REVIEW OF LAST LECTURE

* COMPOSITION OF THE ATMOSPHERE

* CHARACTERISTICS : TEMPERATURE
  PRESSURE
  WATER VAPOUR PRESSURE

* THE MELTING LAYER, VERTICAL STRUCTURE OF THE TROPOSPHERE

* REFRACTIVE INDEX / REFRACTIVITY
  - FLAT EARTH
  - CURVED EARTH
  - MODIFIED REFRACTIVITY

REFRACTIVE CONDITIONS

$$\frac{dM}{dh} = \frac{dN}{dh} + 157 \quad N\,km^{-1}$$

$\frac{dM}{dh} > 0$: RAYS REFRACTED AWAY FROM THE EARTH.

$\frac{dM}{dh} < 0$: RAYS REFRACTED TOWARDS THE EARTH.

THE VALUE OF $\frac{dM}{dh}$ IS A GOOD INDICATOR

AS TO WHETHER DUCTING MAY OCCUR

BECAUSE OF REFRACTION AN <u>ANTENNA ANGLE CORRECTION</u> IS REQUIRED WHEN DIRECTING A GROUND BASED STEERABLE ANTENNA AT A TARGET SUCH AS;

* A SATELLITE, OUTSIDE THE TROPOSPHERE
* AN AIRCRAFT
* A VERY DISTANT RECEIVER.

A TECHNIQUE USED TO STUDY THE EFFECT OF REFRACTION IS <u>RAY-TRACING</u>. AT HIGH ELEVATIONS (SAY ABOVE 6°) THE EFFECT IS SMALL, AT LOW ELEVATION ANGLES THE EFFECT CAN BE SIGNIFICANT. – THIS IS BECAUSE THE REFRACTIVE INDEX IS MOST VARIABLE AT THE SURFACE (SINCE IT FORMS A BOUNDARY).

<u>RAY-TRACING</u> IS AN ITERATIVE PROCESS THAT INVOLVES EVALUATING THE RADIUS OF CURVATURE r, OF THE RAYS ACCORDING TO THE REFRACTIVE INDEX GRADIENT $\frac{dn}{dh}$ AND ELEVATION ANGLE α FOR SUCESSIVE HEIGHTS USING

$$\frac{1}{r} = -\frac{1}{n}\frac{dn}{dh}\cos\alpha$$

RAY TRACING HAS THE FOLLOWING LIMITATIONS;

* THE R.I SHOULD NOT CHANGE APPRECIABLY OVER A WAVELENGTH

* THE FRACTIONAL CHANGE IN THE SPACING BETWEEN NEIGHBOURING RAYS MUST BE SMALL COMPARED TO A WAVELENGTH.

IN ORDER TO SATISFY THESE CONDITIONS THE REFRACTIVE - INDEX - HEIGHT PROFILE MUST NOT HAVE AN ABRUPT CHANGE OR TOO LARGE A GRADIENT. EVEN IF THESE CONDITIONS ARE NOT FULLY FULFILLED, RAY-TRACING MAY STILL GIVE US AN IDEA OF WHAT IS GOING ON.

DUCTING

UNDER SOME ATMOSPHERIC CONDITIONS, WHERE OVER A LARGE HORIZONTAL AREA THE REFRACTIVE INDEX DECREASES RAPIDLY WITH HEIGHT, RADIOWAVES CAN BE TRAPPED AND WE CAN GET LOW-LOSS PROPAGATION OVER LONG DISTANCES

