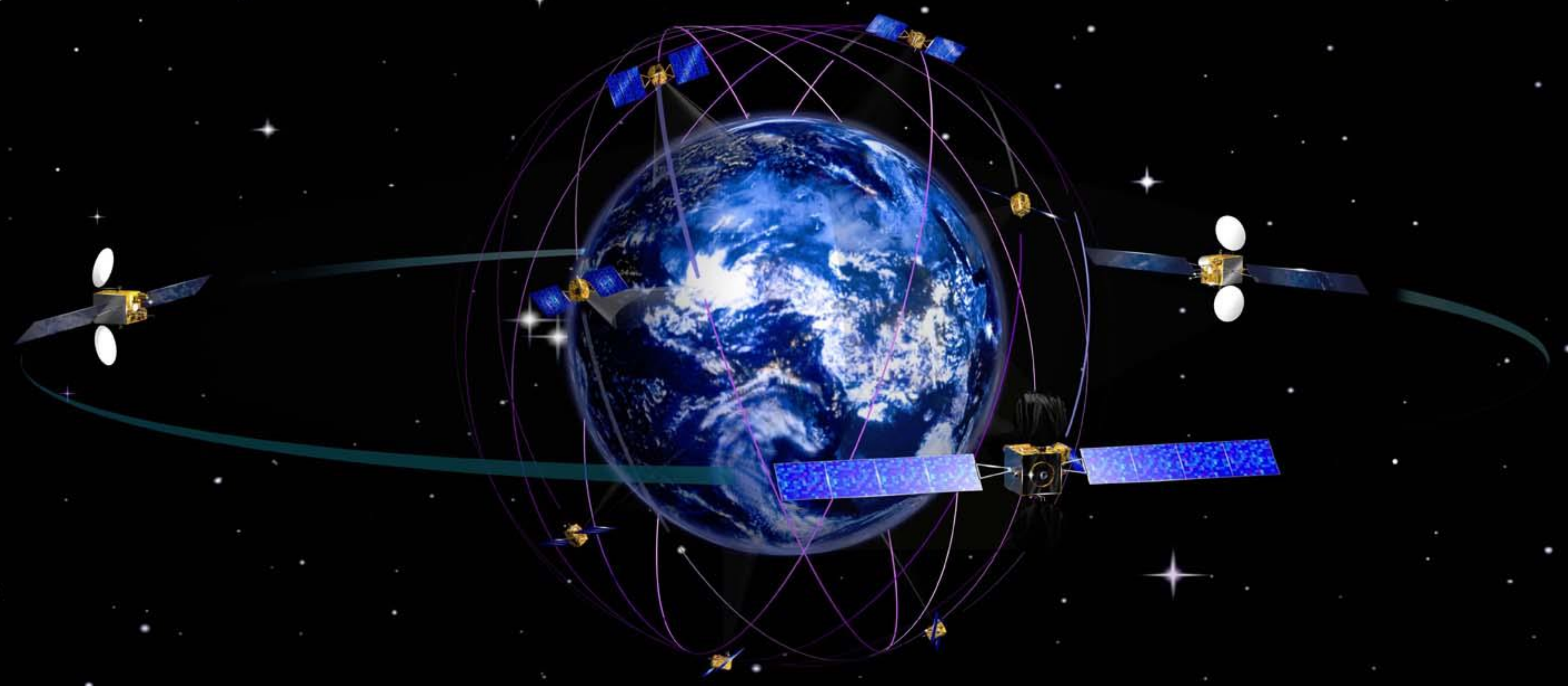
# Satellite Communications
# – RRY100 –



2024 Study Period 1

Lecturer: Rüdiger Haas

Lecture-6: Signal propagation

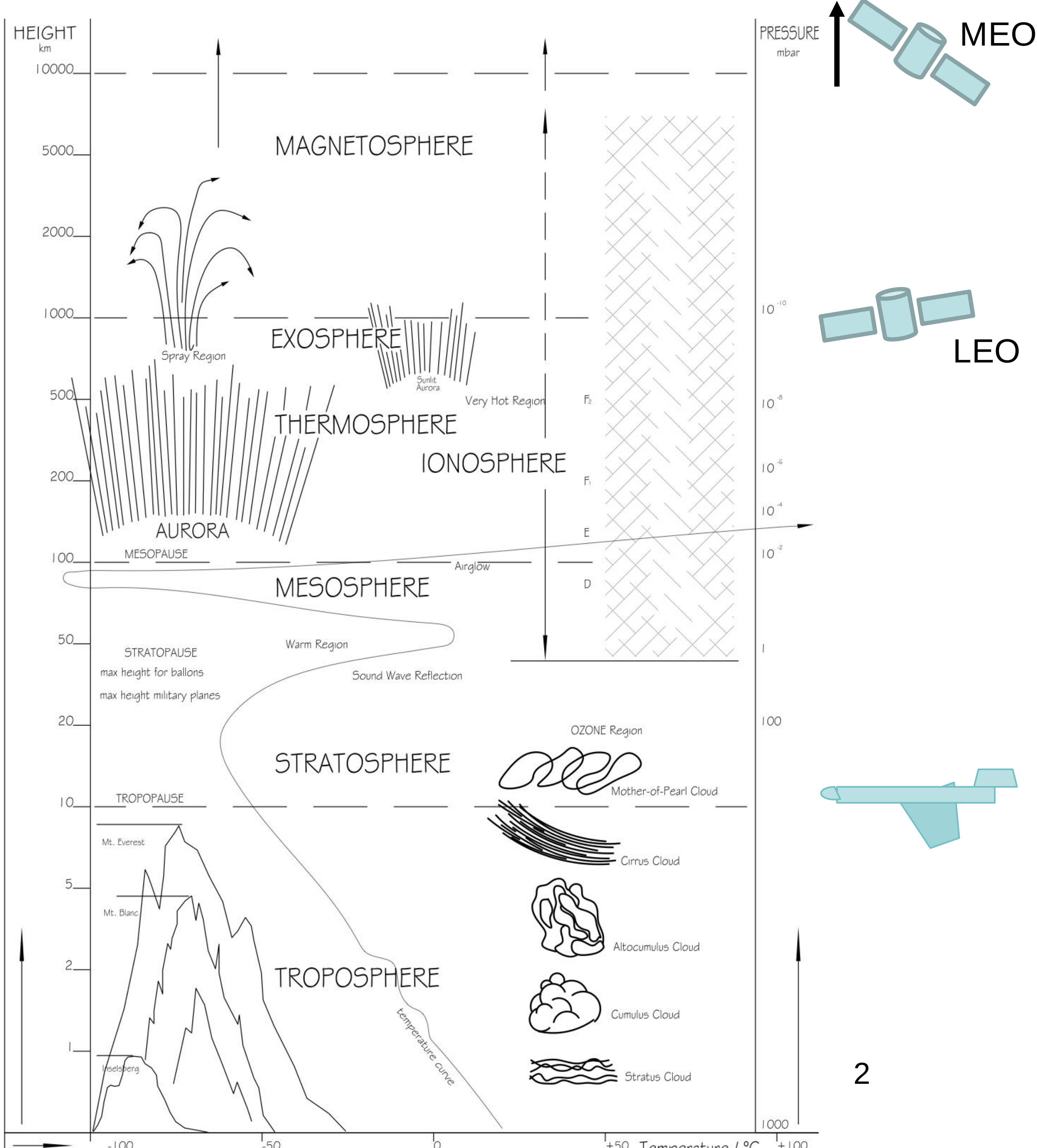
# Signal propagation:

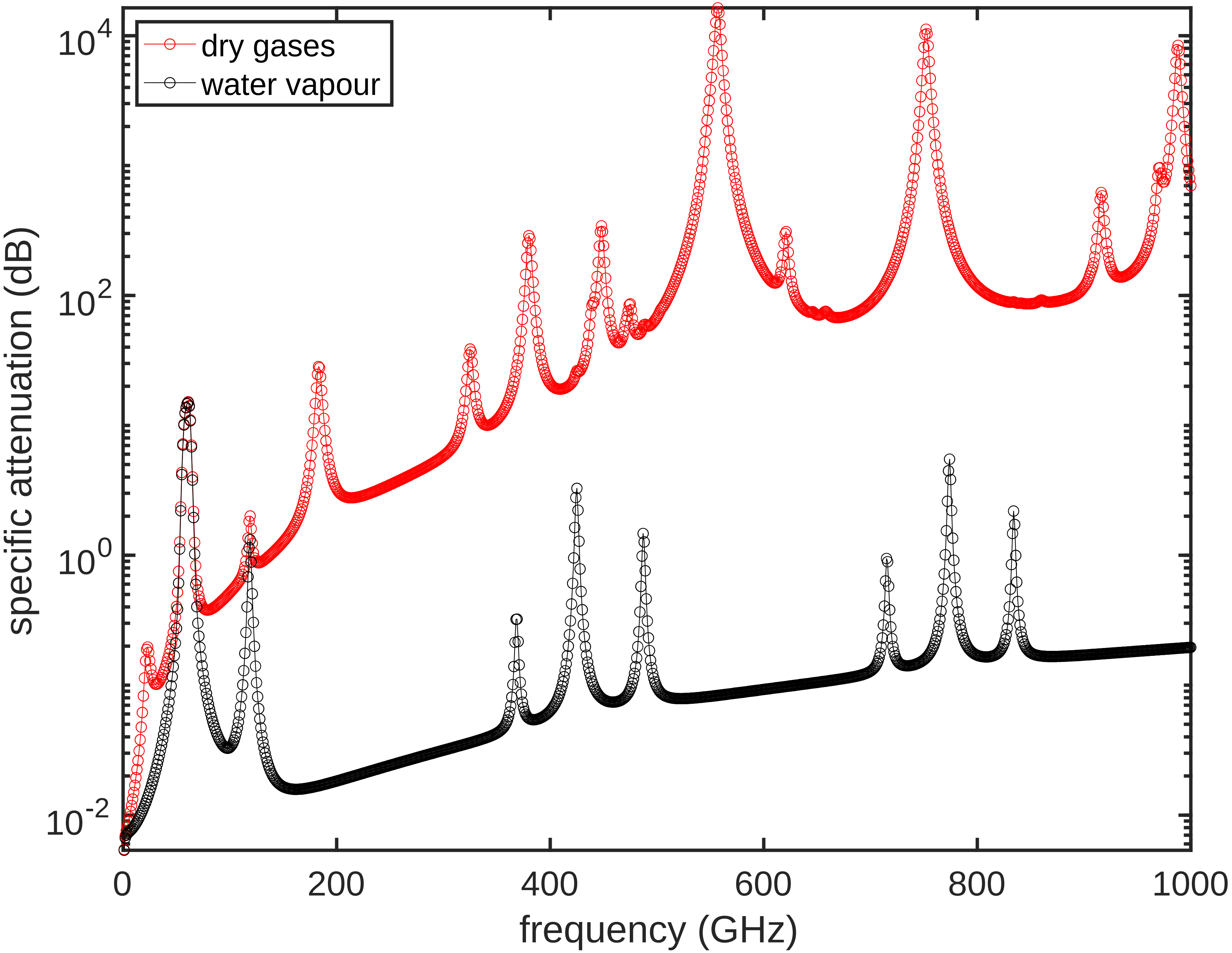
- Satellite communication signals pass through the Earth's atmosphere

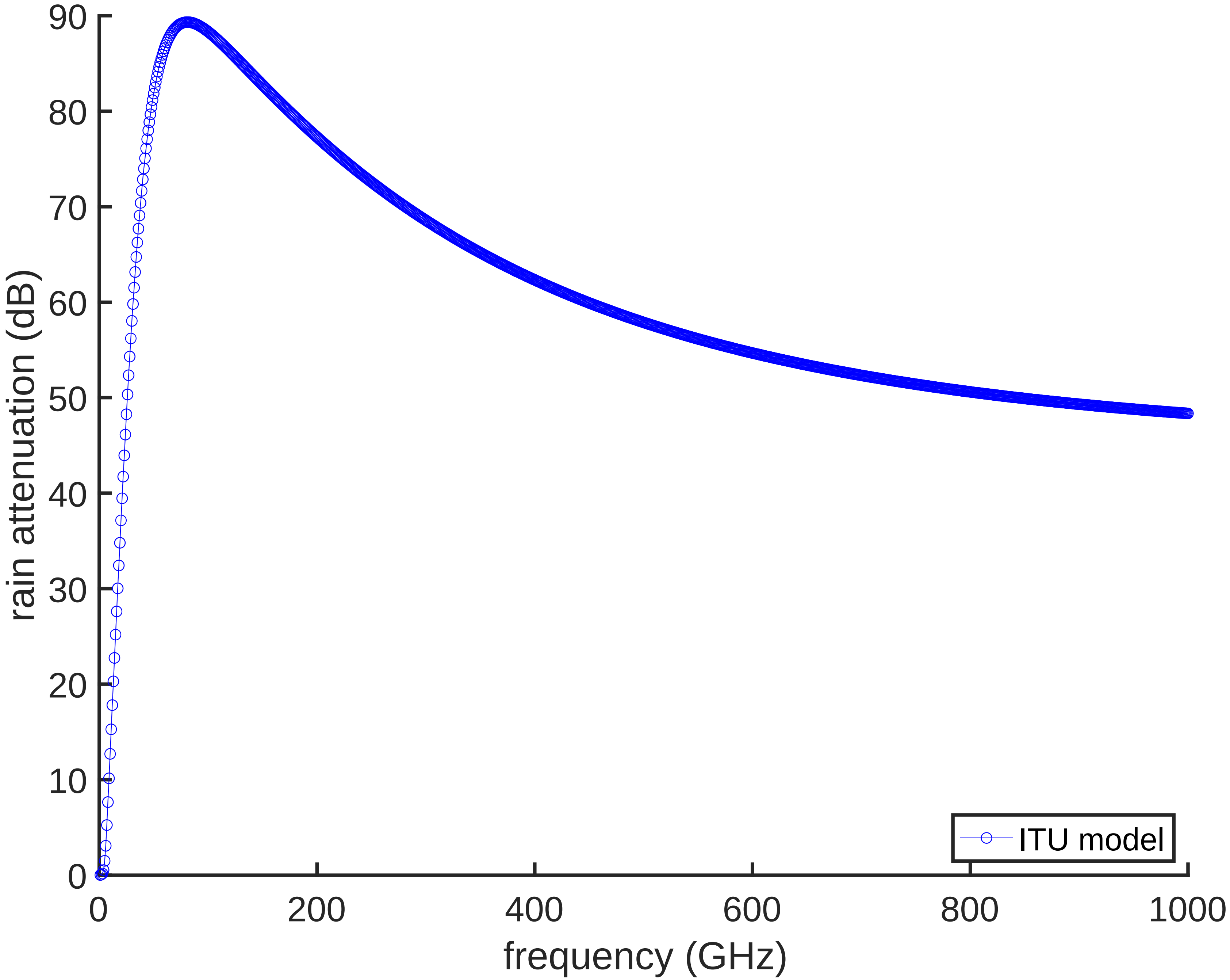
- effects in ionosphere:
  - attenuation
  - depolarization

