overlap at equator. Low heights give longer occultations.

Meteorological satellites – generally > 500 km because of sidescanning requirement.

Fine height tuning if need repeating orbits (still ample scope to choose approx. height).

Manned missions (Shuttle, Spacelab) currently imply low (300 km) orbits.

Microwave Sounding

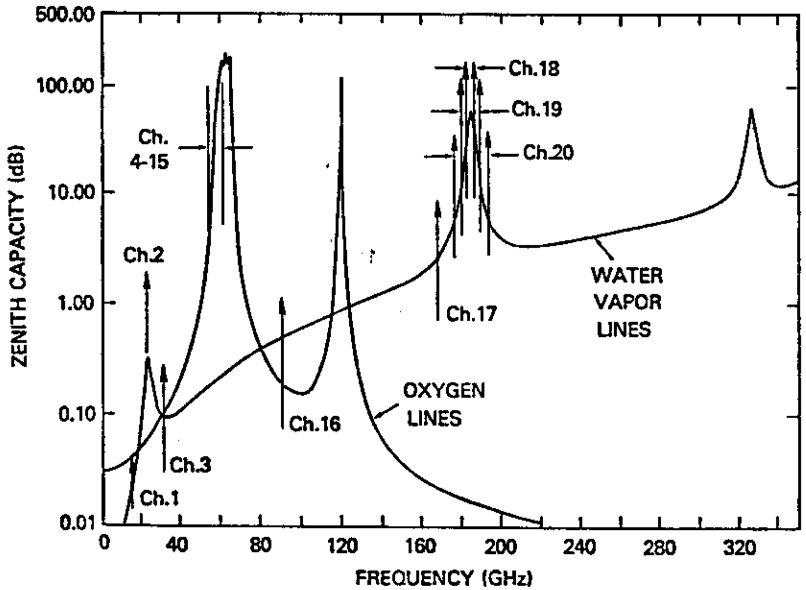
Use O_2 emission to measure T.

Dry clouds transparent to microwaves – big advantage over I.R.

Wet clouds (much liquid H_2O) absorb – can design channels to measure liquid water

Surface emissivity < 1 – big disadvantage but can be used to determine surface type.

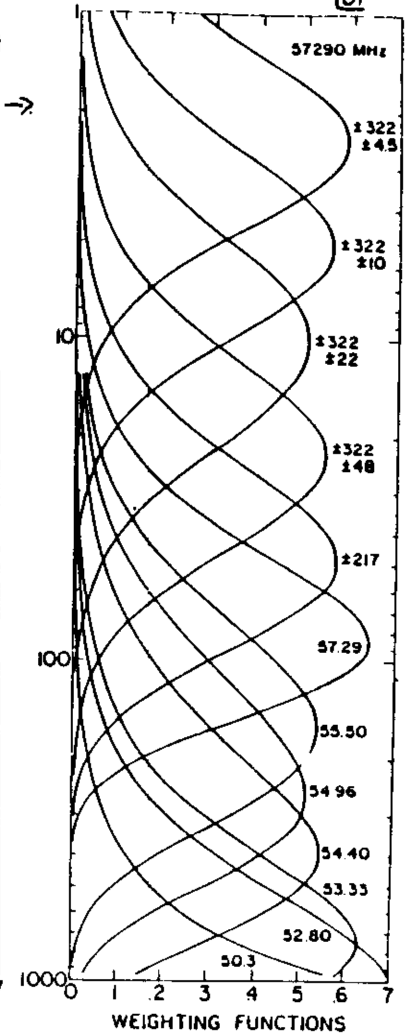
OXYGEN AND WATER VAPOR LINES AND AMSU CHANNEL FREQUENCIES



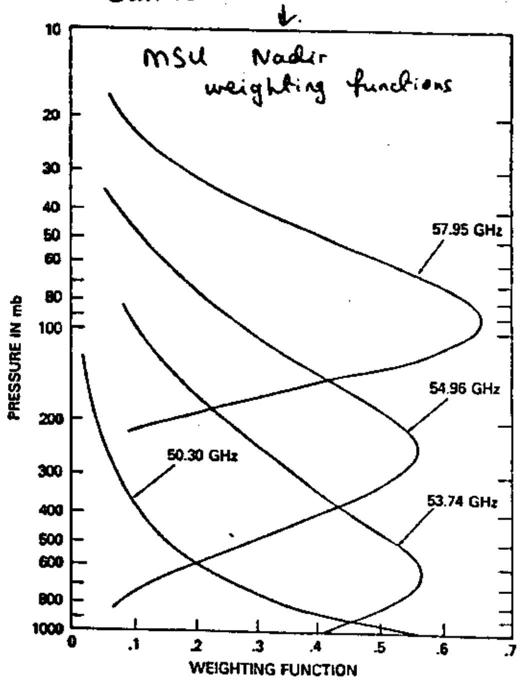
Proposed AMSU (Advanced Microwave Sounder Unit) channels. AMSU will probably fly on Tiros-N series in 1990's to replace the MSU.

In microwave surface emissivity (1 – reflectivity) affects lower weighting functions because atmosphere seen 2nd time reflected in surface.