– TROPOSPHERIC DUCTING

FOR DUCTING $\frac{dM}{dh} < 0$ AND FOR MANY WAVELENGT

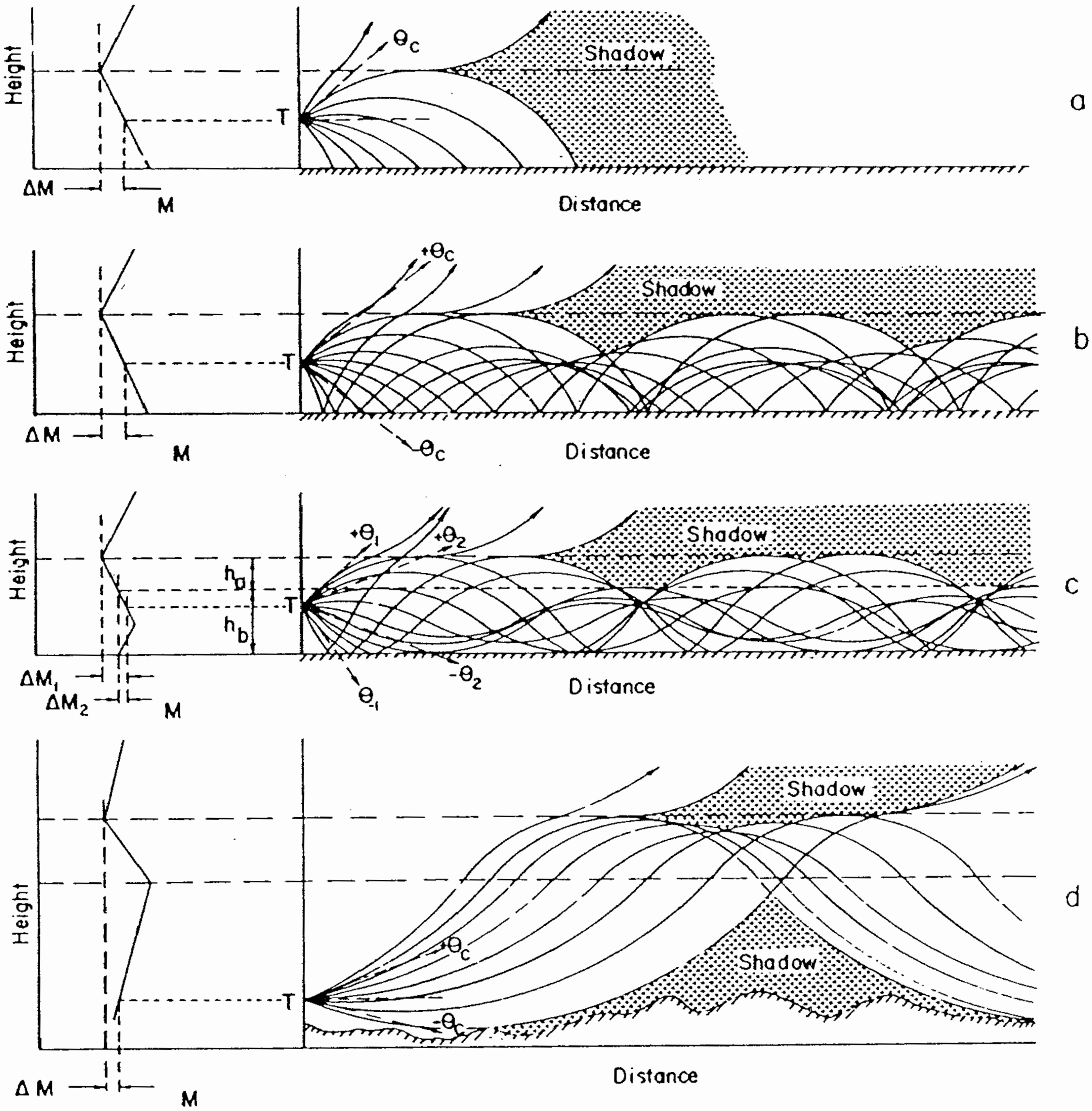


Fig. 2.8. *Rays propagating from a transmitter situated in a ground-based duct*

a Uniform $dM/dh < 0$ in duct ($dN/dh < -157$ N/km) and $dM/dh > 0$ above duct ($dN/dh > -157$ N/km). Rays trapped for $\theta < \theta_c = \sqrt{(2\Delta M \times 10^{-6})}$