- effects in troposphere:
  - rain attenuation and
  - depolarization

- frequency dependent




dry gases
water vapour
specific attenuation (dB)
$10^4$
$10^2$
$10^0$
$10^{-2}$
0
200
400
600
800
1000
frequency (GHz)



90
80
70
60
50
40
30
20
10
0
rain attenuation (dB)
0
200
400
600
800
1000
frequency (GHz)
ITU model

- Electromagnetic wave is a transverse wave and consists of
  - electric field (E) and
  - magnetic field (H)
- Field strength E and H are perpendicular to each other
- Propagation direction:
  - vector product of E and H vector => Poynting vector, direction of energy flow
- Polarization direction: direction of E field vector
- Plane of polarization: made by E field vector and propagation direction
- Electric field vector can be split up into two components:

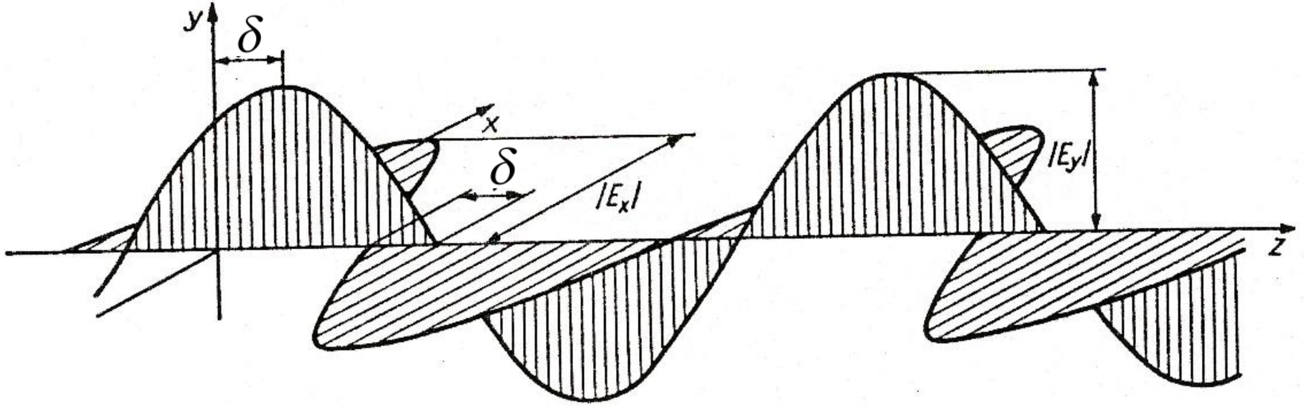
$$E_x = E_1 \cdot \sin(\omega \cdot t - k \cdot z)$$

$$E_y = E_2 \cdot \sin(\omega \cdot t - k \cdot z + \delta)$$

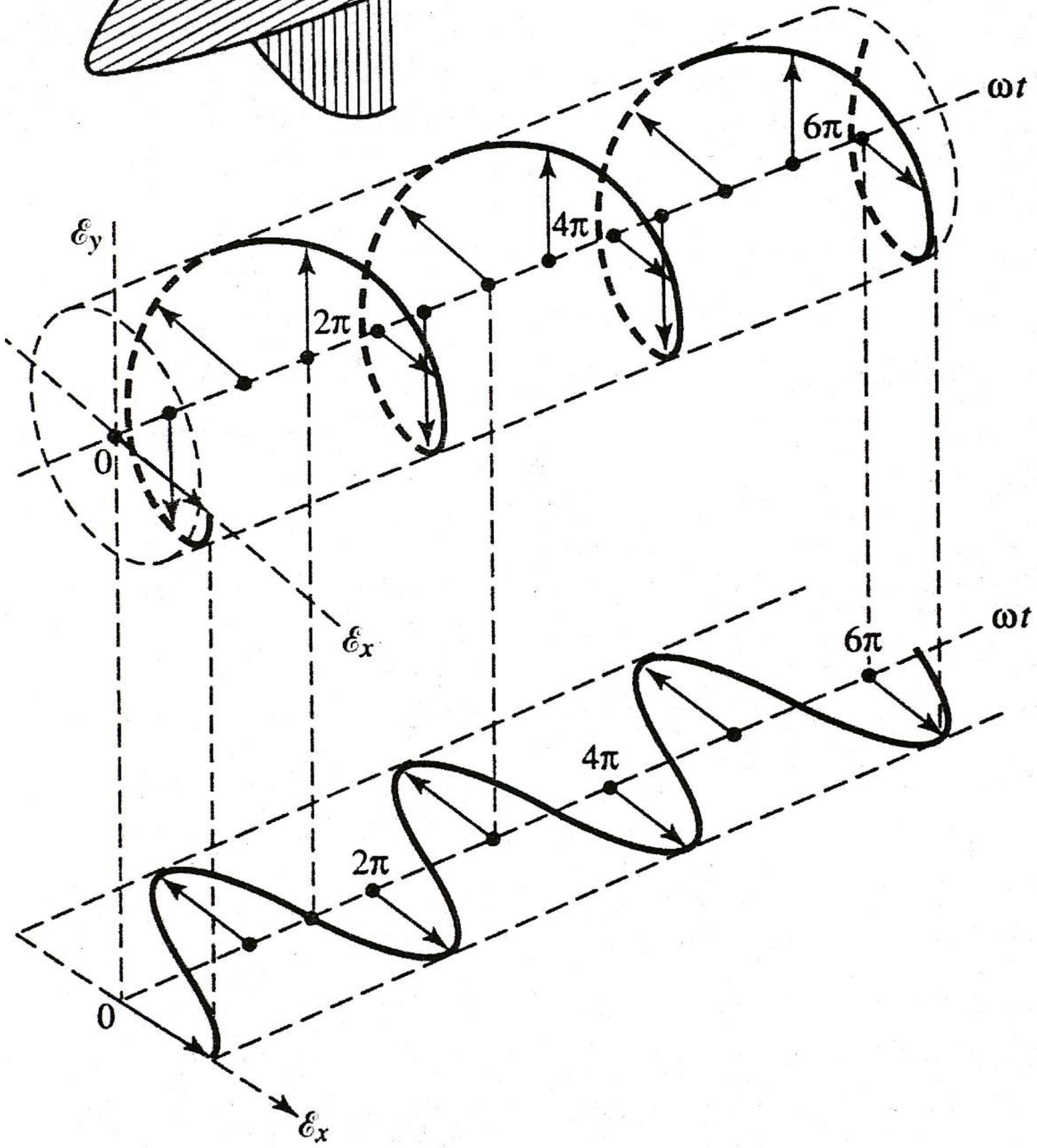
circular frequency: $\omega = 2 \cdot \pi \cdot f$

