Navigation

SS-2004

Chapter 4 – Physical fundamentals

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4 Physical fundamentals (1)

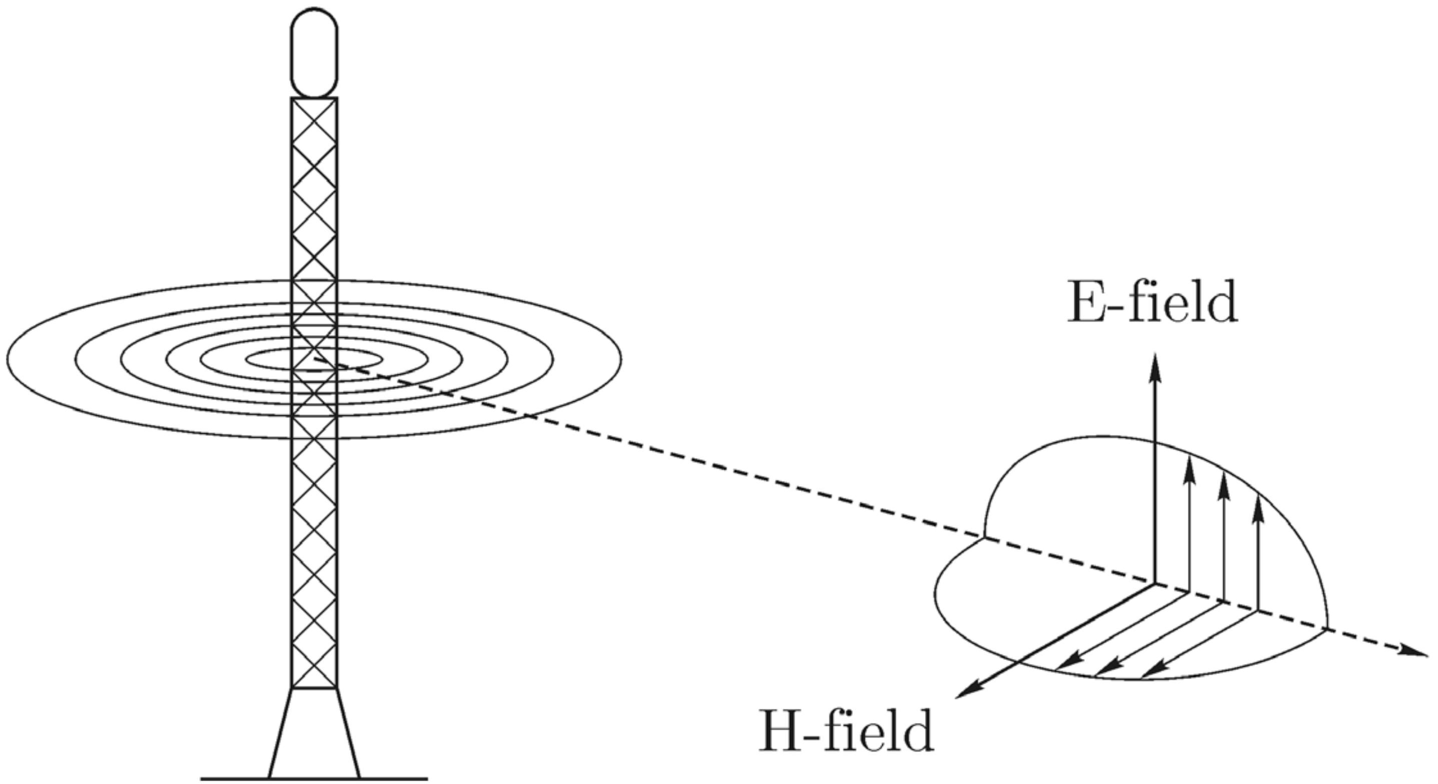
4.1 Fundamentals of electromagnetic waves

4.1.1 Definition of electromagnetic waves

- Oscillating **electric force** propagates through space (vacuum, atmosphere, solid, fluid)
- Electromagnetic waves are formed when an electric (**E-**) field **couples** with the orthogonal magnetic (M- or **H-**) field
- Field vectors of E- and H-field are **perpendicular** to each other and to the propagation direction
- Plane of E-field defines the **polarization** of the wave (constant, circular, elliptical)

4 Physical fundamentals (2)

– Principal components of an electromagnetic wave emitted radially from a vertical tower:



4 Physical fundamentals (3)

Propagation: Maxwell's laws. Assuming a sinusoidal propagation, the wave motion is

$$y = a \sin(2\pi f t) \tag{4.1}$$

a **. . . amplitude,** f **. . . frequency,** t **. . . time**

Circular frequency ω**, also called angular velocity:**

$$\omega = 2\pi f \tag{4.2}$$

so that (4.1) may also be written as

$$y = a \sin \omega t\,. \tag{4.3}$$

Current value of ωt **describing the current state, is denoted as phase angle (or briefly phase)** φ**.**