b As for *a*, but with ground reflection

c As for *a*, but with $dM/dh > 0$ near ground. If transmitter is in height region h_a, rays remain in duct for θ between $\pm\theta_1 = \pm\sqrt{(2\Delta M_1 \times 10^{-6})}$ as for *a* and *b* above. If transmitter is in height region h_b, rays remain in duct without ground reflection for θ between $\pm\theta_2 = \pm\sqrt{(2\Delta M_2 \times 10^{-6})}$ and within the duct but with ground reflection if θ between $\pm\theta_1 = \pm\sqrt{(2\Delta M_1 \times 10^{-6})}$

d A special case of *c* above. Rays trapped for θ between $\pm\theta_c = \pm\sqrt{(2\Delta M \times 10^{-6})}$

GROUND BASED DUCTS

CAUSED BY AN UNUSUALLY RAPID DECREASE IN WATER VAPOUR WITH HEIGHT

OR/AND

INCREASE IN TEMPERATURE WITH HEIGHT (TEMPERATURE INVERSION.

DUCTING ASSOCIATED WITH LAKES/SEAS

EVAPORATION OF WATER VAPOUR FROM THE SURFACE MAY CAUSE A REGION OF HIGH HUMIDITY (I.e HIGH REFRACTIVE INDEX) BELOW A REGION OF DRIER AIR - THESE USUALLY OCCUR IN THE AFTERNOON DUE TO PROLONGED SOLAR HEATING. $\Delta h \approx 15m$

OVER TROPICAL SEAS THE HIGH HUMIDITY AT THE SURFACE PRODUCES ALMOST PERMANENT DUCTS.

ADVECTION MAY CAUSE HOT DRY AIR (FROM LAND) TO BE BLOWN OVER COLD WET AIR PRODUCING A REGION OF LOW REFRACTIVE INDEX ABOVE A REGION OF HIGH REFRACTIVE INDEX.
- THESE OCCUR MAINLY IN THE EVENING WITH THE ONSET OF A LAND BREEZE.

RADIATION COOLING

WHEN THE GROUND COOLS AT NIGHT, THE AIR CLOSE TO THE GROUND BECOMES COOLER THAN THE AIR ABOVE IT. – THIS IS QUITE A COMMON OCCURENCE IN DESERTS AND TROPICAL CLIMATES

RADIATION COOLING FOLLOWED BY SOLAR HEATING THE NEXT DAY CAN LEAD TO AN ELEVATED DUCT – THESE ARE USUALLY SHORT LIVED

ELEVATED DUCTS

ARE ALSO ASSOCIATED WITH ANTICYCLONIC WEATHE (HIGH PRESSURE SYSTEMS) – IN THIS CASE THE DUCTS CAN LAST SEVERAL DAYS.

COUPLING INTO DUCTS

THE FREQUENCY DEPENDENCE OF THE MODES OF OUR DUCT (ANALOGOUS TO THE MODES IN AN OPTICAL FIBRE) CAN CAUSE PROBLEMS

WE CAN HAVE FREQUENCY DEPENDENT MULTI PATH FADING. IN FM SYSTEMS THIS GIVES RISE TO DELAY DISTORTION. IN DIGITAL COMMS. SYSTEMS, ESPECIALLY SPREAD SPECTRUM SYSTEMS THIS CAN CAUSE ISI