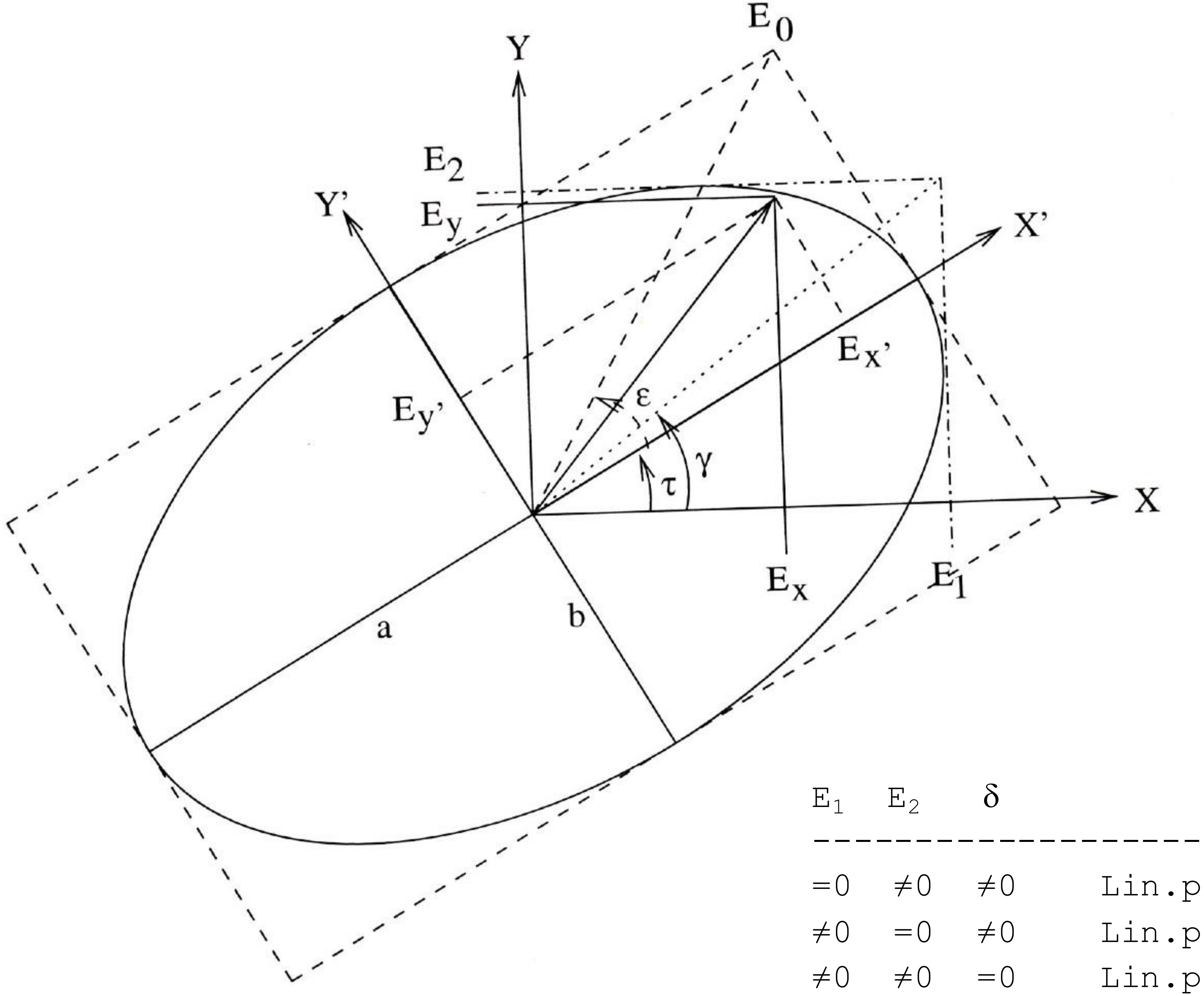
phase difference: $\delta$

wave constant *k*: $k = \frac{2 \cdot \pi}{\lambda}$




Propagation of an
electromagnetic wave

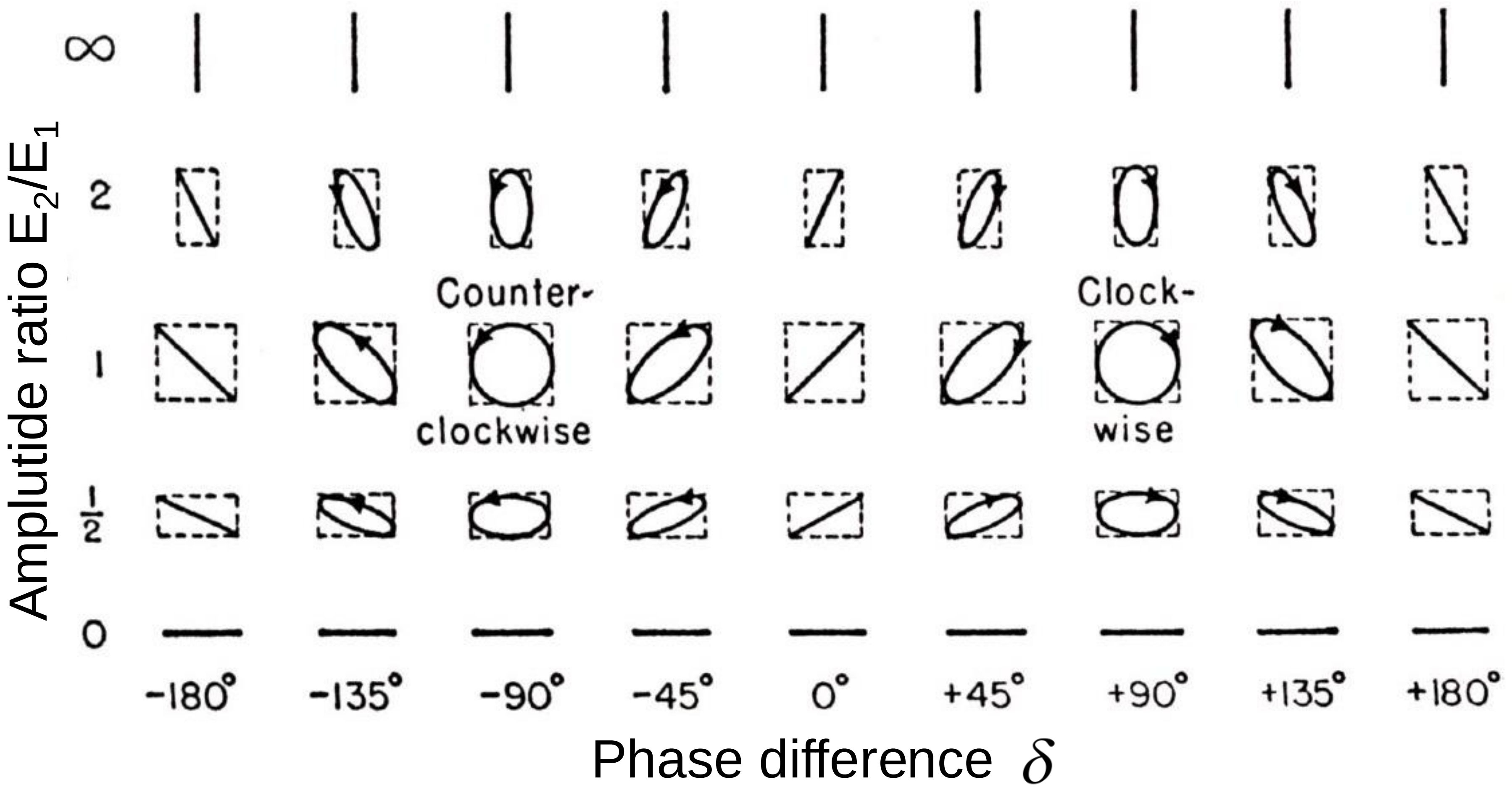





| $E_1$ | $E_2$ | $\delta$ | |
|---|---|---|---|
| $=0$ | $\neq 0$ | $\neq 0$ | Lin.pol. Y |
| $\neq 0$ | $=0$ | $\neq 0$ | Lin.pol. X |
| $\neq 0$ | $\neq 0$ | $=0$ | Lin.pol.tilted $\tau$ |
| $=E$ | $=E$ | $+\pi/2$ | R.circ.pol. |
| $=E$ | $=E$ | $-\pi/2$ | L.circ.pol. |

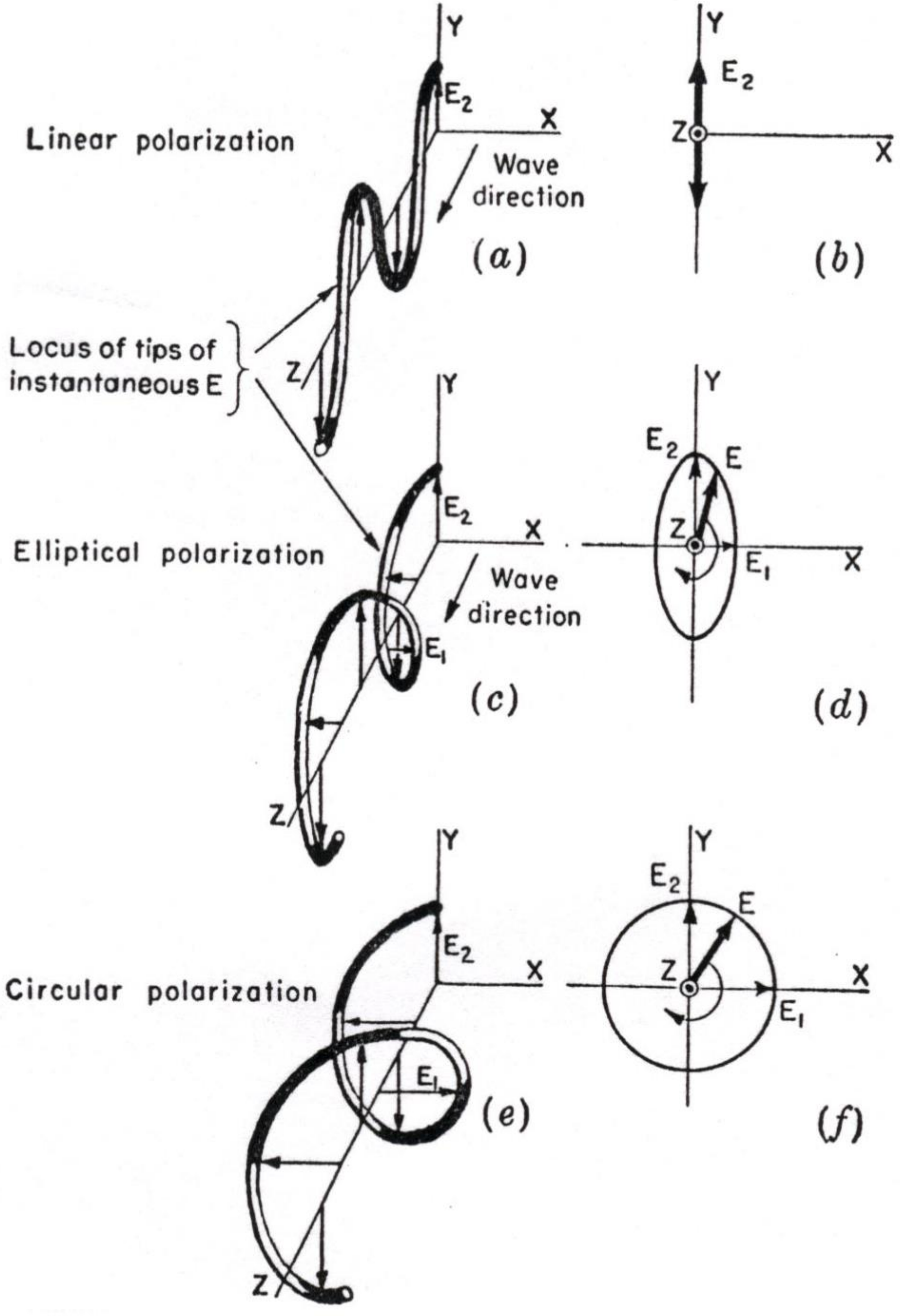
Polarization ellipse:

# Different polarization states of an approaching wave:




| Polarization | Radiowaves | | Classical physics | |
|---|---|---|---|---|
| Right-hand | wave receeding | clockwise | wave approaching | counterclockwise |
| Left-hand | wave receeding | counterclockwise | wave approaching | clockwise |

Examples:

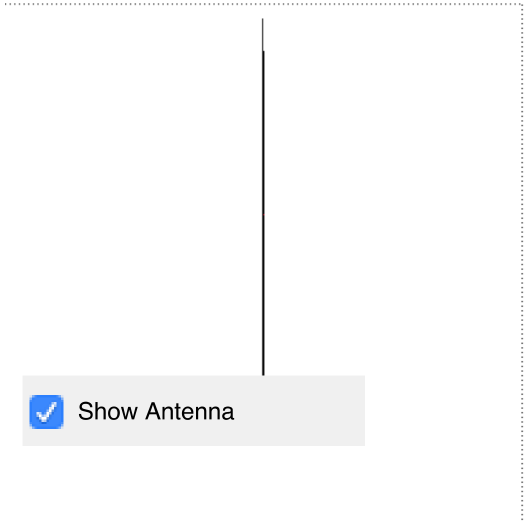


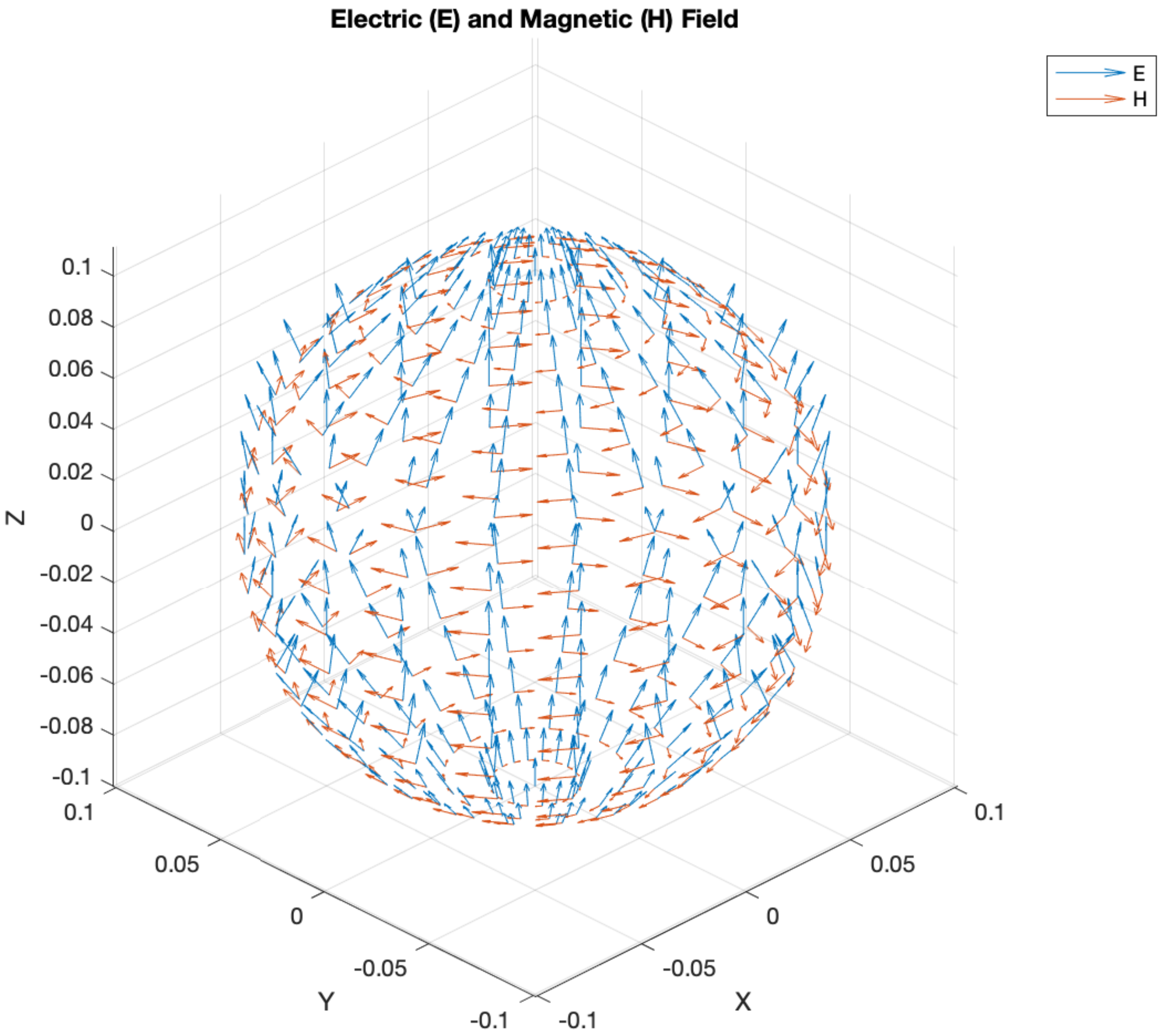

linear polarization

elliptical polarization

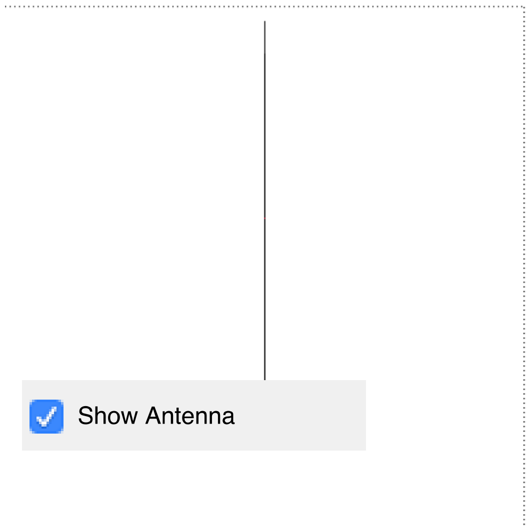
circular (LHCP)