4 Physical fundamentals (4)

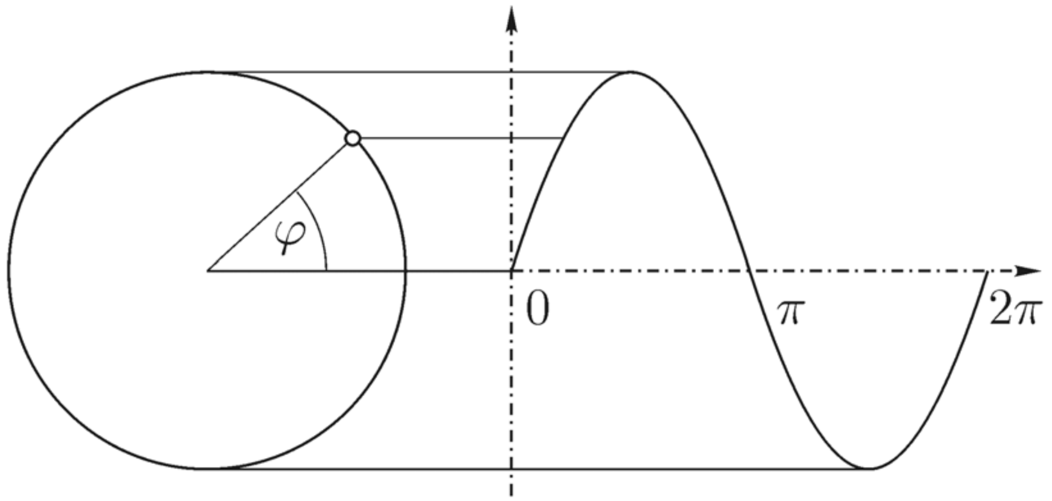
Introducing this phase angle

$$\varphi = \omega\, t \tag{4.4}$$

in (4.3) leads to

$$y = a \sin \varphi\, . \tag{4.5}$$

Phase angle: time-dependent, bounded between 0 and 2π, see Fig.



4 Physical fundamentals (5)

- **Wavelength λ: distance between two points of equal phase, i.e., after the variation of φ by 2π.**
- **Period T: time needed for this variation**
- **Cycle: one full variation of the phase by 2π. Accordingly, the time needed for one cycle is the period T.**
- **Temporal variation of the phase:**

$$\frac{\varphi}{2\pi} = \frac{t}{T} \tag{4.6}$$

- **Local variation of the phase while propagating in analogy to (4.6):**

$$\frac{\varphi}{2\pi} = \frac{\varrho}{\lambda} \tag{4.7}$$

where ϱ is the range equivalent to the phase.

4 Physical fundamentals (6)

- **Elementary relations implying the period T are**

$$\omega = 2\pi/T \tag{4.8}$$

$$T = 1/f = 2\pi/\omega\,. \tag{4.9}$$

- **Frequency f, wavelength λ, and velocity v:**

$$v = \lambda\, f\,. \tag{4.10}$$

- **Electromagnetic wave in vacuum: velocity v becomes c, the velocity of light in vacuum:**

$$c = \lambda\, f \tag{4.11}$$

where

$$c = 299\,792\,458\ \mathbf{m\,s}^{-1}\,. \tag{4.12}$$

4 Physical fundamentals (7)

Table 4.1. Physical quantities

Quantity	Symbol	Unit
Frequency	f	s^{-1}
Phase	φ	radians
Wavelength	λ	m
Period	T	s
Velocity of light	c	$m\,s^{-1}$

The angular velocity or circular frequency ω is also defined by the derivation of the phase angle φ with respect to time

$$\omega = \frac{d\varphi}{dt}\,. \tag{4.13}$$

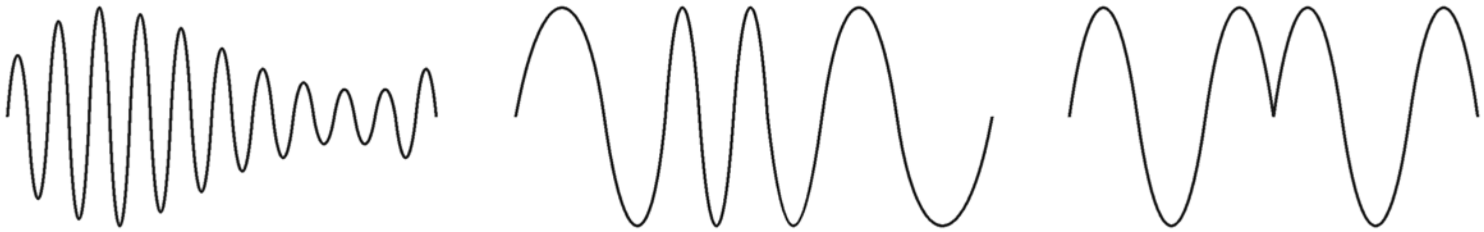
Thus, between the epochs t_0 and t the phase is

$$\varphi = \int_{t_0}^{t} \omega\, dt \tag{4.14}$$

4 Physical fundamentals (8)

- **Modulation**: Variation of
  - (a) Amplitude
  - (b) Frequency
  - (c) Phase

  Provides a tool to communicate information of many types (audio, video, data)