AMSU temp. weighting functions → future Tiros-N →



Current Tiros-N series ↓



microwave sounding not yet tried from geostationary orbit – diffraction means need giant antenna to focus beam.

Microwave Sea Ice measurement.

Choose microwave window e.g. Nim.6 SCAMS used 32 GHz
Nim.6 ESMR 37 GHz
Nim.5 ESMR 19 GHz

$$I = T' = \epsilon_0 T_0 + (1-\epsilon_0) T_s$$

T' ↑ apparent temp; ϵ_0 ↑ surface emissivity; T_0 ↖ surface T; T_s ↖ space temp. = 3K.

Ice Type	ε (nadir view, 19.35 GHz 1.55 cm)
Open water	0.44
New ice (<10 cm)	0.45 to 0.92
First-year ice (>10 cm)	0.92
Multiyear ice	0.84
Summer ice	0.45 to 0.95

ϵ_0 much more variable than T_0

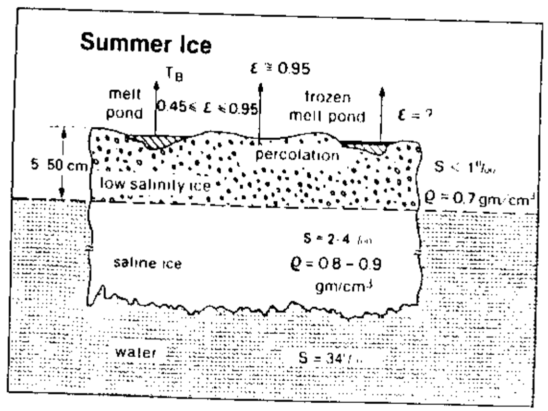
so T' primarily measures surface characteristics.

e.g. sea has $T' = 140K$
thick ice $= 250K$

Nimbus 6 ESMR FOV ≃ 25 km diam.

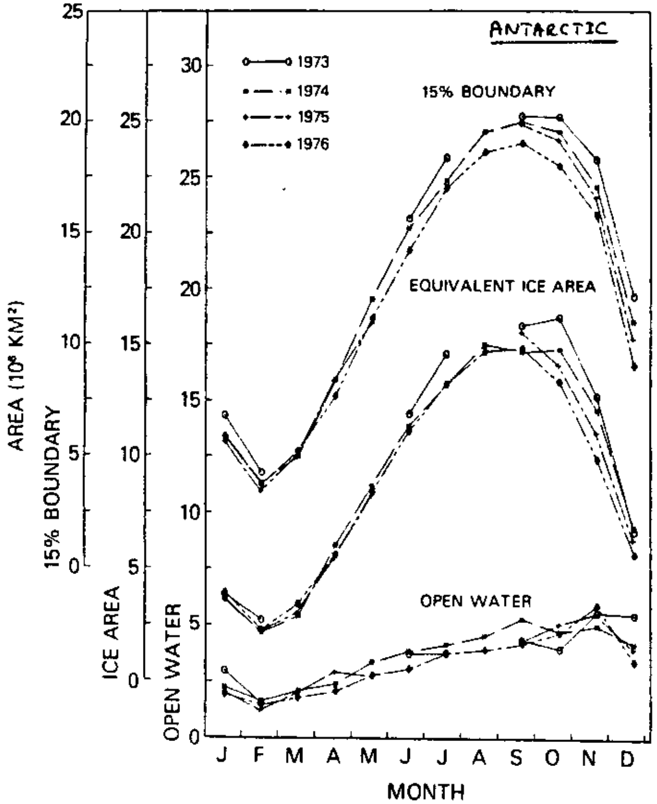
may get fractional ice cover or ice with melt ponds.

$T' = 250K \Rightarrow$ 100% sea
$T' = 140K \Rightarrow$ 100% ice
$T' = 200K \Rightarrow$ 50% ice? or thin ice? etc.



Air-sea interaction important factor in weather and climate. Snow-covered ice effectively perfect insulator. Microwave mapping provide accurate mapping of polar ice.

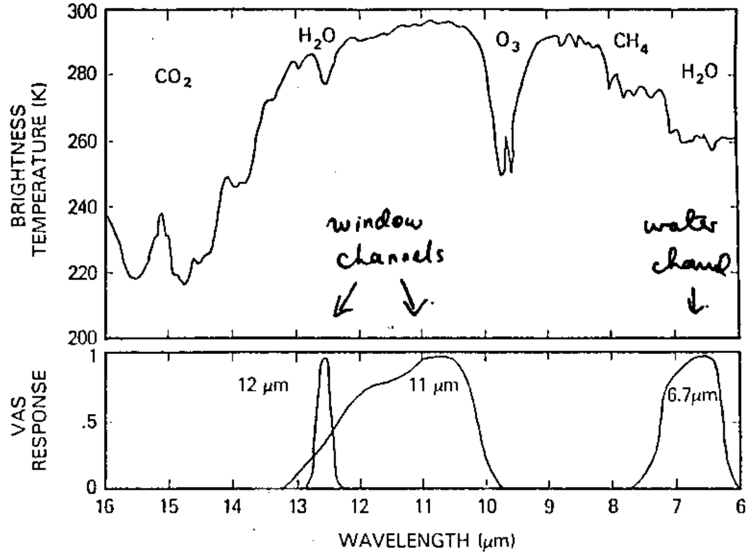
Sea ice cover [illegible]erent years in the Antarctic region from Nimbus 5 ESMR data. The area of open water within the ice pack is shown, also the area of ice and the area of ocean with more than 15% ice cover. Note the progressive decrease in ice cover during the 4 years (from NASA).