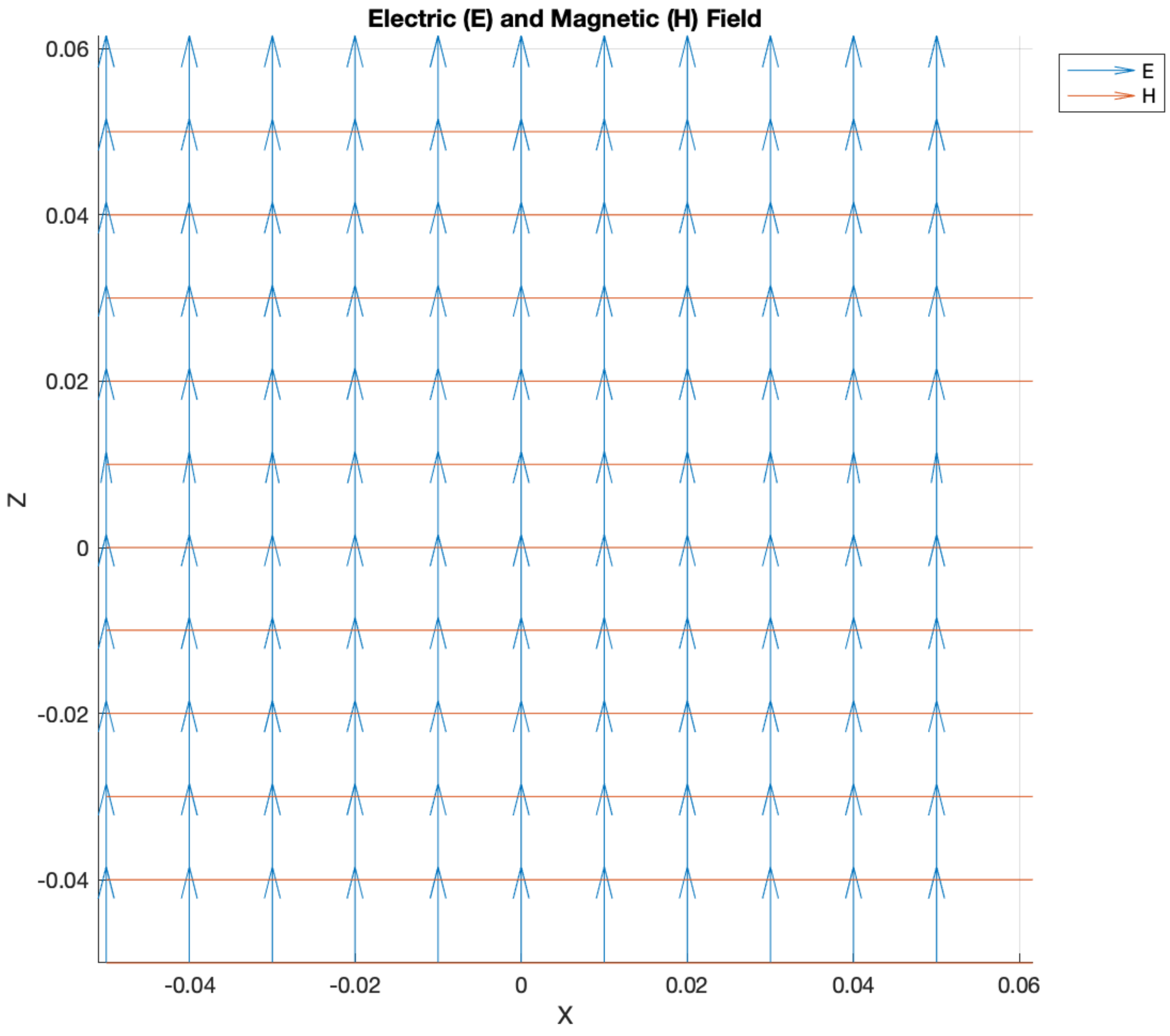
# Dipole


Show Antenna


Electric (E) and Magnetic (H) Field
E
H
Z
0.1
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
-0.1
Y
0.1
0.05
0
-0.05
-0.1
X
-0.1
-0.05
0
0.05
0.1