(a) (b) (c)

4 Physical fundamentals (9)

– Relationship between frequency and wavelength

Frequency	Wavelength
1 Hz	$3 \cdot 10^{8}$ m
1 kHz	$3 \cdot 10^{5}$ m
1 MHz	$3 \cdot 10^{2}$ m
1 GHz	$3 \cdot 10^{-1}$ m

4 Physical fundamentals (10)

4.1.2 Doppler frequency shift

- In case of relative motion between transmitter and receiver
- First approximation:

$$\Delta f = f_r - f_e = -\frac{v_\rho}{c} f_e$$

- Doppler frequency is **proportional to radial velocity ➔** integration over time yields range differences

4 Physical fundamentals (11)

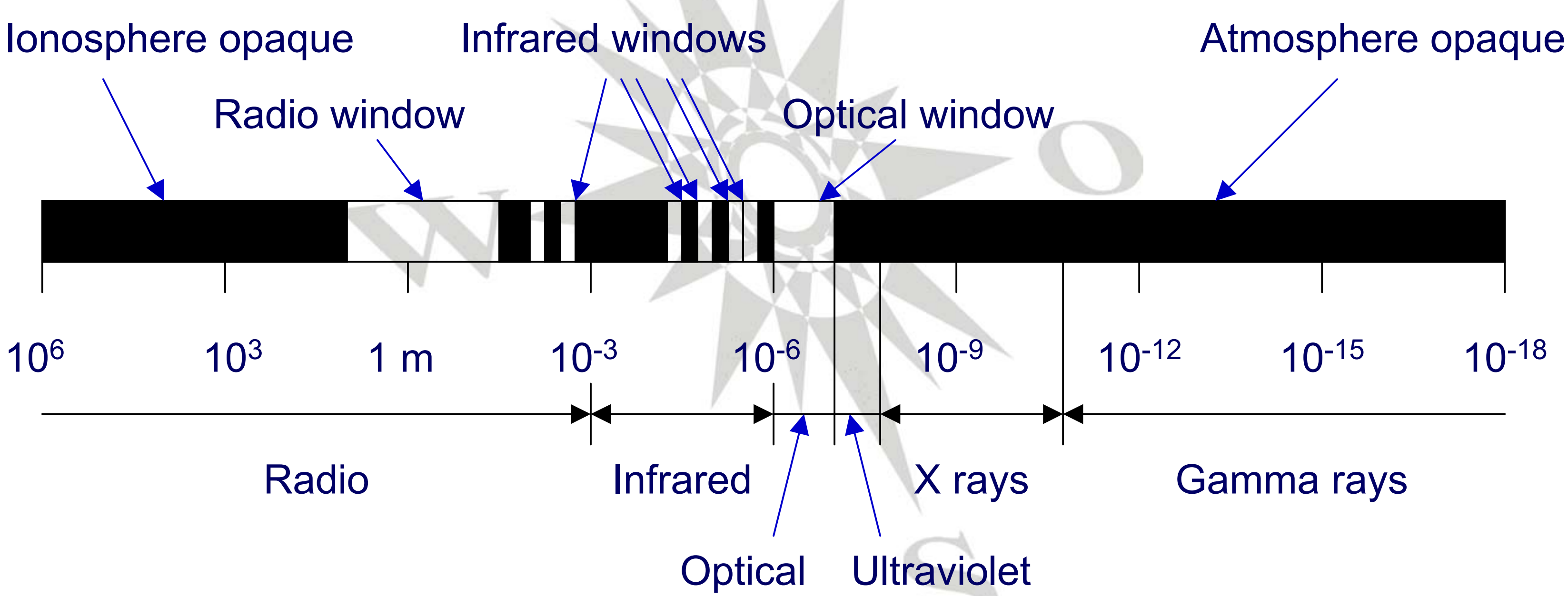
4.1.3 The electromagnetic spectrum

- Components
  - Radio
  - Infrared
  - Optical
  - Ultraviolet
  - X rays
  - Gamma rays
- Opaque types
  - Ionosphere opaque (reflection)
  - Atmosphere opaque (absorption)
- Windows
  - Radio window (10 cm – 1cm)
  - Infrared window (1 mm – 1 µm)
  - Optical window (1 µm – 100 nm)

4 Physical fundamentals (12)

– **Electromagnetic spectrum**

➔ In function of wavelength λ [m]



4 Physical fundamentals (13)

– **Radio frequency (RF) part of EM spectrum**
  - RF spectrum: $f \leq 3 \cdot 10^3$ GHz
  - RF band assignment:

Frequency band	Wavelength	Identification
3-30 kHz	100-10 km	VLF
30-300 kHz	10-1 km	LF
300-3000 kHz	1000-100 m	MF
3-30 MHz	100-10 m	HF
30-300 MHz	10-1 m	VHF
300-3000 MHz	100-10 cm	UHF
3-30 GHz	10-1 cm	SHF
30-300 GHz	10-1 mm	EHF