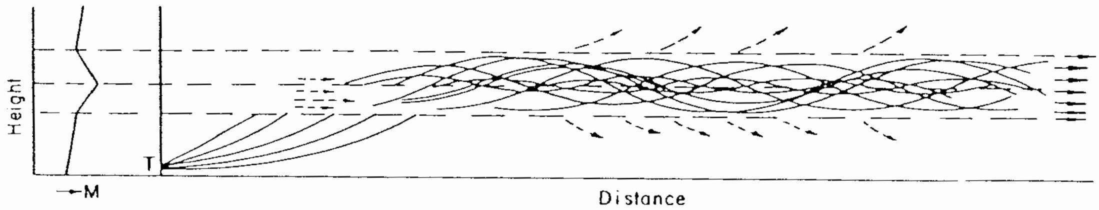


Fig. 2.10. *Rays propagating from a transmitter situated below an elevated duct*

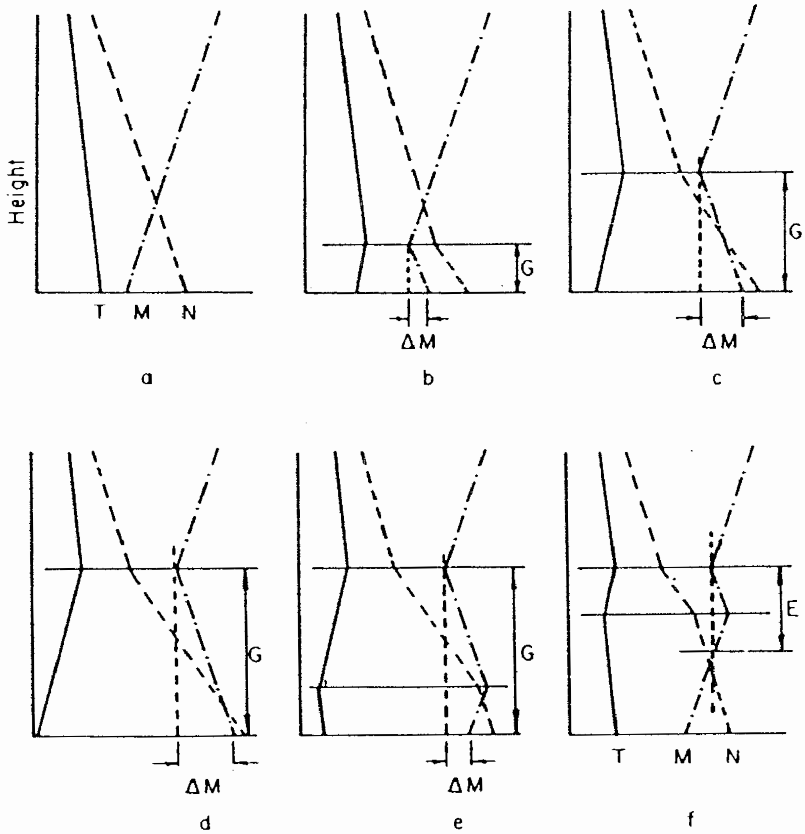


Fig. 2.9. *Profiles of temperature T refractive index N and modified refractive index M as ground-based ducts and elevated ducts form by thermal radiation processes*

Progressive night cooling of ground (*a* to *d*) produces ground-based duct (G). Subsequent solar heating of ground (*e* and *f*) produces elevated duct (E).