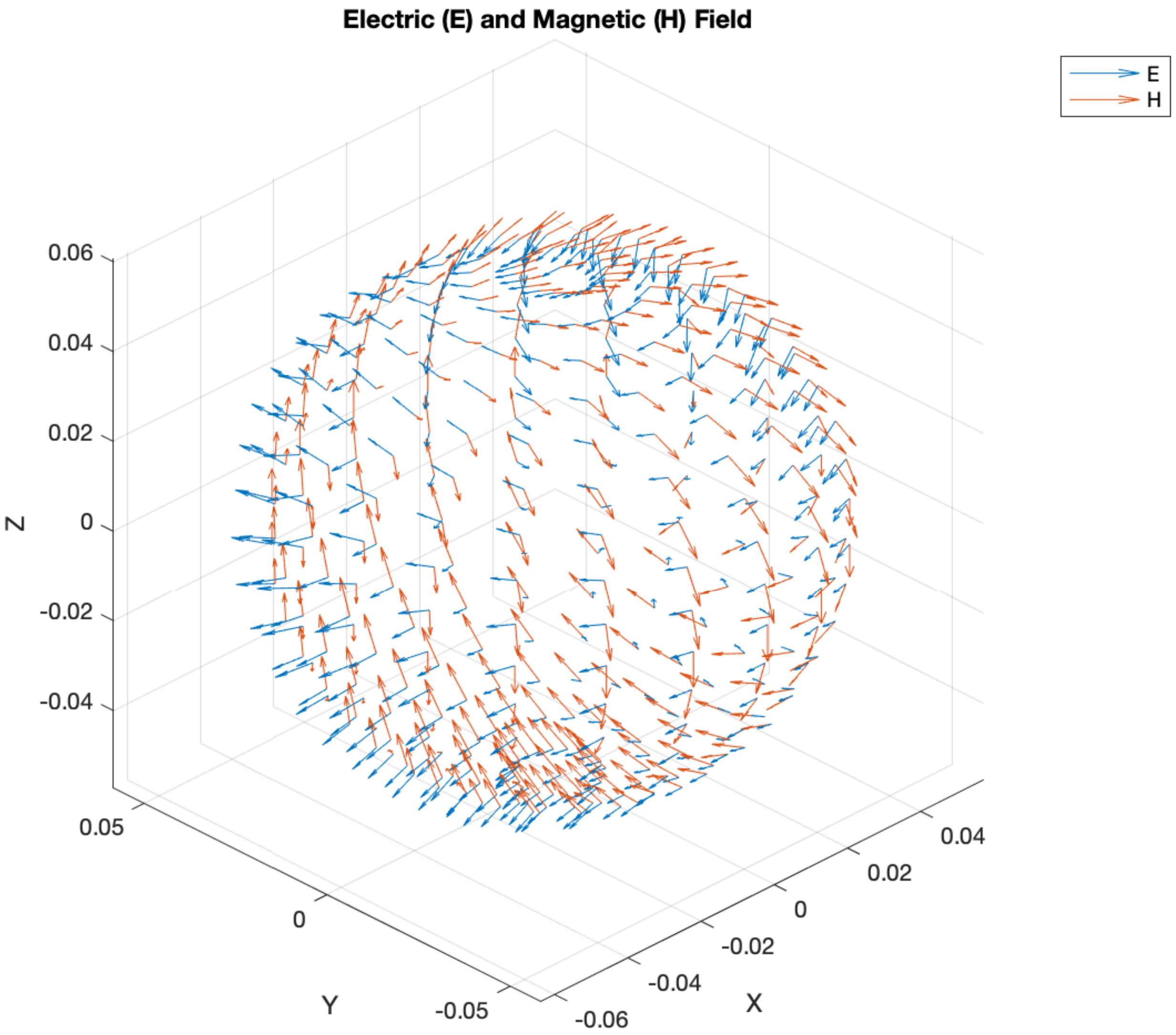
Dipole

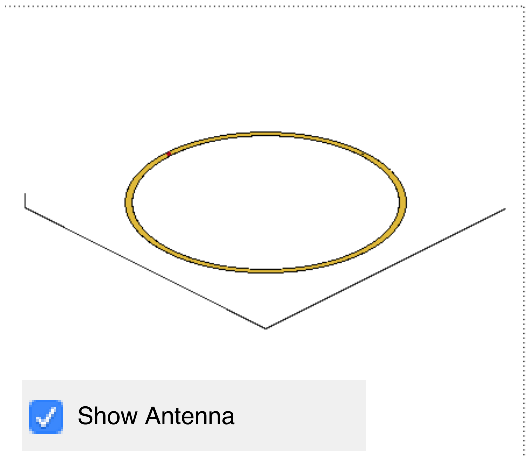


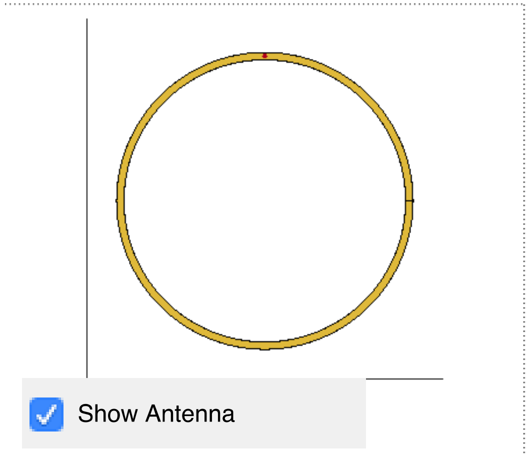

=> linear polarization

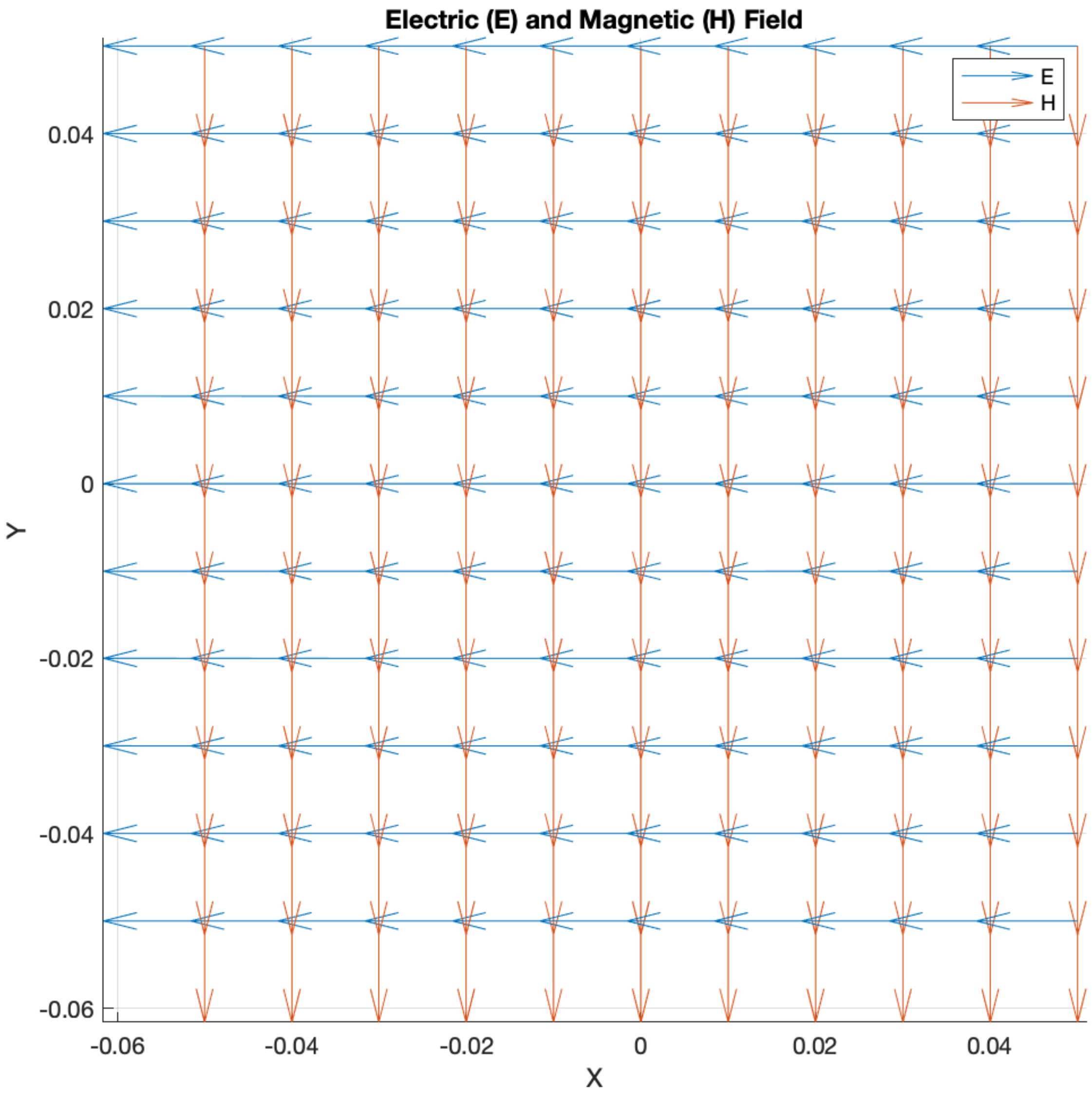
# Circular loop



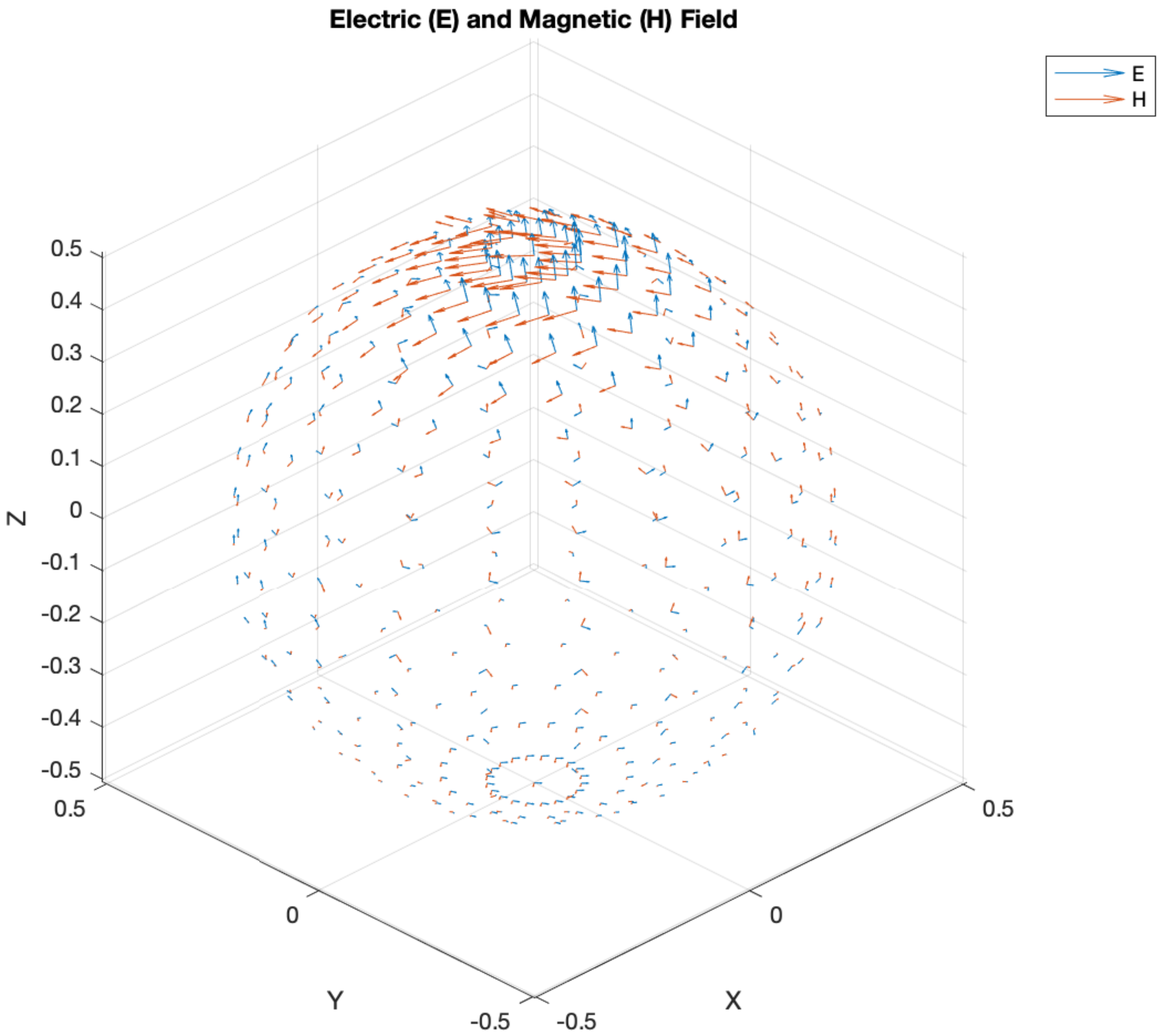
# Circular loop

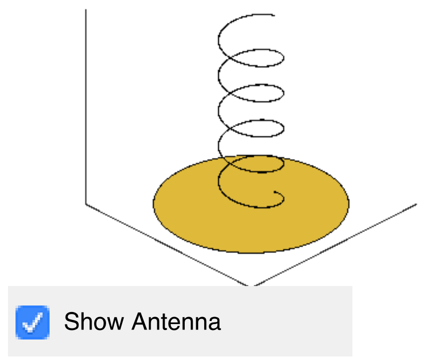


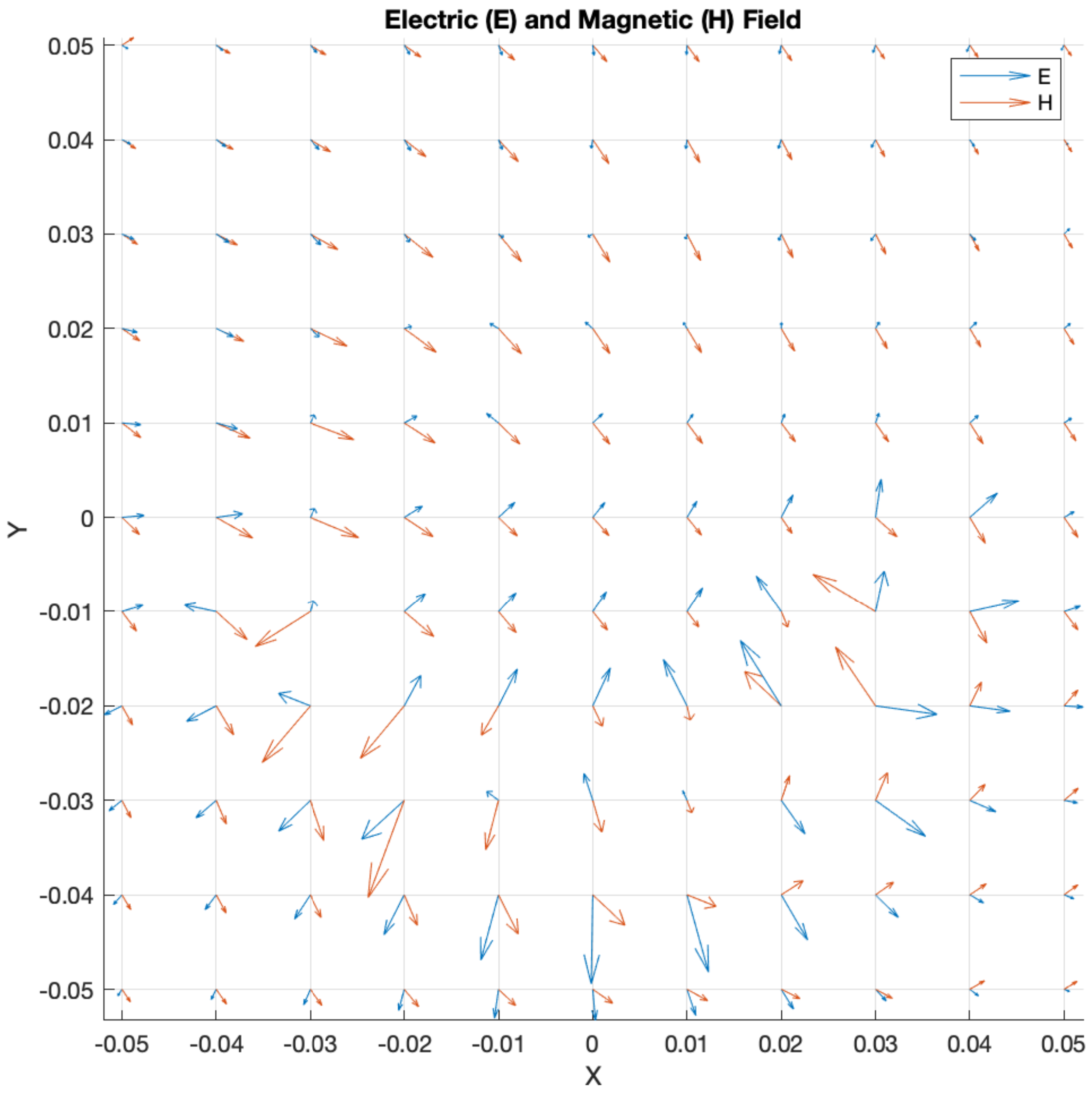

=> linear polarization

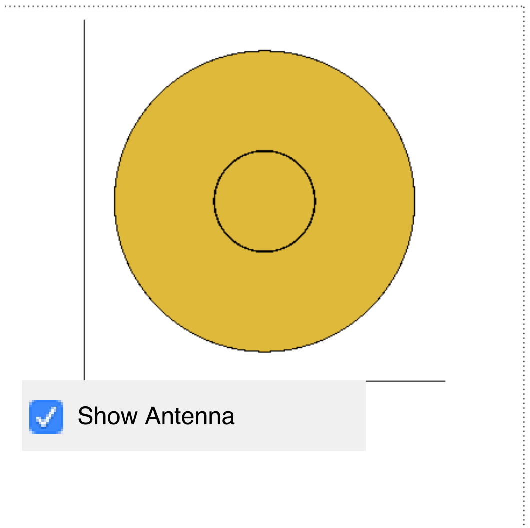
# Helix (end-fire mode)



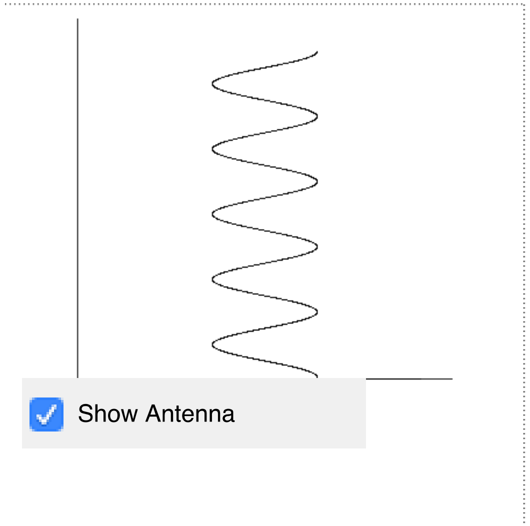
# Helix (end-fire mode)

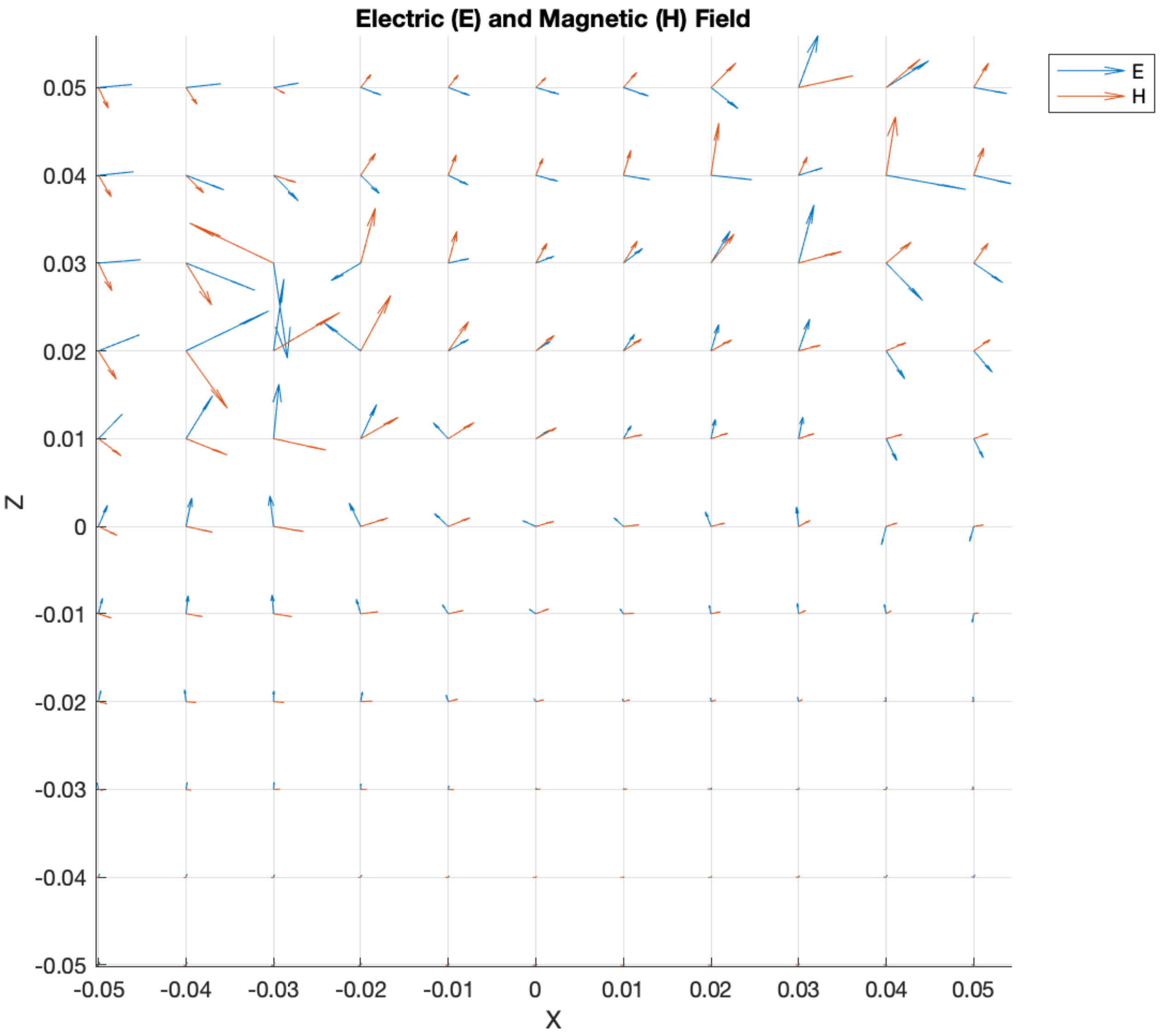



=> elliptical polarization

# Helix (end-fire mode)




=> elliptical polarization

- Two sets to describe state of polarization
  - Using $\gamma$ and $\delta$, i.e. based on the amplitudes and the phase difference
  - Using $\varepsilon$ and $\tau$, i.e. based on the semi-major and semi-minor axes and the tilt angle
- Visualization with Poincarés sphere:
  - Expressing a point on the sphere with either $\gamma$ and $\delta$ or $\varepsilon$ and $\tau$
  - Orthogonal polarization states are on opposite sides of the Poincaré sphere
  - Equator represents linear polarization
  - Poles represent circular polarization
  - Latitude represents axial ratio
  - Longitude represents tilt angle