4 Physical fundamentals (14)

Band	Typical service
VLF	Sonar, submarine communication, terrestrial navigation (Omega)
LF	Radio beacons, terrestrial navigation (Loran-C), navigation aids
MF	AM broadcasting, maritime radio, coast guard communication, direction finding, emergency
HF	Telephone, telegraph, fax, short wave international broadcasting, amateur radio, citizen´s band, ship-to-coast communication
VHF	Television, FM broadcast, air-traffic control, police, taxi mobile radio, aircraft navigational aids
UHF	Satellite-based navigation (GPS, GLONASS, Galileo), TV, mobile telephone, cellular radio, paging, sat. communication
SHF	Airborne radar, microwave links, land mobile communication, satellite communication
EHF	Radar, experimental communication

4 Physical fundamentals (15)

– Letter designation of frequency bands (simplified):

Letter	Frequency band
L	0.39 – 1.55 GHz
S	1.55 – 5.20 GHz
C	3.90 – 6.20 GHz
X	5.20 – 10.90 GHz
K	10.90 – 36.00 GHz
Q	36.00 – 46.00 GHz

– Radio transmission and reception
  - Continuous-wave transmission
  - Pulse transmission

4 Physical fundamentals (16)

4.2 Electromagnetic wave propagation

4.2.1 Terminology

- Absorption: **Conversion** into another type of energy (e.g., heat)
- Attenuation: Decrease of field strength with increasing distance; inverse term: Gain. Unit: dB. Attenuation of *n* dB means a **decrease of original power** by a factor of $10^{-0.1\,n}$; 1 dB ➔ 0.79 of original power remains
- Diffraction: Deviation of energy flow direction when passing a gap; involves a **change in direction**
- Dispersion: **Dependency of refraction on frequency**. Medium: Dispersive and nondispersive media
- Interference: Superposition of waves ➔ produce **combined effect**

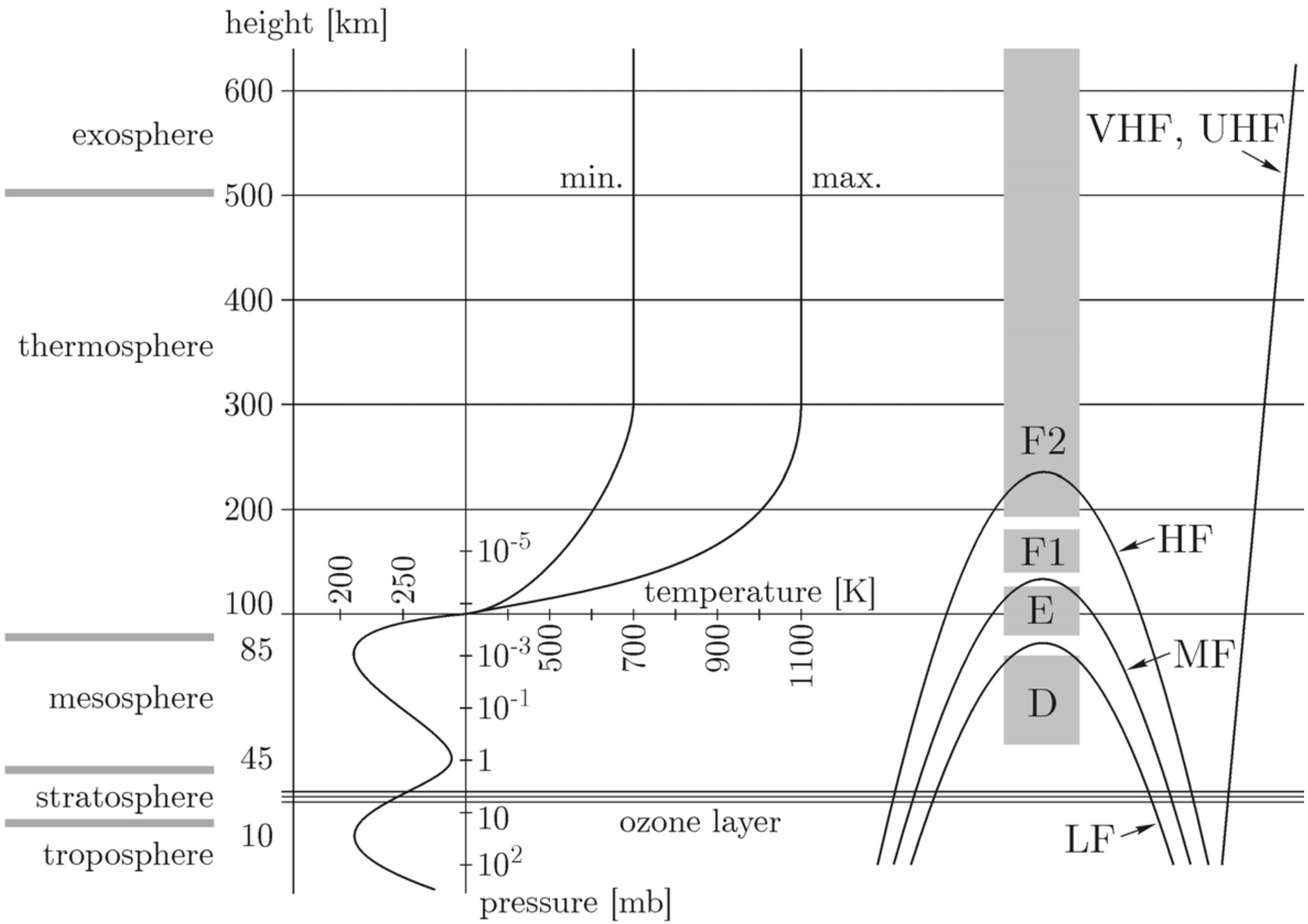
4 Physical fundamentals (17)