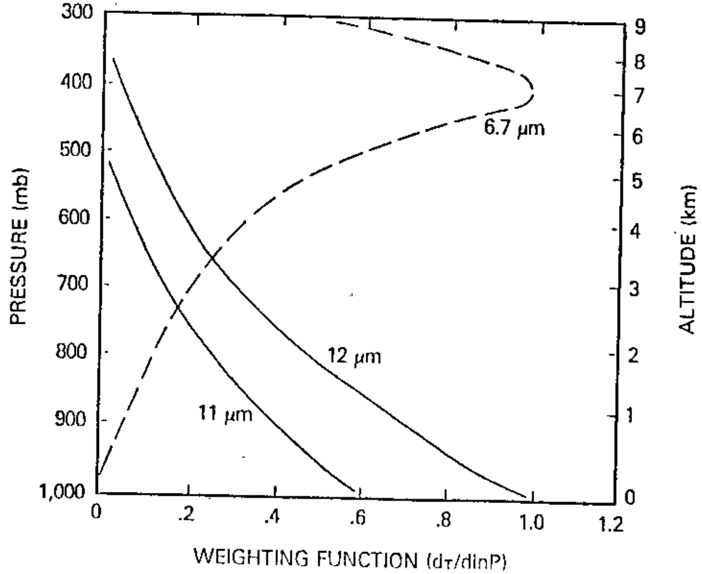


Note large variation during year.
- factor of 8× Feb. to August.

Sea Surface Temperature.

Affects medium / long range weather forecasting, climate. Need to measure to ¼ - ½ K.





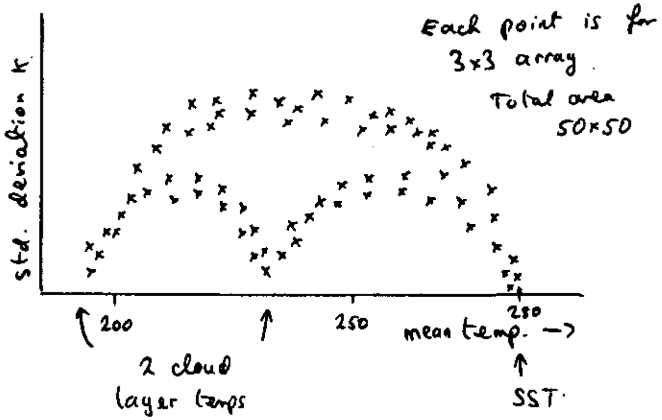
Normally use IR images to measure SST.
~ 1 km resolution – hope to see through gaps in cloud
e.g. Tiros – N series AVHRR and AVHRR/2.
window at 3·7 μm (problems from scattered sunlight during day)

11 μm

Problems

1) Clouds – dense cloud obvious
zero cloud also obvious because field very uniform
Need to identify pixels partly cloud contaminated.

Coakley and Bretherton method



3 branches due to various mixtures of 2 cloud layers and SST.

Identify arches, see where hit temperature axis
– give cloud layer temps and SST.

2) Water vapour.

Seriously affects 11 μm window. Effect worst where total column water greatest, i.e. tropics. Water absorption reduces apparent temp. because measure weighted mean of SST and air temp. (which is lower)

Current approach – use 2 channels in 11 μm window

I – best channel, least water contamination

II – channel more affected by water.

Use difference to determine problem and extrapolate to zero water vapour.

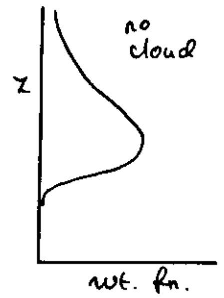
Errors for best channel – may be several K
After correction 0·3 K in North Atlantic.

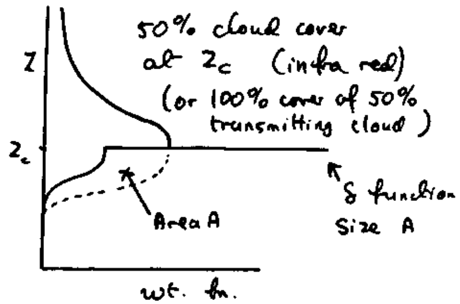
3) Dust, Aerosol, Low Cloud, Fog.

Low uniform cloud and fog can be hard to detect; use of 3·5 μm and 11 μm in combination may help.

Aerosol bigger problem. – very uniform – can affect all channels by similar amount. Currently hope ATSR will solve this (1989 launch) – view same spot from different angles – atmosphere deficit varies as cosec (zenith angle) – extrapolate to zero deficit.