Polarization description with γ and δ:

$$\gamma = \arctan\left(\frac{E_2}{E_1}\right)$$

$$\alpha$$

$$0^\circ < \gamma < 90^\circ$$

$$-180^\circ < \delta < +180^\circ$$

Polarization description with ε and τ:

$$\varepsilon = \arctan\left(\frac{b}{a}\right)$$

$$\tau$$

$$-45^\circ \le \varepsilon \le +45^\circ$$

$$-90^\circ < \tau < +90^\circ$$

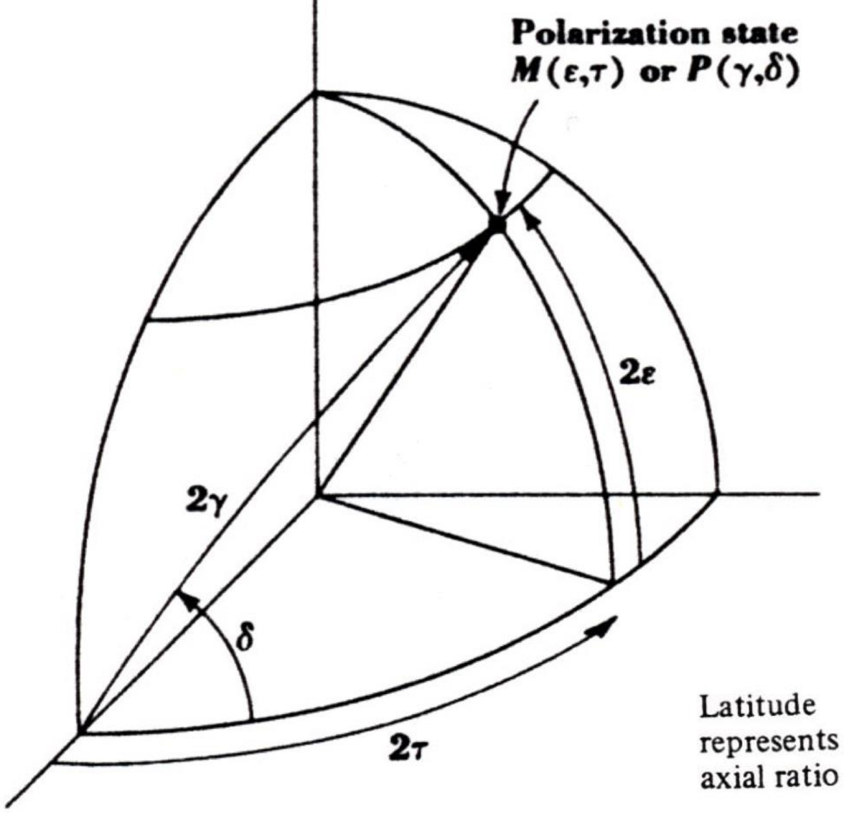
Conversion formulas:

$$\cos(2\gamma) = \cos(2\varepsilon)\times\cos(2\tau)$$

$$\tan(2\tau) = \tan(2\gamma)\times\cos(\delta)$$

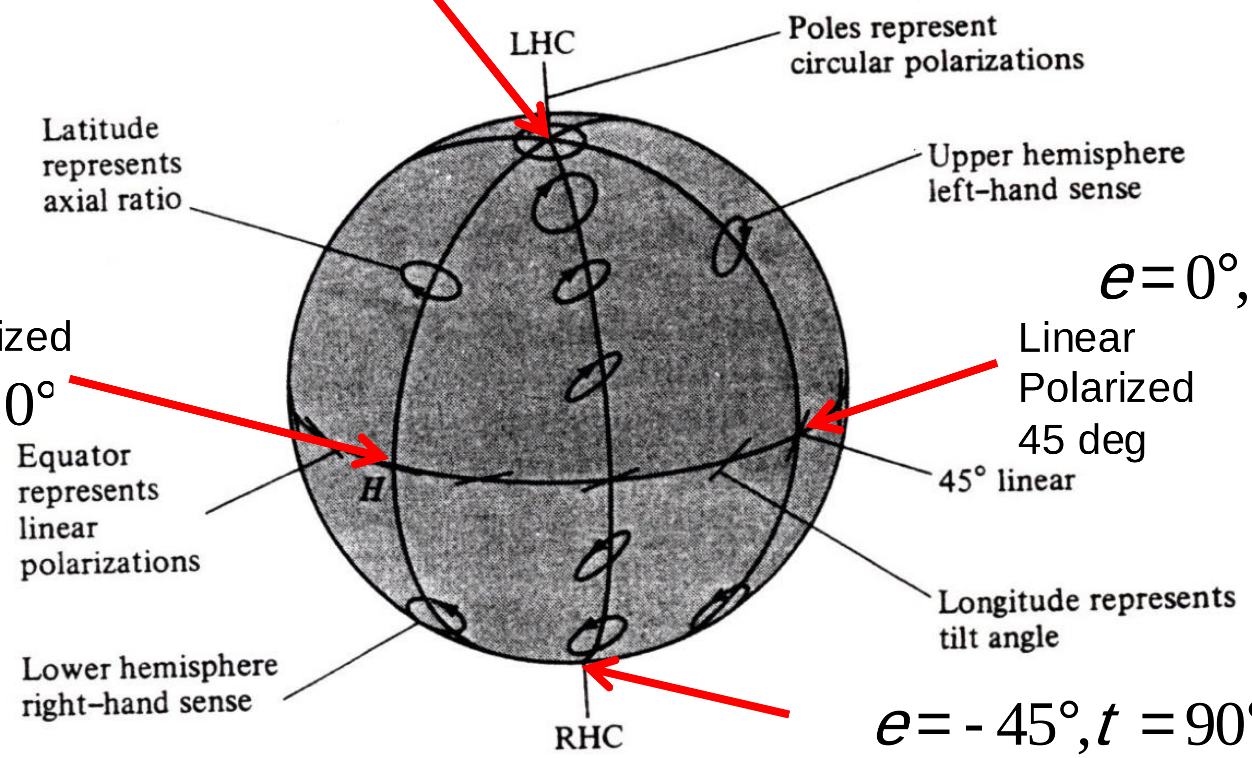
$$\tan(\delta) = \frac{\tan(2\varepsilon)}{\sin(2\tau)}$$

$$\sin(2\varepsilon) = \sin(2\gamma)\times\sin(\delta)$$




Left Hand Circular Polarized

$e = +45°, t = 90°$




$e = 0°, t = 45°$

Linear Polarized 45 deg

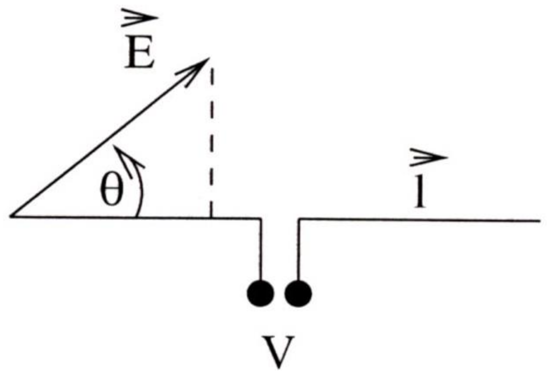
Linear Horizontal Polarized

$e = +0°, t = 0°$

$e = -45°, t = 90°$

Right Hand Circular Polarized

- Antenna signal for an arbitrarily polarized wave:
  - Example linear polarized antenna
  - Output voltage is:




$$V = \vec{E} \cdot \vec{l} = E \cdot l \cdot \cos\theta$$

  - Can be described with great circle distances between polarization states on Poincaré's sphere:

$$V = E \cdot l \cdot \cos\left(\frac{M_W M_A}{2}\right)$$

  - Matched antenna and wave: => $M_W M_A = 0^\circ$ => V=E l
  - Orthogonal circular polarizations: => $M_W M_A = 180^\circ$ => V=0
  - Orthogonal linear polarizations: => $M_W M_A = 180^\circ$ => V=0

- Polarization states:
  - Complete polarization: => $E_1$, $E_2$ and $\delta$ are constants
  - Random polarization: => sum of many independent waves with different polarization (e.g. atmospheric emission), also called unpolarized: => no preferred direction of oscillation when averaged over time

$$E_x = E_1(t) \cdot \sin(\omega \cdot t)$$
$$E_y = E_2(t) \cdot \sin(\omega \cdot t + \delta(t))$$

  - Partial polarization: mix of complete and random polarization, is the most common case

- Stokes parameters for a completely polarized wave
  - Magnitude of Poynting vector (Flux density):

$$S = S_x + S_y = \frac{E_1^{\ 2} + E_2^{\ 2}}{Z} = \frac{E_0^{\ 2}}{Z}$$

- Definition of four Stokes parameters:

total power $$I = S = S_x + S_y$$

Difference between Lin. H-V $$Q = S_x - S_y$$

Difference between Lin. tilted $$U = (S_x - S_y) \times \tan(2t) = S \times \cos(2e) \times \cos(2t)$$

Difference between circular $$V = (S_x - S_y) \times \frac{\tan(2e)}{\cos(2t)} = S \times \sin(2e)$$

Relations:

$$I^2 = Q^2 + U^2 + V^2$$

$$\frac{U}{Q} = \tan(2t)$$

$$\frac{V}{S} = \sin(2e)$$

- Six special cases of completely polarized waves:

  - 1) Linear polarization, $\tau=0^\circ$
    - Sx=S, Sy=0, a/b=∞, => $\varepsilon= 0^\circ$ IQUV = [S S 0 0]
  - 2) Linear polarization, $\tau=90^\circ$
    - Sx=0, Sy=S, a/b=∞, => $\varepsilon= 0^\circ$ IQUV = [S –S 0 0]
  - 3) Linear polarization, $\tau=45^\circ$
    - Sx=Sy=S/2, a/b=∞, => $\varepsilon= 0^\circ$ IQUV = [S 0 S 0]
  - 4) Linear polarization, $\tau=-135^\circ$
    - Sx=Sy=S/2, a/b=∞, => $\varepsilon= 0^\circ$ IQUV = [S 0 –S 0]
  - 5) Left circular polarization, $\tau=0^\circ$
    - Sx=Sy=S/2, a/b+=1, => $\varepsilon= 45^\circ$ IQUV = [S 0 0 S]
  - 6) Right circular polarization, $\tau= +90^\circ$
    - Sx=Sy=S/2, a/b= –1, => $\varepsilon= -45^\circ$ IQUV = [S 0 0 –S]

- Consequences:
  - Two waves with identical Stokes parameters => identical
  - Superposition of two waves that propagate in same direction => add Stokes parameters
  - Randomly polarized waves => [S 0 0 0]
  - Degree of polarization:

$$d = \frac{\sqrt{Q^2 + U^2 + V^2}}{I}$$

  - Normalizing Stokes parameters:

$$s_0 = I/S = 1$$
$$s_1 = Q/S$$
$$s_2 = U/S$$
$$s_3 = V/S$$

- Splitting up in polarized and non-polarized part:

$$S[s_i] = S \cdot \left| \begin{matrix} 1 - d \\ 0 \\ 0 \\ 0 \end{matrix} \right| + S \cdot \left| \begin{matrix} d \\ d \cdot \cos(2\varepsilon) \cdot \cos(2\tau) \\ d \cdot \cos(2\varepsilon) \cdot \sin(2\tau) \\ d \cdot \sin(2\varepsilon) \end{matrix} \right|$$