- Reflection — When a wave meets a boundary: Reflection (or transmission); partial or complete reflection; involves a **change in direction**; irregular (scattered) vs. regular (specular) reflection
- Refraction — Involves **change in direction** when wave passes from one to the other medium;
  ionospheric (dispersive for radio window)
  tropospheric (dispersive for optical window)
- Scintillation — **Rapid fluctuation** of amplitude and phase (caused by irregularly structured regions) is characteristic for scintillation

4.2.2 Atmospheric structure

Height [km]	Layer structure	Refractivity	Electromagnetic structure
0 – 12 12 12 – 50 50	Troposphere Tropopause Stratosphere Stratopause	Troposphere	Neutral atmosphere
50 – 80 80 – 300 > 300 > 1000	Mesosphere Thermosphere Exosphere	Ionosphere	Ionosphere
> 1000 > 25000			Plasmasphere Magnetosphere

4 Physical fundamentals (19)



4 Physical fundamentals (20)

- **Ionosphere**
  - Definition: **Electrically charged** component of the upper atmosphere (National Research Council 1982)
  - Contains free, neutral, and charged particles
  - Historically, the ionosphere is **divided into regions called layers**
    - D, E, F (F1, F2)
    - No free electrons below 45 km
    - Extents according to previous figure
  - **Electron density**: Maximum in the F2 layer at about 300 km

4 Physical fundamentals (21)

- **D layer**: 50 km – 90 km; ionization varies strongly with sunlight; low electron density; lower ionization or even absence in the night, maximal ionization at noon.
- **E layer**: 90 km – 140 km; ionization based on multiple sources: During daytime primarily because of solar ultraviolet and X-rays, at night because of cosmic rails and meteors; maximum ionization at noon, minimal before sunrise
- **F layer**: 150 km – 500 km; ionization is maximal around noon and decreases towards sunset (but remains ionized during night), minimum before sunrise; during the day: F splits into F1 and F2:
  - **F1 layer**: Central part at about 150 – 200 km
  - **F2 layer**: Central part at about 300 km

4 Physical fundamentals (22)

TUG

4.2.3 Phase and group velocity

Electromagnetic waves:

- in vacuum: $c = 299\,792\,458\,\mathrm{m\,s^{-1}}$, the speed of light
- in a dispersive medium: phase and group velocity must be distinguished.

Phase velocity:

- periodic in space, represent a wave train of infinite duration
- consider a single electromagnetic wave propagating in space with wavelength λ and frequency f. The velocity of its phase

$$v_{\mathrm{ph}} = \lambda\, f \tag{4.17}$$

  is denoted phase velocity.
- Carrier waves are typical examples of waves propagating with phase velocity

4 Physical fundamentals (23)

Group velocity:

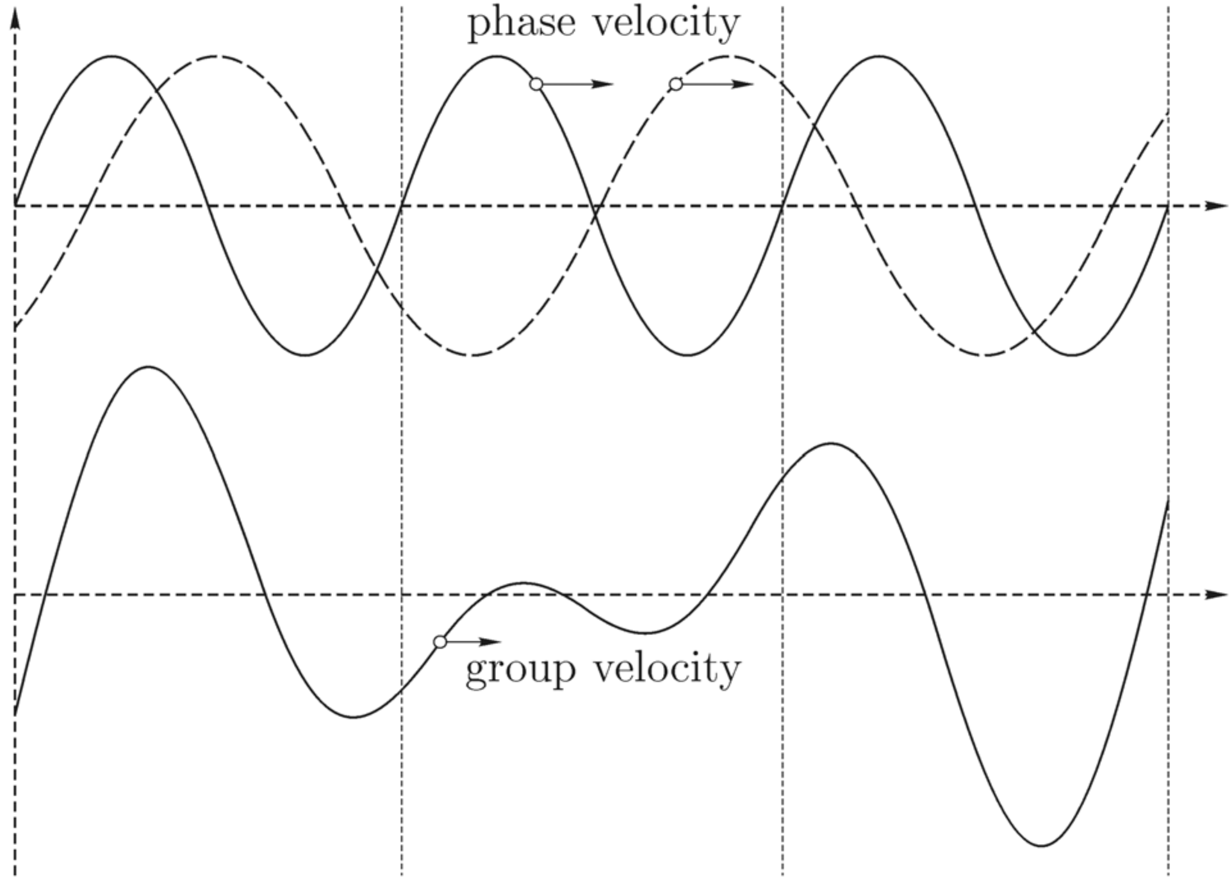
- electromagnetic wave with varying amplitude may be considered as a wave of many frequencies
- this carrier wave has a modulated envelope as shown in Fig. 4.6 which travels with the group velocity

$$v_{\mathbf{gr}} = -\frac{df}{d\lambda}\lambda^2 \,. \tag{4.18}$$

- GPS code measurements are a typical example where this velocity applies

4 Physical fundamentals (24)

– The **modulated envelope** of the amplitude modulated carrier propagates with group velocity



4 Physical fundamentals (25)

Relation between phase and group velocity → total differential of Eq. (4.17) resulting in

$$dv_{\text{ph}} = f\,d\lambda + \lambda\,df \tag{4.19}$$

which can be rearranged to

$$\frac{df}{d\lambda} = \frac{1}{\lambda}\frac{dv_{\text{ph}}}{d\lambda} - \frac{f}{\lambda}\,. \tag{4.20}$$

The substitution of (4.20) into (4.18) yields

$$v_{\text{gr}} = -\lambda\,\frac{dv_{\text{ph}}}{d\lambda} + f\,\lambda \tag{4.21}$$

or finally the Rayleigh equation

$$v_{\text{gr}} = v_{\text{ph}} - \lambda\,\frac{dv_{\text{ph}}}{d\lambda}\,. \tag{4.22}$$

- **In free space: phase = group velocity =** c
- **in a medium: wave propagation depends on refractive index** n**.**

4 Physical fundamentals (26)

Generally, the propagation velocity is obtained from

$$v = c/n\,. \tag{4.23}$$

Applying this expression to the phase and group velocity:

$$v_{\mathbf{ph}} = c/n_{\mathbf{ph}} \tag{4.24}$$

$$v_{\mathbf{gr}} = c/n_{\mathbf{gr}} \tag{4.25}$$

are achieved. A relation of the two refractive indices $n_{\mathbf{ph}}$ and $n_{\mathbf{gr}}$ is given by the modified Rayleigh equation

$$n_{\mathbf{gr}} = n_{\mathbf{ph}} - \lambda\,\frac{dn_{\mathbf{ph}}}{d\lambda}\,. \tag{4.26}$$

A slightly different form is obtained by differentiating the relation $c = \lambda f$ with respect to λ and f, that is

$$d\lambda/\lambda = -df/f\,, \tag{4.27}$$

and by substituting the result into (4.26):

$$n_{\mathbf{gr}} = n_{\mathbf{ph}} + f\,\frac{dn_{\mathbf{ph}}}{df}\,. \tag{4.28}$$

4 Physical fundamentals (27)

"Phenomenon":

- Refractive index n may be less than 1 implying by (4.23) that v may be greater than c.
- Contradiction to the fact that the velocity of light is the maximum velocity as concluded by Einstein?
- Reason: a wave train of finite length cannot be represented by a simple harmonic formula as used in (4.3). Moreover, no information can be transmitted by the simple harmonic form.