Special problem of cloud contamination.





when cloud blocks path, measure emission from cloud instead of underlying atmosphere. e.g. cloud cover α ($0 \le \alpha \le 1$); weighting function below multiplied by $1-\alpha$. Area lost tranfered to delta function at cloud level.

~~Nee~~ Need to (a) identify cloud contaminated views
(b) if possible retrieve contaminated regions

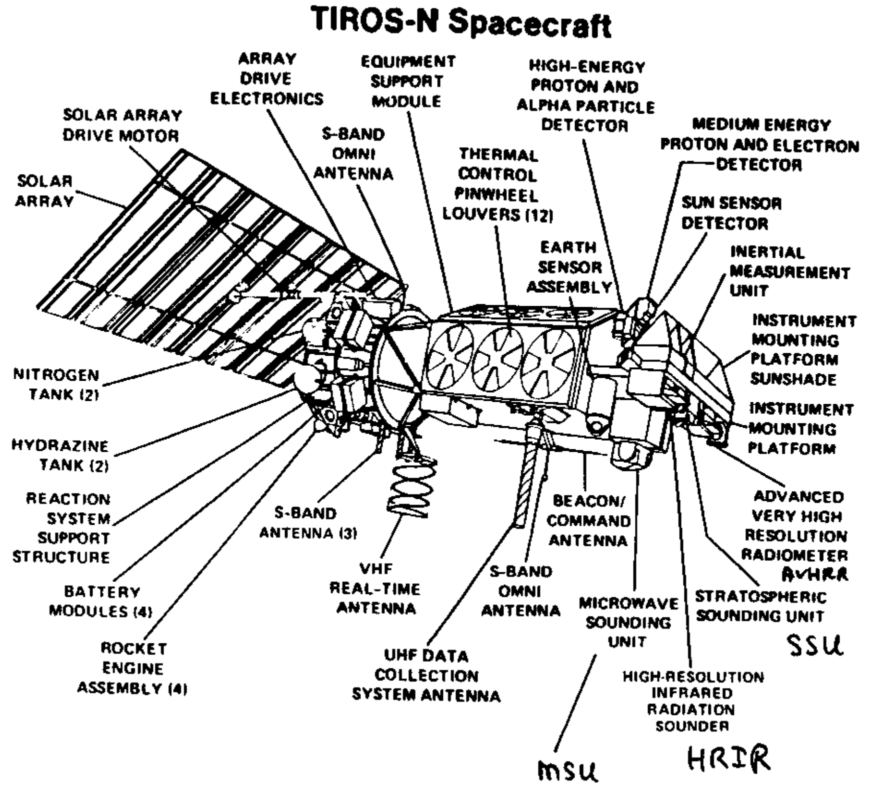
Clearly if cloud cover 100% no way to retrieve below cloud using infra red.

Clouds transparent to microwave, but serious surface emissivity problems.

Current U.S. Operational temperature sounders

Tiros - N series TOVS
TIROS-N NOAA-8 etc.
NOAA-6
NOAA-7

- HIRS - 20 channel 17km FOV IR. troposphere + stratosphere
- MSU - 4 channel 109km FOV μwave trop. + stratosphere
- SSU - 3 channel IR. CO_2 PMRs. Stratosphere



Circular orbit. ~ 830 km altitude
2 spacecraft operational at any one time
orbit planes at 90° 0730/1930 and 0130/1330 approx local times. - gives 4 passes per day 6 hours apart.

[Currently NOAA-6 and NOAA-7 but NOAA 6 has serious problems as of Sept. 1984].

Characteristics of TOV sounding channels.

HIRS Channel number	Channel central wavenumber	Central wavelength (μm)	Principal absorbing constituents	Level of peak energy contribution	Purpose of the radiance observation
1	668	15.00	CO_2	30 mb	*Temperature sounding.* The 15-μm band channels provide better sensitivity to the temperature of relatively cold regions of the atmosphere than can be achieved with the 4.3-μm band channels. Radiances in Channels 5, 6, and 7 also are used to calculate the heights and amounts of cloud within the HIRS field of view.
2	679	14.70	CO_2	60 mb	
3	691	14.50	CO_2	100 mb	
4	704	14.20	CO_2	400 mb	
5	716	14.00	CO_2	600 mb	
6	732	13.70	CO_2/H_2O	800 mb	
7	748	13.40	CO_2/H_2O	900 mb	
8	898	11.10	Window	Surface	*Surface temperature* and cloud detection.
9	1 028	9.70	O_3	25 mb	*Total ozone* concentration.
10	1 217	8.30	H_2O	900 mb	*Water vapor sounding.* Provides water vapor corrections for CO_2 and window channels. The 6.7-μm channel also is used to detect thin cirrus cloud.
11	1 364	7.30	H_2O	700 mb	
12	1 484	6.70	H_2O	500 mb	
13	2 190	4.57	N_2O	1 000 mb	*Temperature sounding.* The 4.3-μm band channels provide better sensitivity to the temperature of relatively warm regions of the atmosphere than can be achieved with the 15-μm band channels. Also, the short-wavelength radiances are less sensitive to clouds than those for the 15-μm region.
14	2 213	4.52	N_2O	950 mb	
15	2 240	4.46	CO_2/N_2O	700 mb	
16	2 276	4.40	CO_2/N_2O	400 mb	
17	2 361	4.24	CO_2	5 mb	
18	2 512	4.00	Window	Surface	*Surface temperature.* Much less sensitive to clouds and H_2O than the 11-μm window. Used with 11-μm channel to detect cloud contamination and derive surface temperature under partly cloudy sky conditions. Simultaneous 3.7- and 4.0-μm data enable reflected solar contribution to be eliminated from observations.
19	2 671	3.70	Window	Surface	
20	14 367	0.70	Window	Cloud	*Cloud detection.* Used during the day with 4.0- and 11-μm window channels to define clear fields of view.