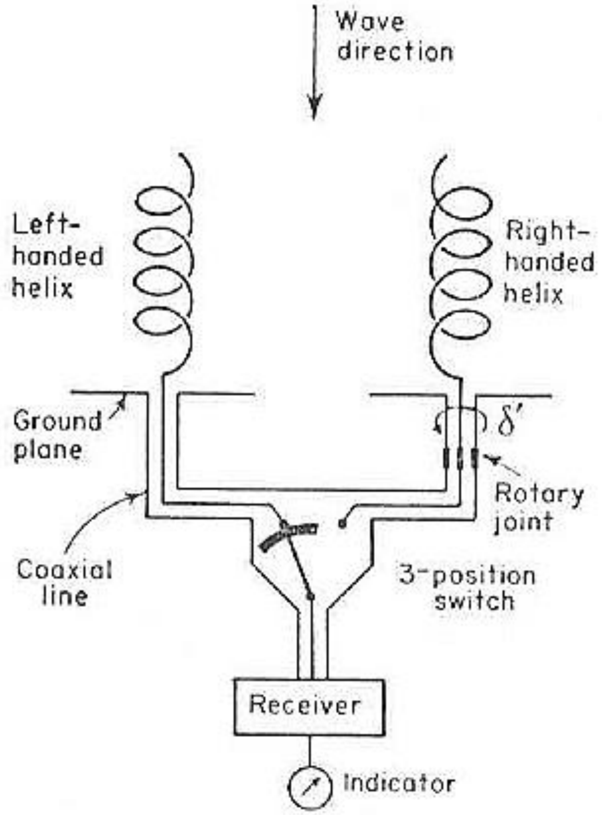
- Antenna aperture can be described in a similar way:

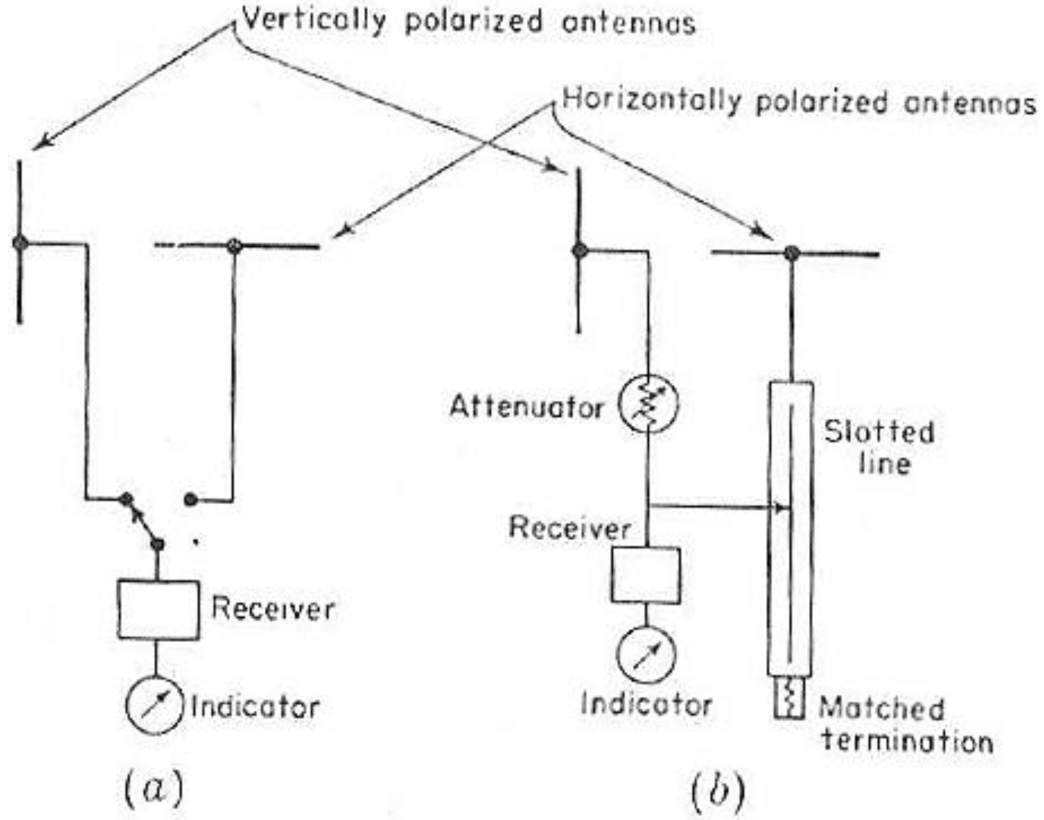
$$A_e[a_i] = A_e \cdot \left| \begin{matrix} a_0 \\ a_1 \\ a_2 \\ a_3 \end{matrix} \right|$$

- Available power from the antenna:

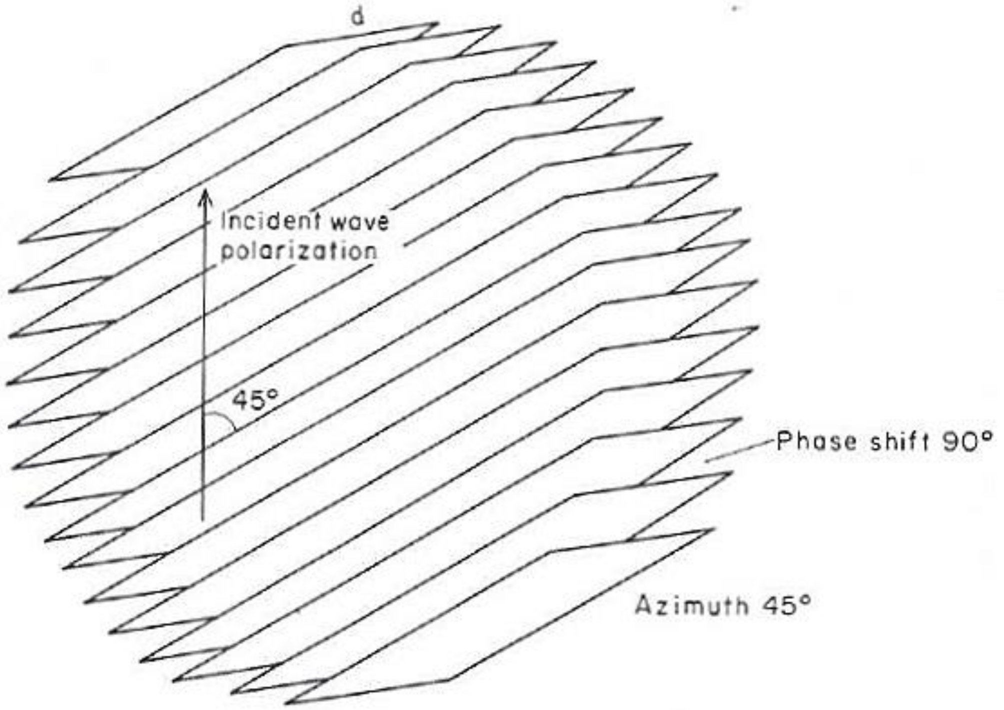
$$P = \frac{1}{2} S \cdot A_e \cdot \sum_{i=0}^{3} a_i \cdot s_i$$

- Polarization measurements:
  - Many methods possible
  - E.g. With six antennas: two pairs of linearly polarized (dipoles) and one pair of circular polarized antennas (helix)
  - Stokes parameters can be derived from power levels



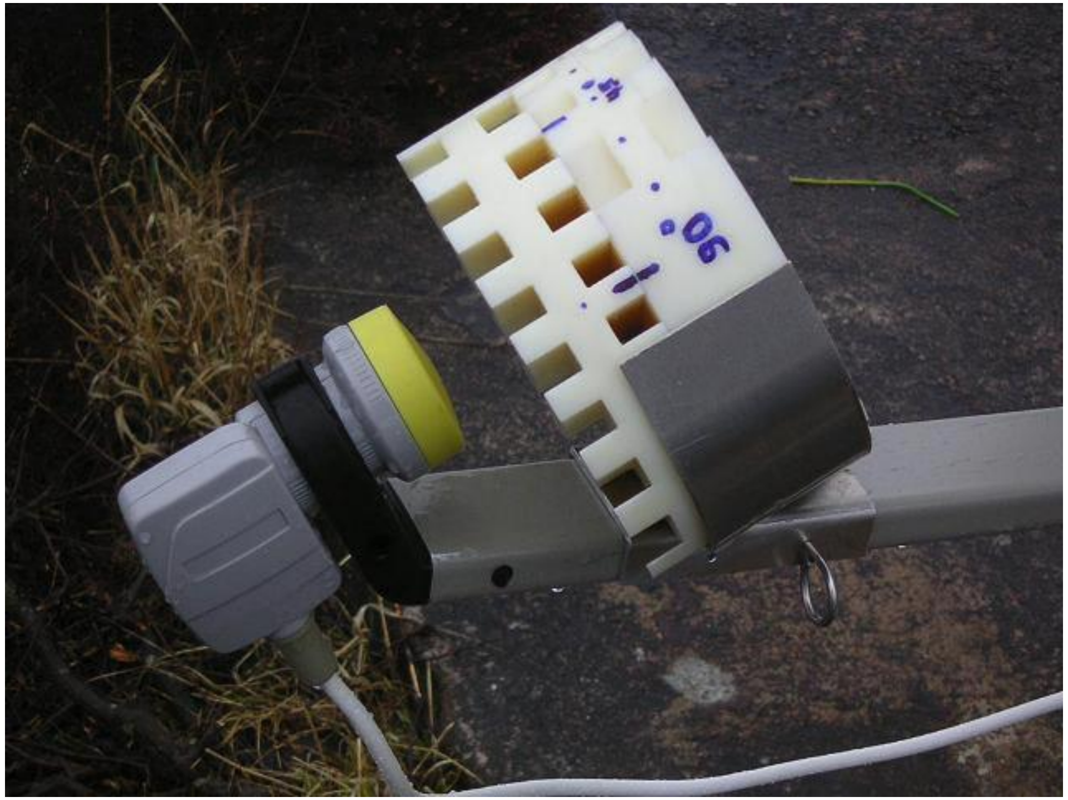
- Changing polarization:
  - E.g. to generate circular polarization
  - Using polarization rotators
  - Natural phenomea (e.g. ionosphere, rain)



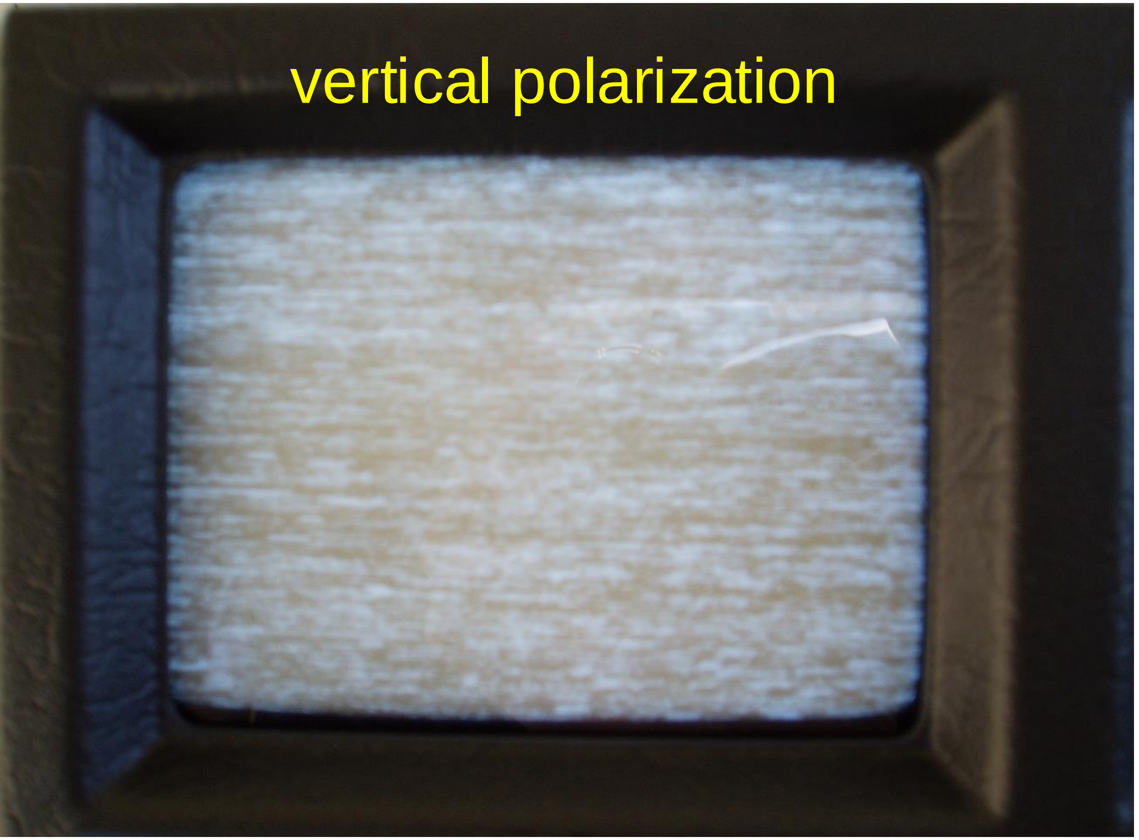
# Experiment with polarizer

- Using a standard satellite TV set
- ”watching” a horizontally polarized TV-channel
- Rotating a polarizer in front of the LNB
  - 0 degree orientation: no change, original polarization
  - 45 degree orientation: generating circular polarization
  - 90 degree orientation: reaching opposite polarization