——— *T*

– – – – *N*

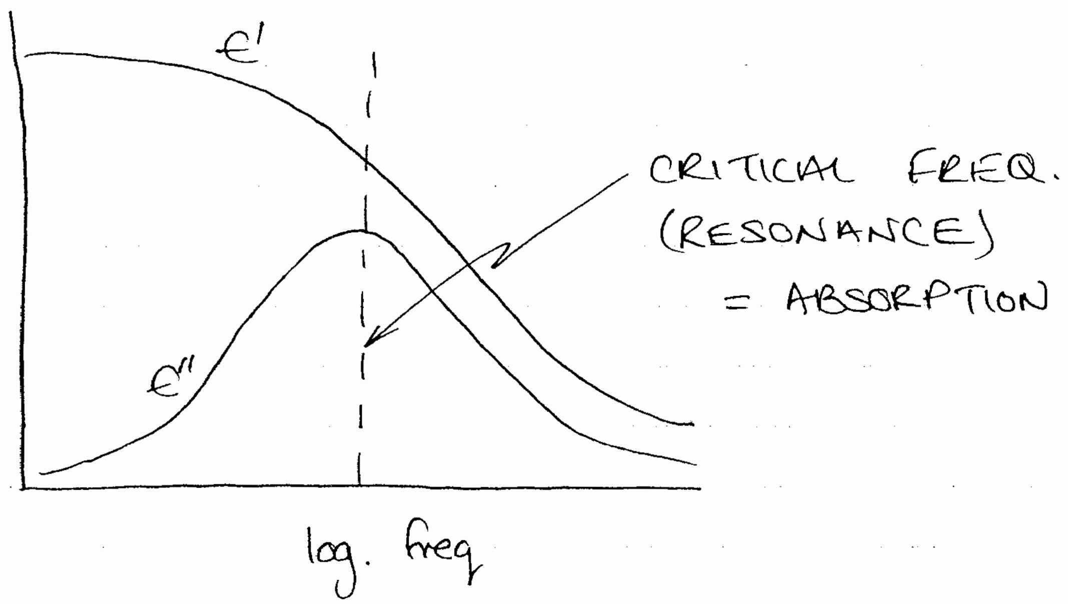
—·—·— *M*

ABSORPTION AND DISPERSION IN ATMOSPHERIC GASES

IF, WHEN WE PLACE A MOLECULE IN A ELECTRIC FIELD, IT ALIGNS ITSELF WITH THE FIELD - IT IS SAID TO BE POLAR

WATER VAPOUR IS A POLAR MOLECULE - IT HAS A PERMANENT ELECTRIC DIPOLE. IN SPITE OF THE FACT THAT WATER VAPOUR REPRESENTS A VERY SMALL FRACTION OF THE ATMOSPHERE - THE STRENGTH OF THE RESONANCE OF THE DIPOLE MAKES IT VERY IMPORTANT

FOR A SUBSTANCE, IF WE PLOT THE COMPLEX PERMITTIVITY AS A FUNCTION OF FREQUENCY...