69

MSU	Frequency (GHz)	Principal absorbing constituents	Level of peak energy contribution	Purpose of the radiance observation
1	50.31	Window	Surface	*Surface emissivity* and *cloud attenuation* determination.
2	53.73	O_2	700 mb	*Temperature sounding.* The microwave channels probe through clouds and can be used to alleviate the influence of clouds on the 4.3- and 15-μm sounding channels.
3	54.96	O_2	300 mb	
4	57.95	O_2	90 mb	

SSU	Wavelength (μm)	Principal absorbing constituents	Level of peak energy contribution	Purpose of the radiance observation
1	15.0	CO_2	15.0 mb	*Temperature sounding.* Using CO_2 gas cells and pressure modulation, the SSU observes thermal emissions from the stratosphere.
2	15.0	CO_2	4.0 mb	
3	15.0	CO_2	1.5 mb	

70

Normal retrieval process.

Take group of 3x3 HIRS pixels

↓

Cloud clear: find clear column radiances provided cloud amount varies (or = 0). HIRS only

↓

Limb darkening correction

↓

Calculate expected MSU radiances using HIRS

↓

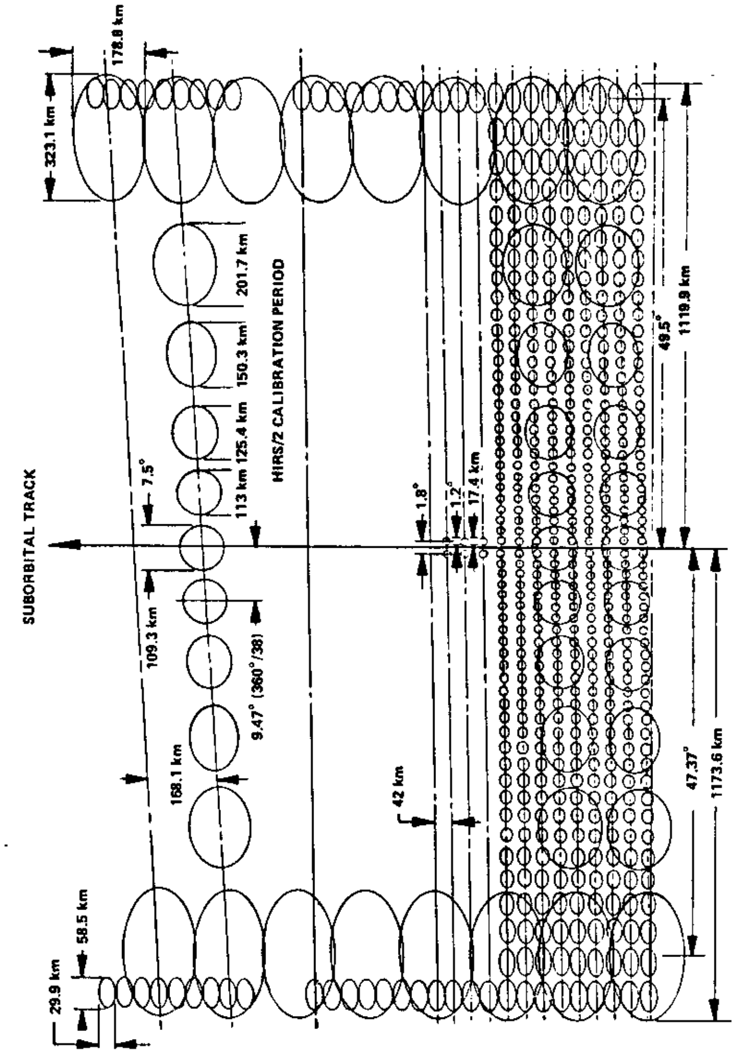
Agree with actual MSU? — N → give up

↓ Y

Retrieve Temp profile, and along and cross track gradients.
Also cloud amount, height.

Cloud clearing assumes single height cloud in 3x3 view.
MSU only used as check of cloud clearing.

HIRS and MSU Scanning Geometries



TIROS operational vertical sounder HIRS/2 and MSU scan patterns projected on Earth

HIRS has 56 elements across scan (AVHRR has 2048 elements)

Data processing (a) Global – data recorded – all processed by NMC to get global field – some hours lag.

(b) local – can receive transmission in real time – 2000 km radius – results within 30 mins.

Tropospheric Analysis – Data source.

European Centre for Medium Range Forecasting. ECMWF.