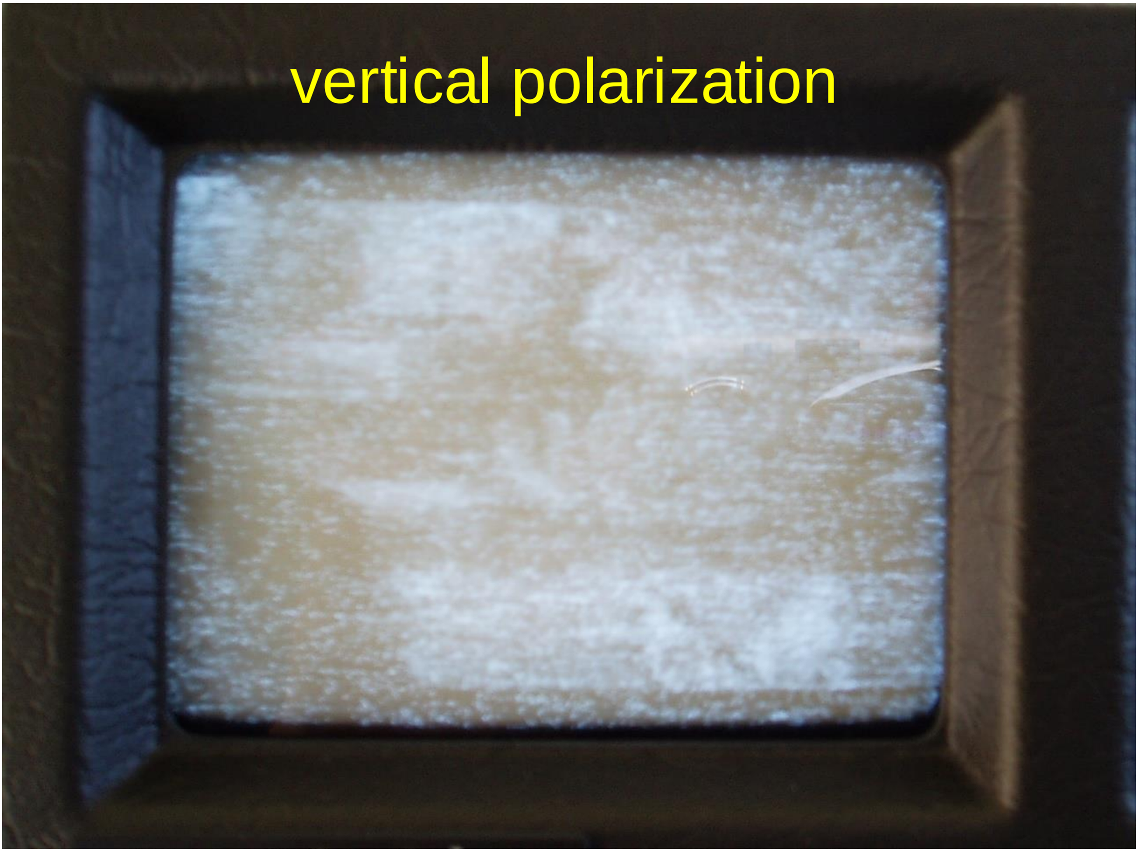
# Experimental setup

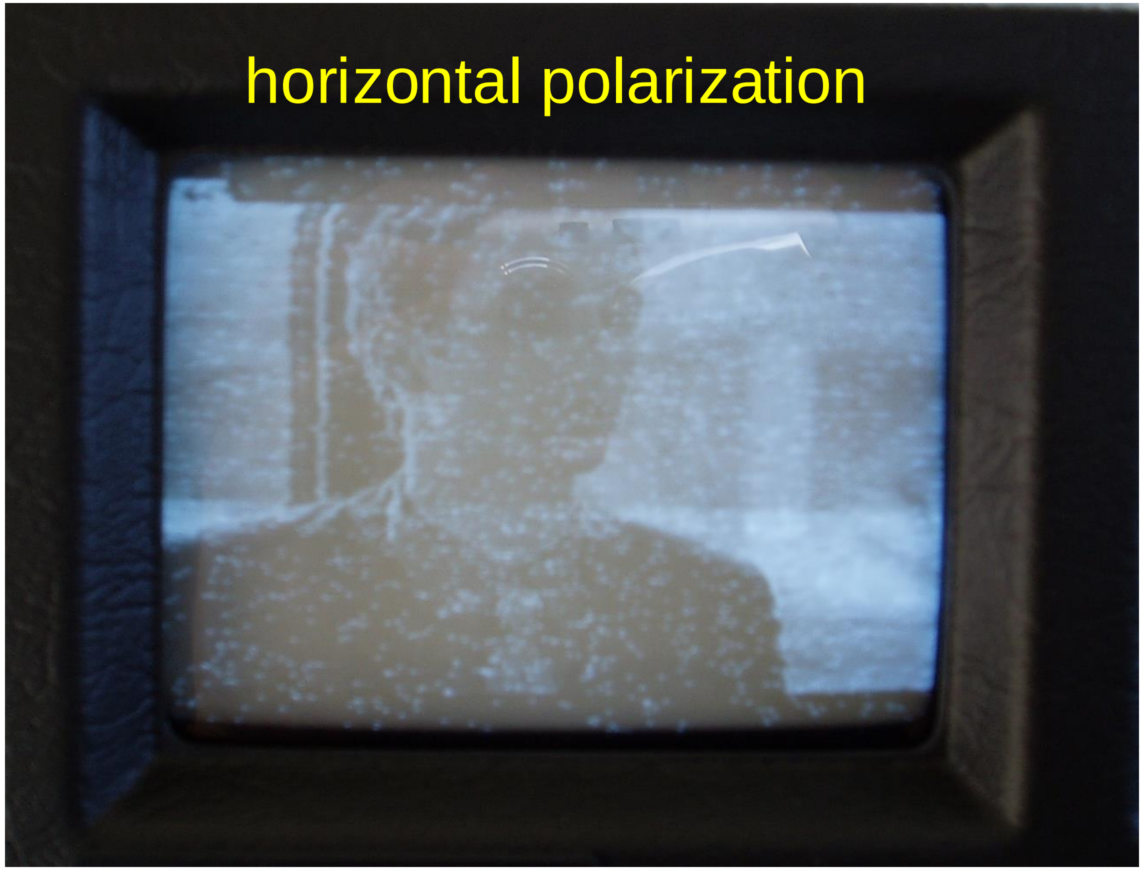



# Polarizer orientation 0 degree

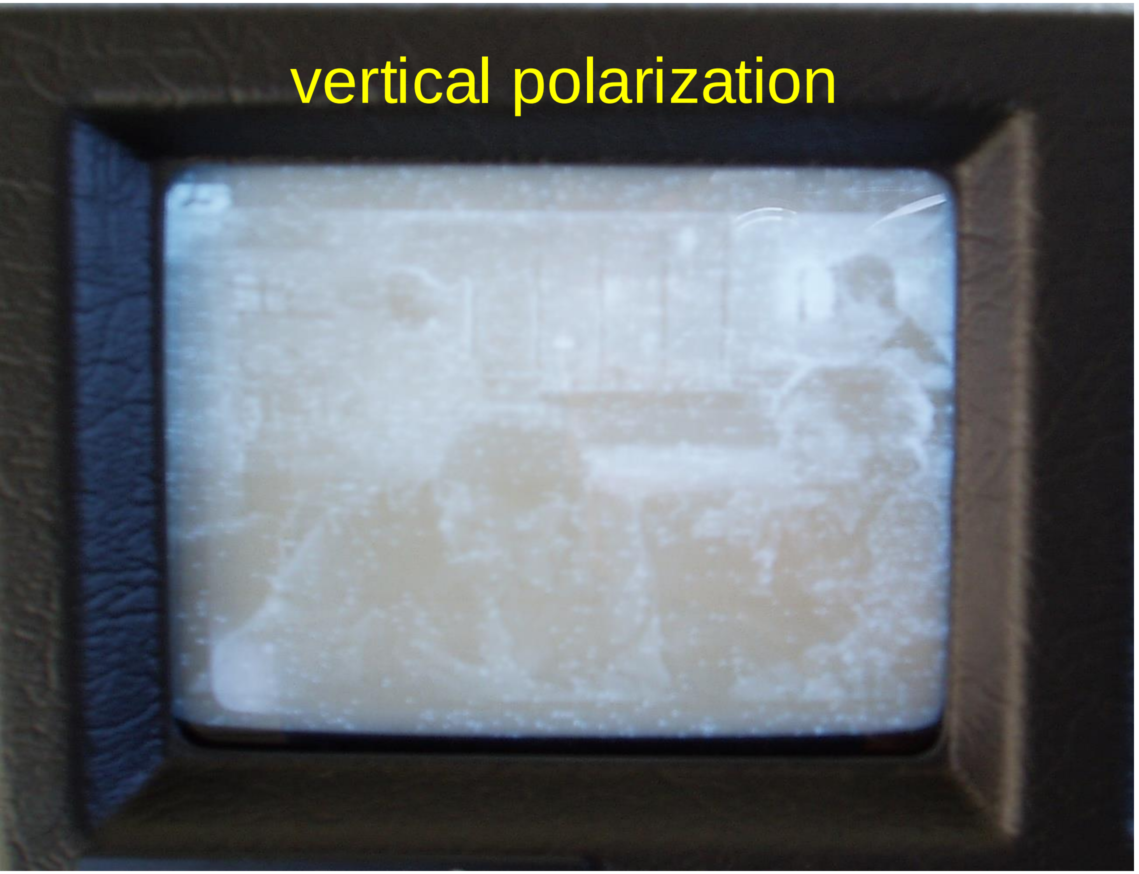


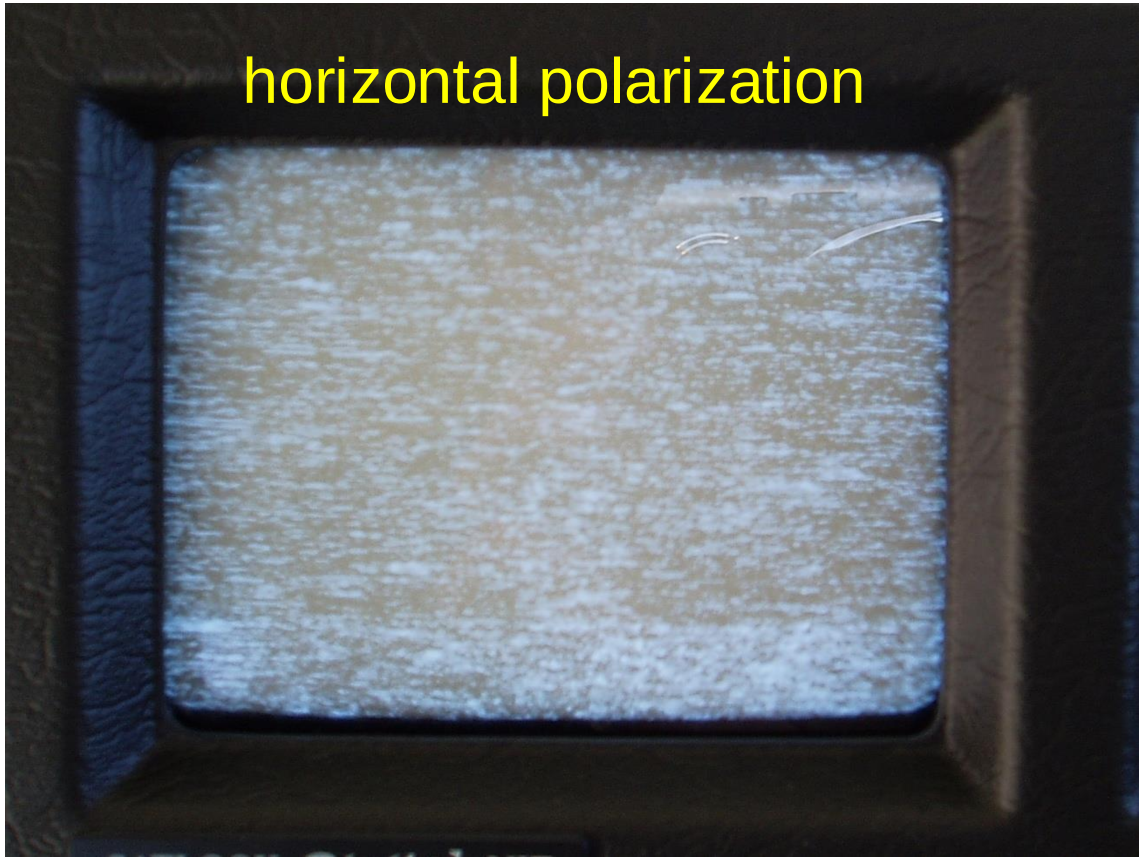

# Polarizer orientation 45 degree



# Polarizer orientation 90 degree



# Short summary of today’s topics

- Earth’s atmosphere
- Polarization definition
- Polarization of antennas
- Poincaré sphere
- Polarization state
- Stokes parameters
- Measuring polarization