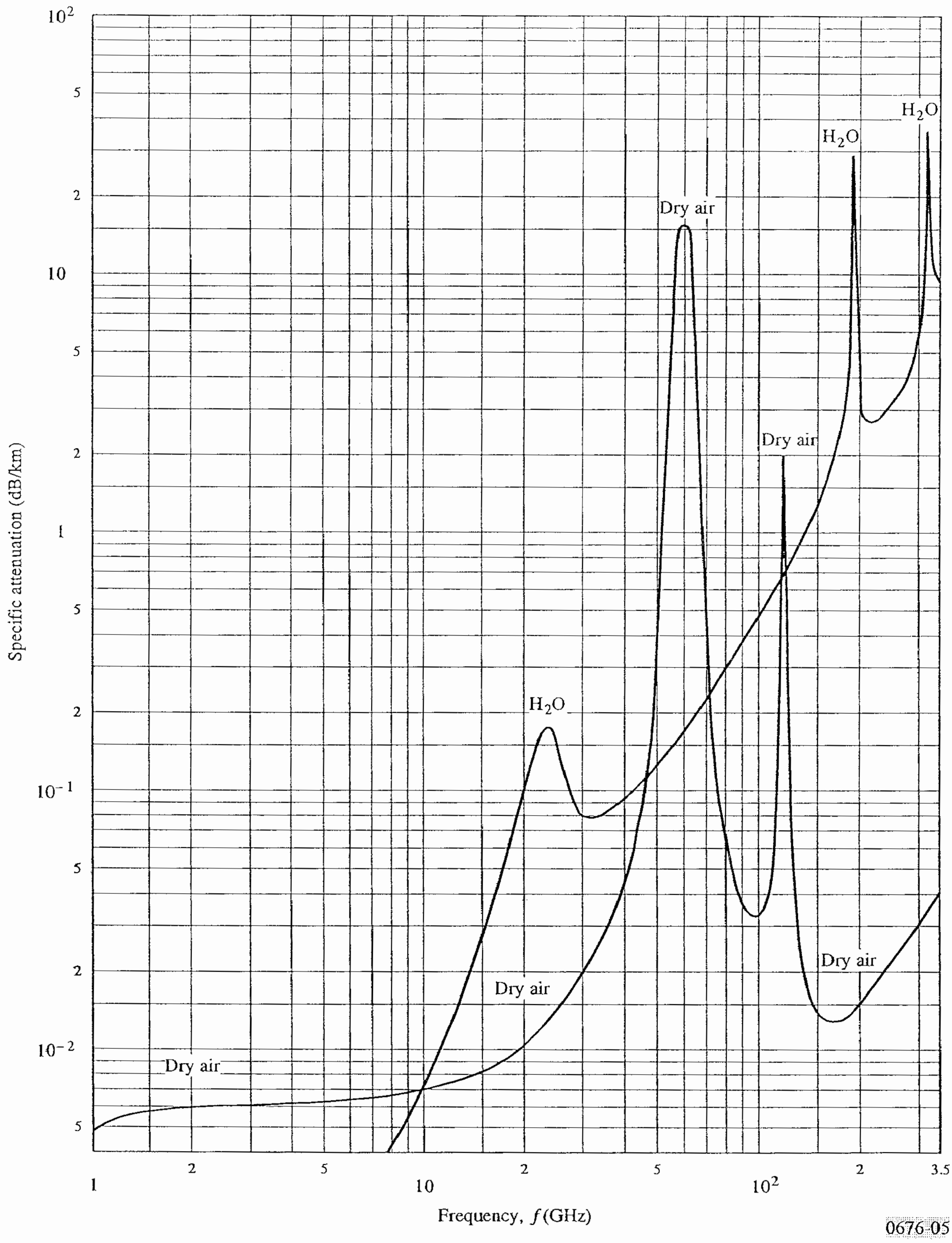


$$\epsilon = \epsilon' + j\epsilon''$$

7a

FIGURE 5

Specific attenuation due to atmospheric gases



Pressure: 1 013 hPa
Temperature: 15° C
Water vapour: 7.5 g/m^3

WATER VAPOUR

ABSORPTION (ATTENUATION) BECOMES SIGNIFICANT ABOVE 30GHz, DUE TO OTHER GASES EVEN IF NO WATER VAPOUR IS PRESENT.

IN THE PRESENCE OF WATER VAPOUR WE HAVE TO START WORRYING FOR FREQUENCIES HIGHER THAN ~ 5GHz.