12 GMT MONDAY JUNE 4 1979			
SYNOPS, SHIPS	2528	1098	
SAT WINDS (LOW LEVEL)	2065		
SAT WINDS (HIGH LEVEL)	1061		
ASDARS, AIDS, AIREPS	83	373	658
BUOYS, NAVAIDS, DSONDES, COLBAS	611	7 18	83
TEMPS, PILOTS	766	583	
SATEMS, LIMS SOUNDINGS	2135	0	

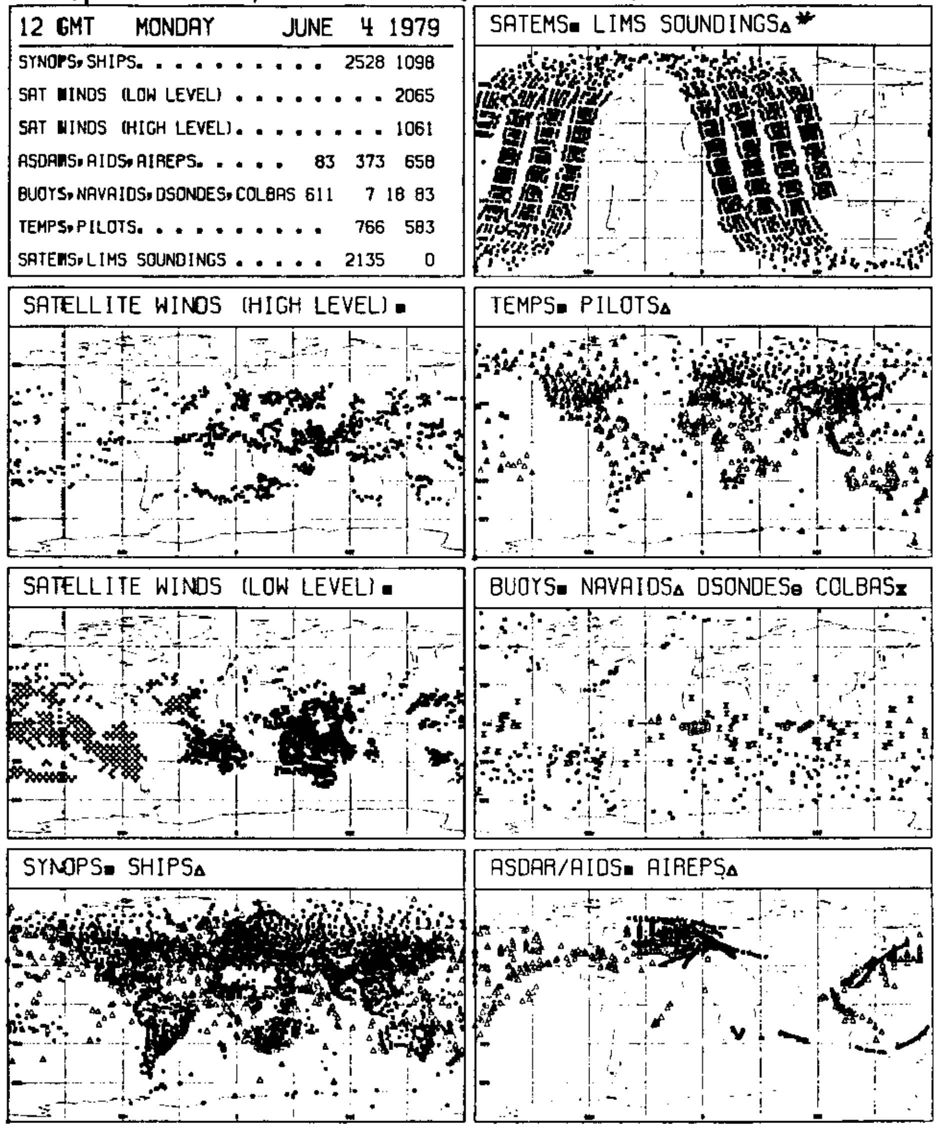
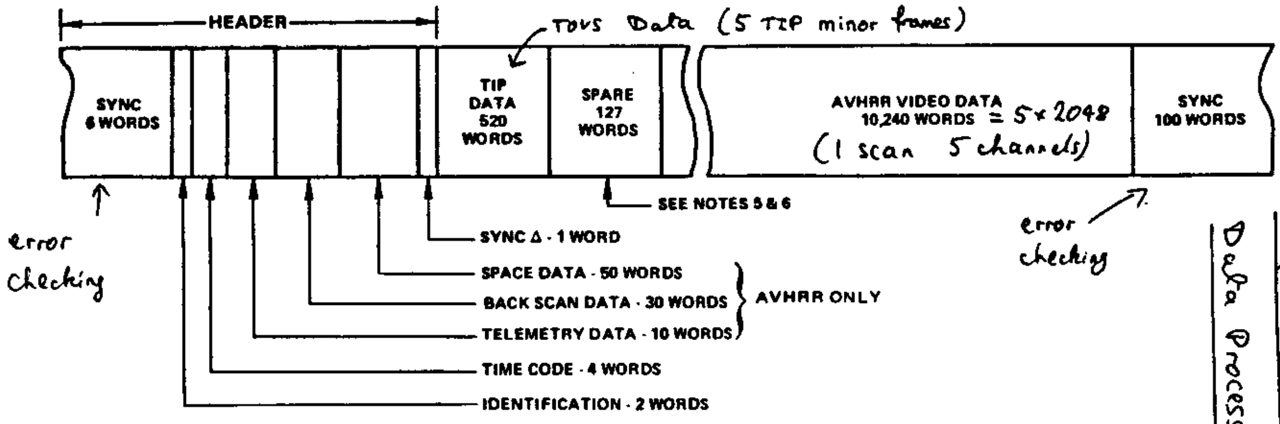