4.2.4 Line-of-sight, ground, sky waves

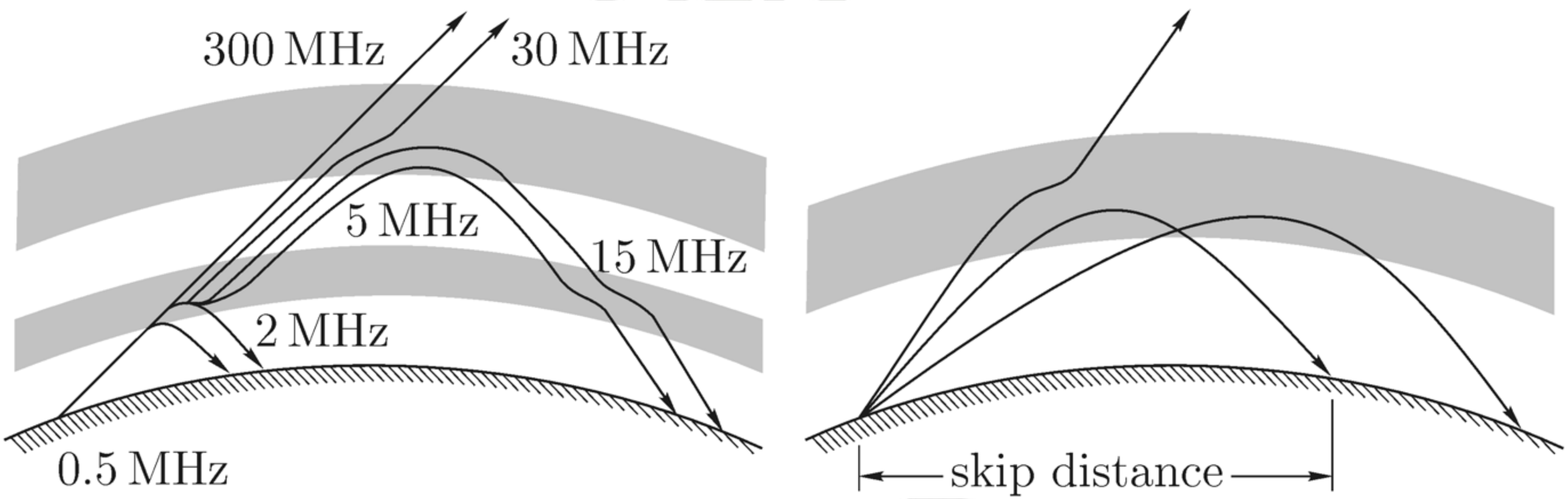
- **Line-of-sight waves**
  - VHF signals are transmitted in straight lines from one antenna to the other
  - Antennas: Directional, facing each other
  - Limitation for terrestrial applications: Curvature of earth
- **Ground waves (surface waves)**
  - Very low frequencies, signals traveling along the surface of the earth
  - Ground waves include direct line-of-sight waves, ground-reflected and waves diffracting around the curved earth

4 Physical fundamentals (29)

- **Sky waves**
  - Definition: “A sky wave is one which, having left the antenna, is refracted/reflected by the ionosphere.”
  - Note that waves above about 30 MHz are not refracted or reflected by the ionosphere to any great extent and pass through to outer space
  - Two factors for propagation: **Frequency**, level of **ionization** (Rule: “The higher the frequency, the less the wave is bent by the ionosphere.”)

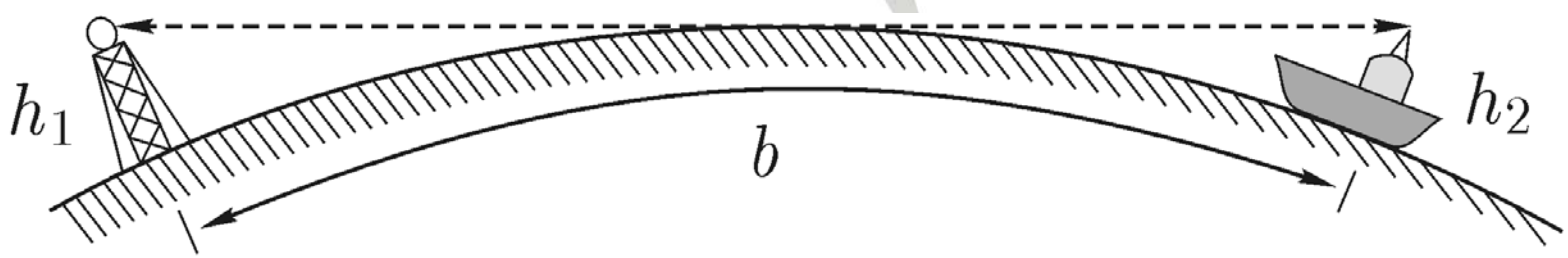
4 Physical fundamentals (30)