THE SPOT RESONANCES FOR WATER VAPOUR BELOW 350GHz ARE 22.8, 183.3 AND 328.3 GHz

OXYGEN

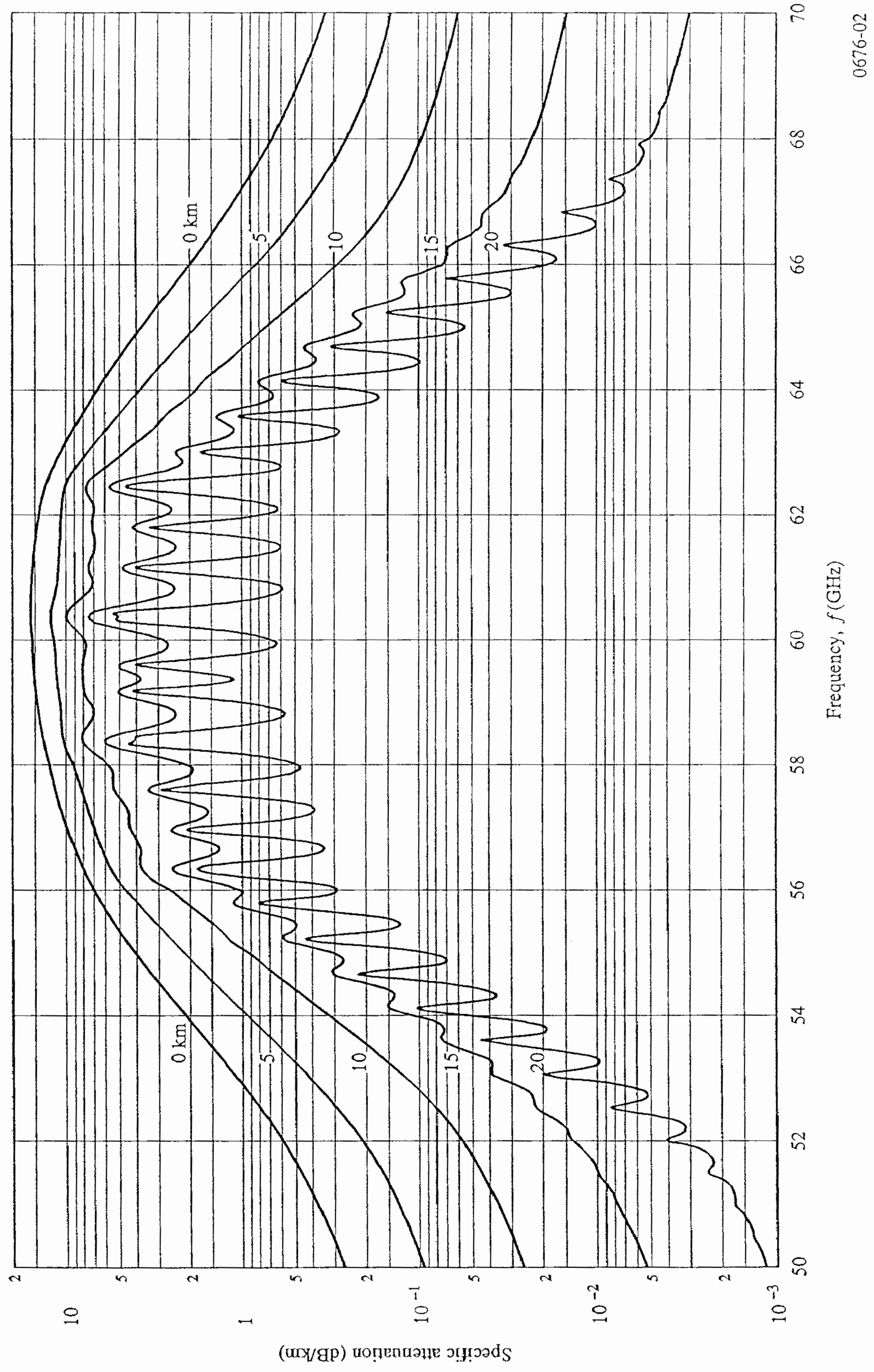
DESPITE NOT HAVING AN ELECTRIC DIPOLE, OXYGEN CAUSES PROBLEMS BECAUSE IT HAS A MAGNETIC DIPOLE. THE OXYGEN RESONANCE OCCURS AT 52-68GHz. THE 52-68GHz RESONANCE IS THE PRODUCT OF MANY BROADENED LINES, CENTRED ON 60GHz. THERE IS ALSO AN ISOLATED LINE AT 118.74GHz. AT THE PEAK RESONANCE ~60GHz THE ATTENUATION CAN BE 12dB km^{-1} - RANGE LIMITED TO A FEW km.

NITROGEN

DESPITE BEING THE MOST ABUNDANT GAS IN THE ATMOSPHERE, NITROGEN HAS NEITHER AN ELECTRIC OR MAGNETIC DIPOLE ⇒ NO RESONANCE ⇒ NO ABSORPTION

FIGURE 2

Specific attenuation in the range 50-70 GHz at the altitudes indicated



ORIGINS OF THE RESONANCES

SPOT FREQUENCIES DUE TO QUANTUM MECHANICS
- HEISENBERG'S UNCERTAINTY PRINCIPLE
USUALLY THE NATURAL LINE WIDTH IS
< 1Hz FOR mm-WAVE FREQUENCIES

THESE LINES ARE BROADENED BY;

PRESSURE BROADENING

COLLISIONS BETWEEN RANDOMLY ABSORBING MOLECULES. - THIS IS THE MECHANISM THAT PRODUCES THE SINGLE OXYGEN PEAK.