FIG. 4. FGGE level II-b data distribution, 4 June 1979 12 GMT ±3 h.

* LIMS had failed by June 4 1979. LIMS was used for stratosphere.



Simple Guide to Data Processing.

NOTES:

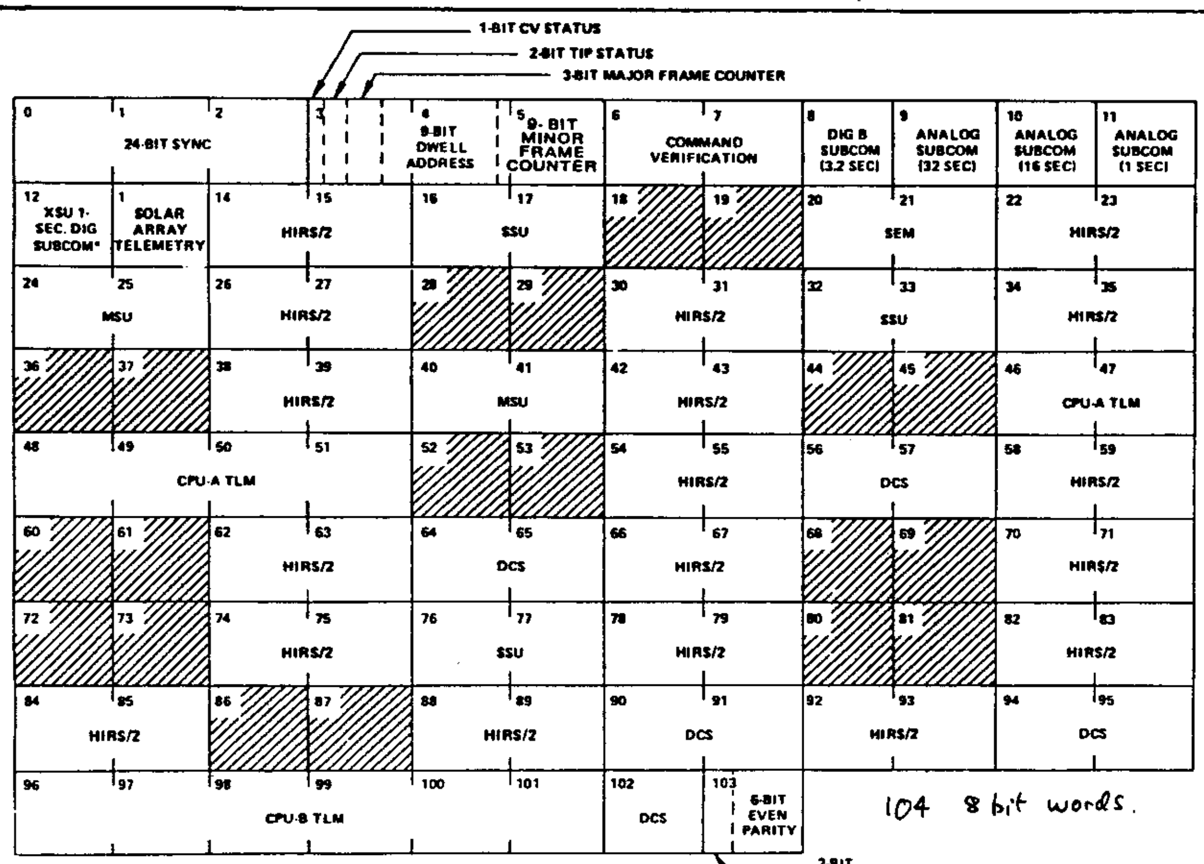
(1) MINOR FRAME LENGTH - 11,090 WORDS
(2) THREE MINOR FRAMES PER MAJOR FRAME
(3) MINOR FRAME RATE - 6 FRAMES/SECOND
(4) WORD LENGTH - 10 BITS/WORD
(5) ALL SPARES ARE 10TH DEGREE P-N CODE (BAR).

TIP words are 8 bit. Other 2 bits used for error checking.

TLM WORD ALLOCATIONS	1D WORD BIT ALLOCATIONS	
	1ST ID WORD	2ND ID WORD
1-5 RAMP CALIBRATION 6 CHANNEL-3 TARGET TEMP (5 PT SUBCOM) 7 CHANNEL-4 TARGET TEMP (5 PT SUBCOM) 8 CHANNEL-5 TARGET TEMP (5 PT SUBCOM) 9 CHANNEL-3 PATCH TEMP 10 SPARE	1 SYNC ID 2-3 FRAME ID 4-7 SPACECRAFT ADDRESS 8 RESYNC MARKER 9 DATA 0 10 DATA 1	(SPARE)

TOVS / AVHRR data received in real-time by ground station.