– Refraction and reflection in the ionosphere for different signal frequencies (left) and for equal signal frequencies but different emission angles (right):



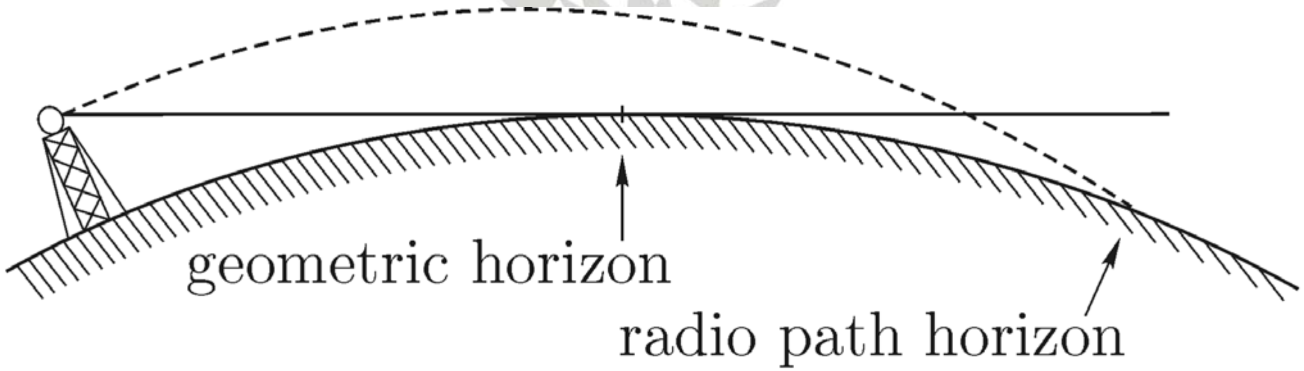
4 Physical fundamentals (31)

- Frequency bands roughly assigned to type of waves
  - Ground waves: VLF, LF, partly MF
  - Sky waves: MF (partly overlapping with ground wave), HF
  - Line-of-sight waves: HF, VHF, UHF, SHF, EHF
- Example: Terrestrial microwaves:
  - Wavelengths 1 mm to 10 cm ➔ SHF, EHF band ➔ line-of sight waves ➔ do not follow the curvature of the earth
- Maximal line of sight:



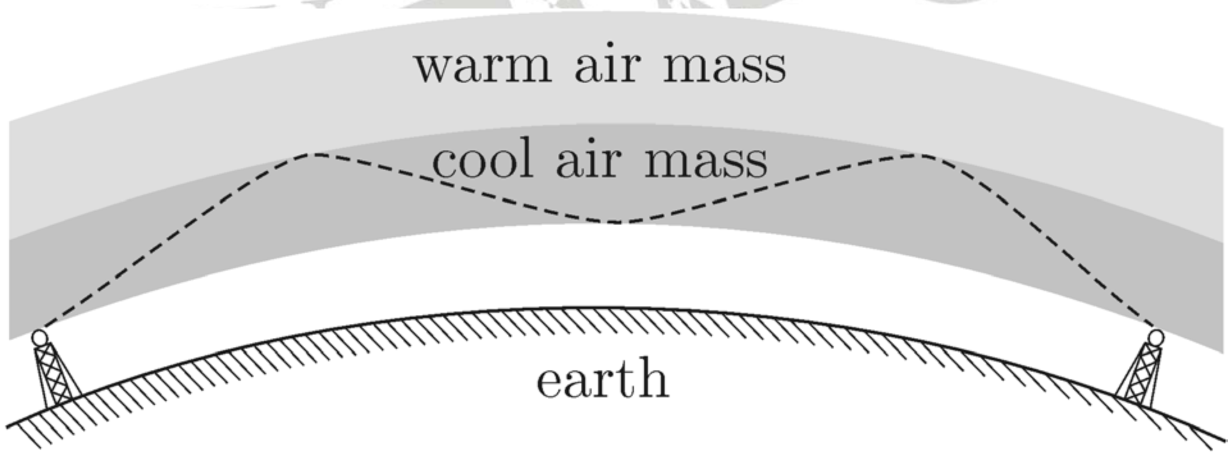
4 Physical fundamentals (32)

– Slight bending of electromagnetic waves in the troposphere
  - Geometric and radio path horizon due to tropospheric bending:



4 Physical fundamentals (33)

- Tropospheric ducting
  - During certain weather conditions
  - Radio signals “trapped” in the troposphere ➔ VHF, UHF signals reach large distances
  - Ducts form usually over water, but also over land
  - Long distance travel: 4000 km over water, 1500 km over land



4.3 Observables derived from electromagnetic waves

- Ranges and range differences
  - Run time measurements
  - Phase measurements
- Range rates (velocity)
  - Direct (e.g., Doppler)
  - Indirect (e.g., electromagnetic velocity log)
- Directions
  - Radio-based direction finders:
    Differential distance measured at two receivers
  - Non-directional beacons:
    Symmetric pattern with cone of silence in between

4 Physical fundamentals (35)

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