DOPPLER BROADENING

FREQUENCY SHIFTS DUE TO MOVING MOLECULES WHICH ARE IN THERMAL MOTION

ZEEMAN BROADENING

ENERGY TRANSITIONS WITHIN MOLECULES IN A MAGNETIC FIELD - SUCH AS THE EARTHS MAGNETIC FIELD.

VARIATION OF ABSORPTION WITH HEIGHT.

GASEOUS ATTENUATION IS HEIGHT DEPENENT SINCE THE DENSITY OF EACH COMPONENT DECREASES WITH HEIGHT

THE AMOUNT OF ABSORPTION DEPENDS ON THE DENSITY OF ABSORBERS, AND ON THE STRENGTH OF THE RELEVANT ABSORPTION LINES.

AT GREAT HEIGHTS, SAY > 10km PRESSURE BROADENING BECOMES LESS IMPORTANT, SO ABORPTION LINES BECOME NARROWER, BUT STRONGER PER MOLAR DENSITY.

PRESENT APPROACHES TO MODELLING

* ITU-R MODELS (SEMI-EMPIRICAL)

* LINE-BY-LINE SUMMATION...

CURRENT MODELS DON'T EXPLAIN THE CONTINUUM VERY WELL, THE PEAKS ARE FINE.

For dry air, the attenuation γ_o (dB/km) is given by:

$$\gamma_o = \left[\frac{7.27 \; r_t}{f^2 + 0.351 \; r_p^2 \; r_t^2} + \frac{7.5}{(f - 57)^2 + 2.44 \; r_p^2 \; r_t^5} \right] f^2 \; r_p^2 \; r_t^2 \times 10^{-3} \qquad (22a)$$

for $f \leq 57$ GHz

$$\gamma_o = \left[2 \times 10^{-4} \, r_t^{1.5} \left(1 - 1.2 \times 10^{-5} \, f^{1.5}\right) + \frac{4}{(f - 63)^2 + 1.5 \, r_p^2 \, r_t^5} + \frac{0.28 \, r_t^2}{(f - 118.75)^2 + 2.84 \, r_p^2 \, r_t^2} \right] f^2 \, r_p^2 \, r_t^2 \times 10^{-3} \qquad (22b)$$

for 63 GHz $\leq f \leq$ 350 GHz

$$\gamma_o = \frac{(f - 60)(f - 63)}{18} \gamma_o(57) - 1.66 \; r_p^2 \; r_t^{8.5} (f - 57)(f - 63) + \frac{(f - 57)(f - 60)}{18} \gamma_o(63) \qquad (22c)$$

for 57 GHz $\leq f \leq$ 63 GHz.

where:

f: frequency (GHz)

$r_p = p/1013$

$r_t = 288/(273 + t)$

p: pressure (hPa)

t: temperature (°C).

For water vapour, the attenuation γ_w (dB/km) is given by:

$$\gamma_w = \left[3.27 \times 10^{-2} \, r_t + 1.67 \times 10^{-3} \frac{\rho \, r_t^7}{r_p} + 7.7 \times 10^{-4} \, f^{0.5} + \frac{3.79}{(f - 22.235)^2 + 9.81 \, r_p^2 \, r_t} + \frac{11.73 \, r_t}{(f - 183.31)^2 + 11.85 \, r_p^2 \, r_t} + \frac{4.01 \, r_t}{(f - 325.153)^2 + 10.44 \, r_p^2 \, r_t} \right] f^2 \, \rho \, r_p \, r_t \times 10^{-4} \qquad (23)$$

for $f \leq 350$ GHz

where ρ is the water-vapour density (g/m^3).

Figure 5 shows the specific attenuation from 1 to 350 GHz at sea-level for dry air and water vapour with a density of 7.5 g/m^3. This figure was derived using the line-by-line calculation as described in Annex 1.

2 Path attenuation

2.1 Terrestrial paths

For a horizontal path, or for slightly inclined paths close to the ground, the path attenuation, A, may be written as:

$$A = \gamma \, r_0 = (\gamma_o + \gamma_w) r_0 \quad \text{dB} \qquad (24)$$

where r_0 is the path length (km).