Figure 3-5. TIROS-N/NOAA HRPT minor frame format



TIP Minor Frame Format.

NOTES: NUMBER IN UPPER LEFT HAND CORNER INDICATES MINOR FRAME WORD NUMBER.
TIME CODE DATA SHALL APPEAR DURING MINOR FRAME "0" WORD LOCATIONS 8 THROUGH 12.
///// WORD LOCATIONS ARE SPARE AND CONTAIN CODE 01010101
* THE [illegible] FUNCTION IS ACCOMPLISHED IN THE EXTERNAL UNIT.

Element 0-55

Bit 1-8	Encoder position (1-56=Earth view, 68=space, 105=ICT, 156=IWT)	← pixel number
Bit 9-13	Electronic cal level (0-31)	
Bit 14-19	Channel 1 period monitor	
Bit 20-25	Element number (1 less than encoder value for Earth views)	
Bit 26	Filter sync designator	
Bit 27-286	Radiant signal output (20 ch x 13 bits)	← main data chanels. Order 1, 17, 2, 3, 13, 4, 18, 11, 19, 7, 8, 20, 10, 14, 6, 5, 15, 12, 16, 9
Bit 287	Valid data bit	
Bit 288	Minor word parity check (odd parity)	

Element 56-63

Bit 1-26	Same as above
Bit 287, 288	Same as above

Element 56

Bit 27-286	Positive electronic cal. (cal level advances one of 32 equal levels on succeeding scans)

Element 57

Bit 27-286	Negative electronic cal.

Element 58

Bit 27-91	Internal warm target #1, 5 times
Bit 92-156	Internal warm target #2, 5 times
Bit 157-221	Internal warm target #3, 5 times
Bit 222-286	Internal warm target #4, 5 times

Element 59

Bit 27-91	Internal cold target #1, 5 times
Bit 92-156	Internal cold target #2, 5 times
Bit 157-221	Internal cold target #3, 5 times
Bit 222-286	Internal cold target #4, 5 times

Element 60

Bit 27-91	Filter housing temp. #1, 5 times
Bit 92-156	Filter housing temp. #2, 5 times
Bit 157-221	Filter housing temp. #3, 5 times
Bit 222-286	Filter housing temp. #4, 5 times

Element 61

Bit 27-91	Patch temp. expanded, 5 times
Bit 92-156	First-stage temp., 5 times
Bit 157-221	Filter housing control power /temp., 5 times)
Bit 222-286	Electronic cal DAC, 5 times (counts)

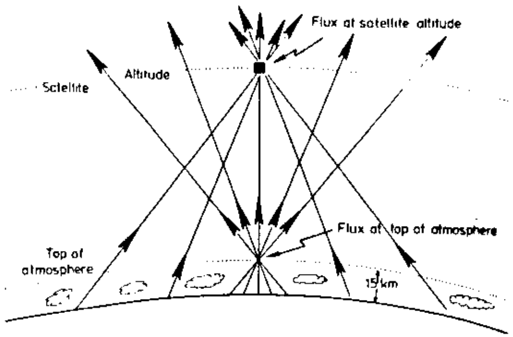
Element 62

Bit 27-39	Scan mirror temp.
Bit 40-52	Primary telescope temp.
Bit 53-65	Secondary telescope temp.
Bit 66-78	Baseplate temp.
Bit 79-91	Electronics temp.
Bit 92-104	Patch temp. - full range
Bit 105-117	Scan motor temp.
Bit 118-130	Filter motor temp.
Bit 131-143	Cooler housing temp.
Bit 144-156	Patch control power

HIRS/2 digital A Data Output

Take TIP Minor Frame. Join all words marked HIRS/2. Decode as here

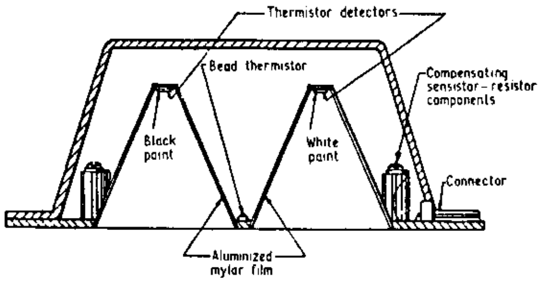
Earth's Radiation Budget



Illustrating the problem of relating the outgoing radiative flux at the top of the atmosphere to measurements at a typical satellite altitude.

To measure outgoing flux integrate over
a) all angles
b) all wavelength
c) all globe
d) all times of day.

early radiometer →
White element measures reflected sunlight
Black measures thermal emission



Schematic diagram of Wisconsin wide-field radiometer. From Astheimer *et al* (1961).

Series of U.S. instruments called E.R.B.
So far integrated over (a), (b), (c), but not (d) since sun synchronous so just get twice / day (noon-midnight).